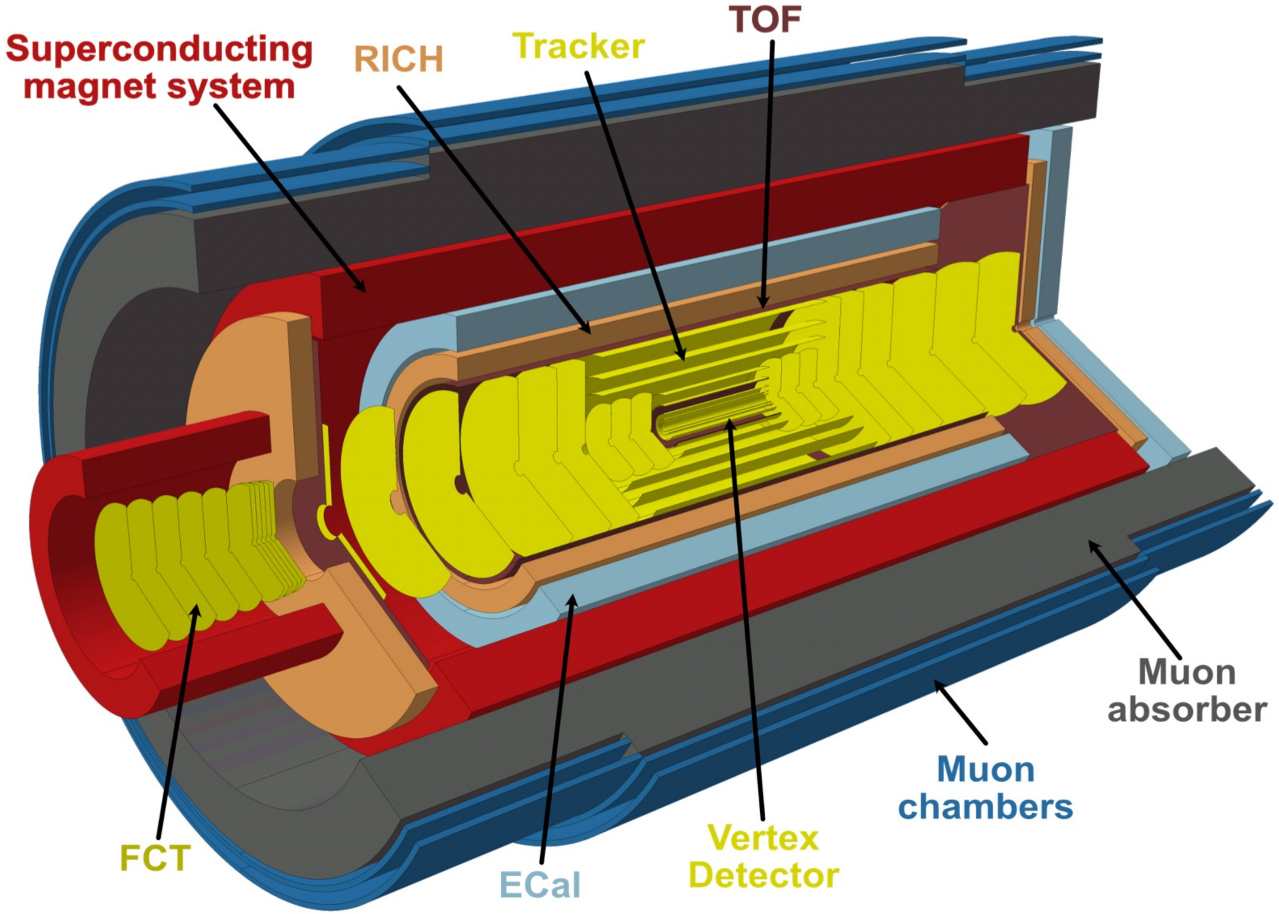
International School of
Subnuclear Physics (ISSP)
58th Course

15-24/06/2022

Performance study of LGADs for the ALICE 3 timing layers

Sofia Strazzi

University of Bologna, Italy



ALICE 3: a next generation heavy-ion experiment

2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
LHC Run 3				LHC LS3			LHC Run 4				LHC LS4

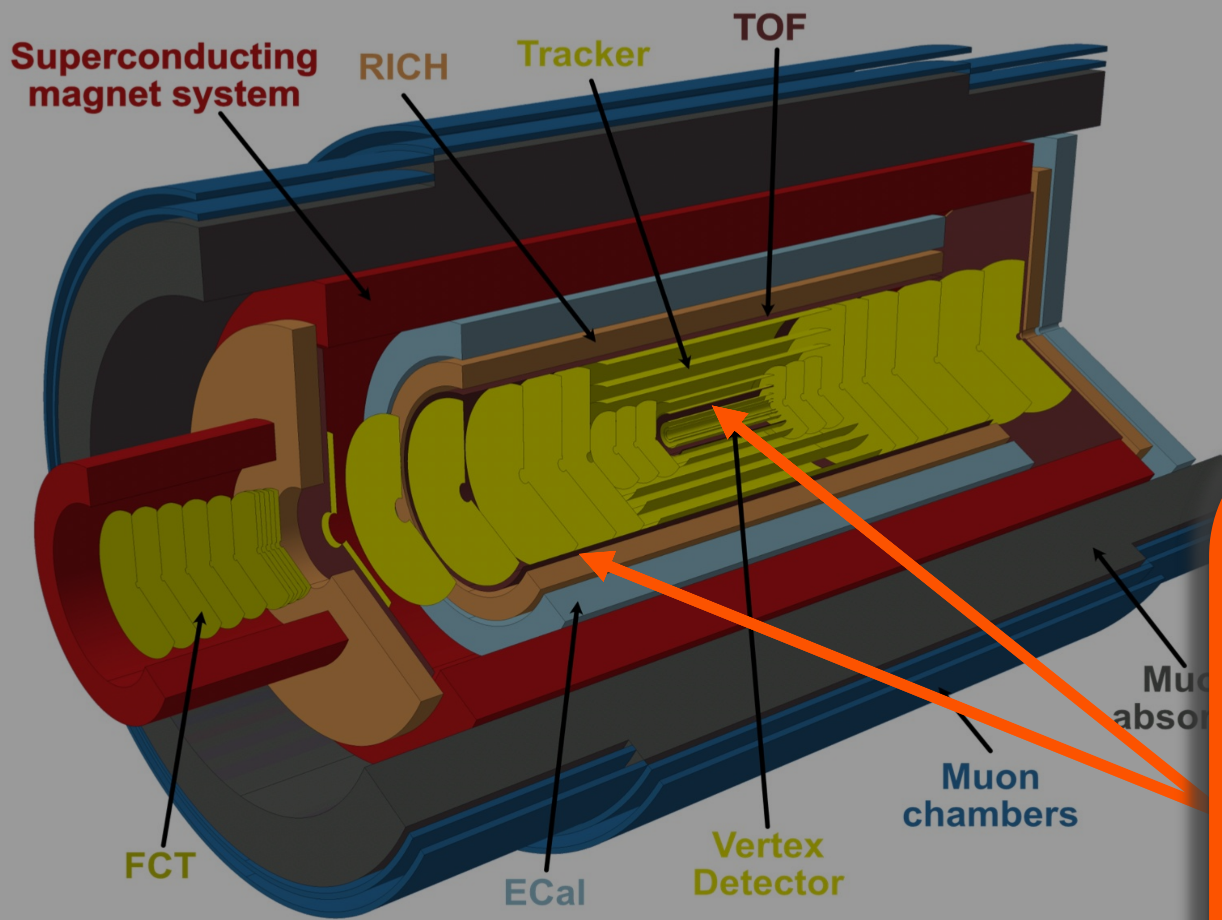
Nearly mass-less, based on the most advanced silicon technologies

- Excellent PID
- Secondary vertex finding
- Reconstruction efficiency at very low momenta

New exciting opportunities for the study of:

✦ **Heavy flavor** hadrons

✦ electromagnetic and hadronic **probes of the QGP** at very low momenta



ALICE 3: a next generation heavy-ion experimen

Nearly mass-less, based on the most advanced silicon technologies

- Excellent PID
- Secondary vertex finding
- Reconstruction efficiency

Silicon-based Time-Of-Flight (TOF)

Required time resolution → **20ps**

Several **innovative technologies** are **under evaluation**

ities

QGP

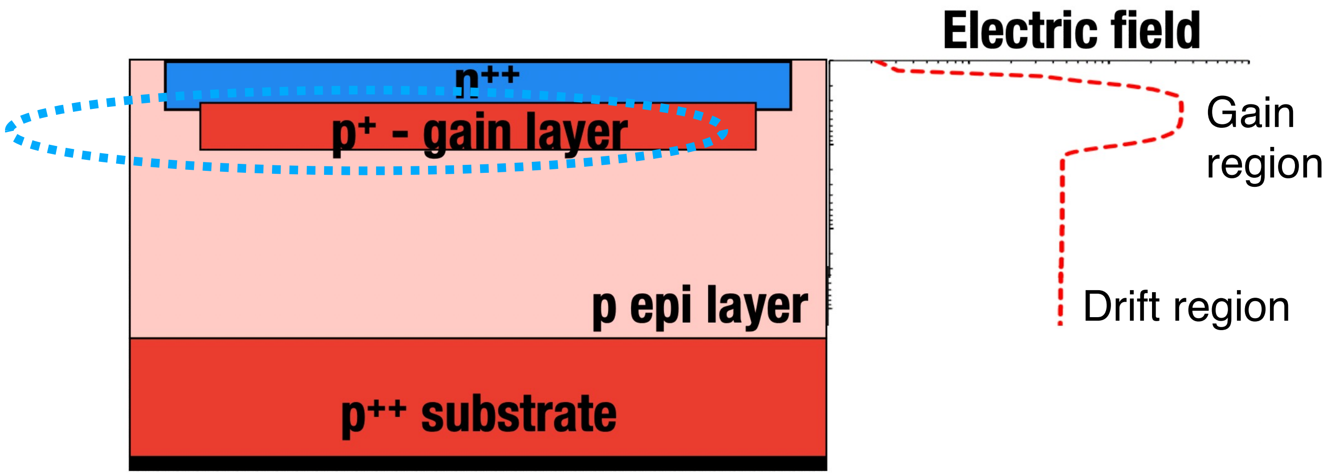
2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032

LHC Run 3 | LHC LS3 | LHC Run 4 | LHC LS4

LOW GAIN AVALANCHE DETECTOR (LGAD)

Developed to detect charged particles → Evolution of n-in-p standard sensors

Additional gain layer implant

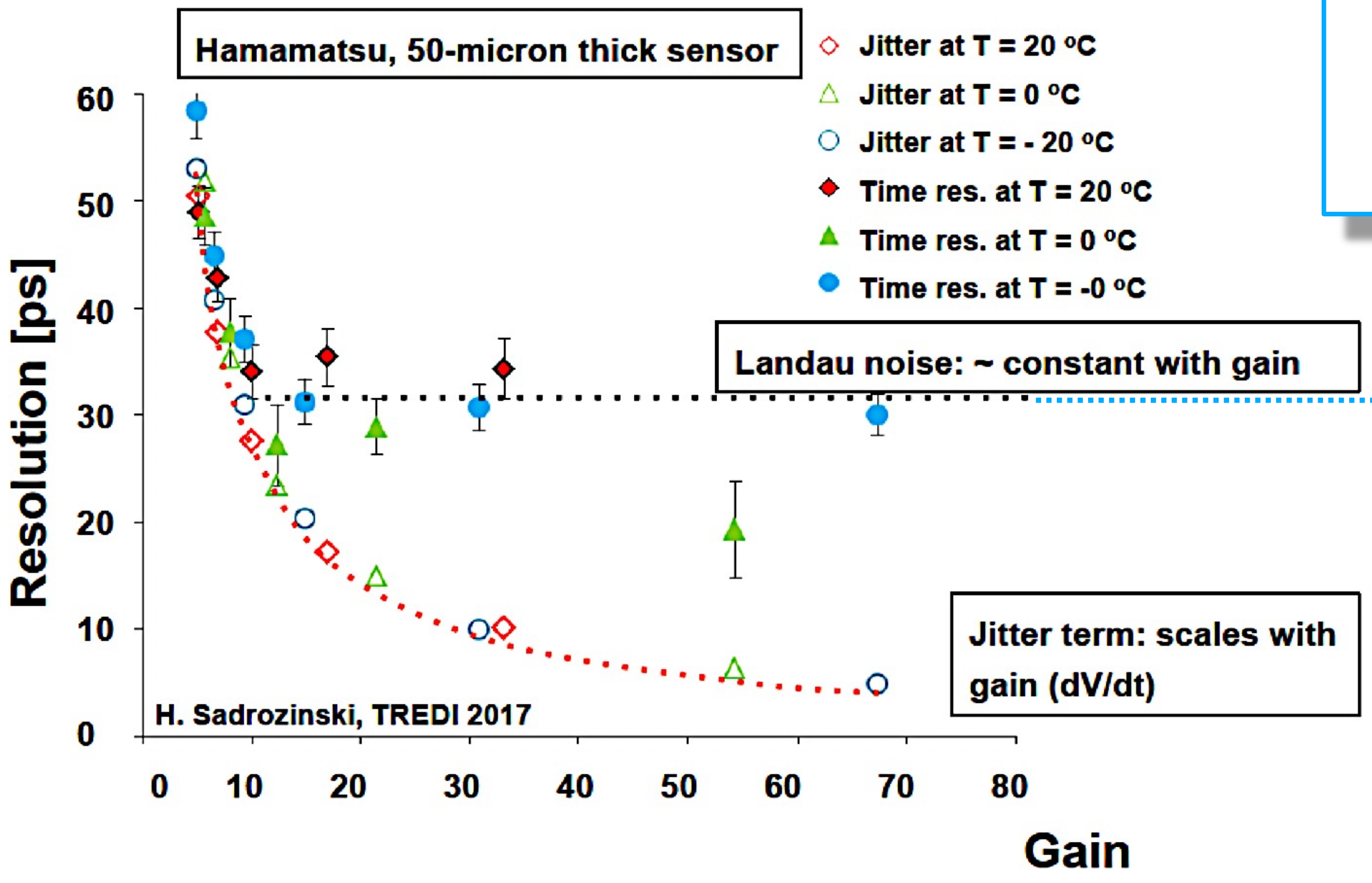


Internal, low gain (10-70) multiplication mechanism

Large and fast signals
in respect to sensors without gain layer

→ **Excellent timing performance**

STATE OF THE ART



Extensively studied in recent years

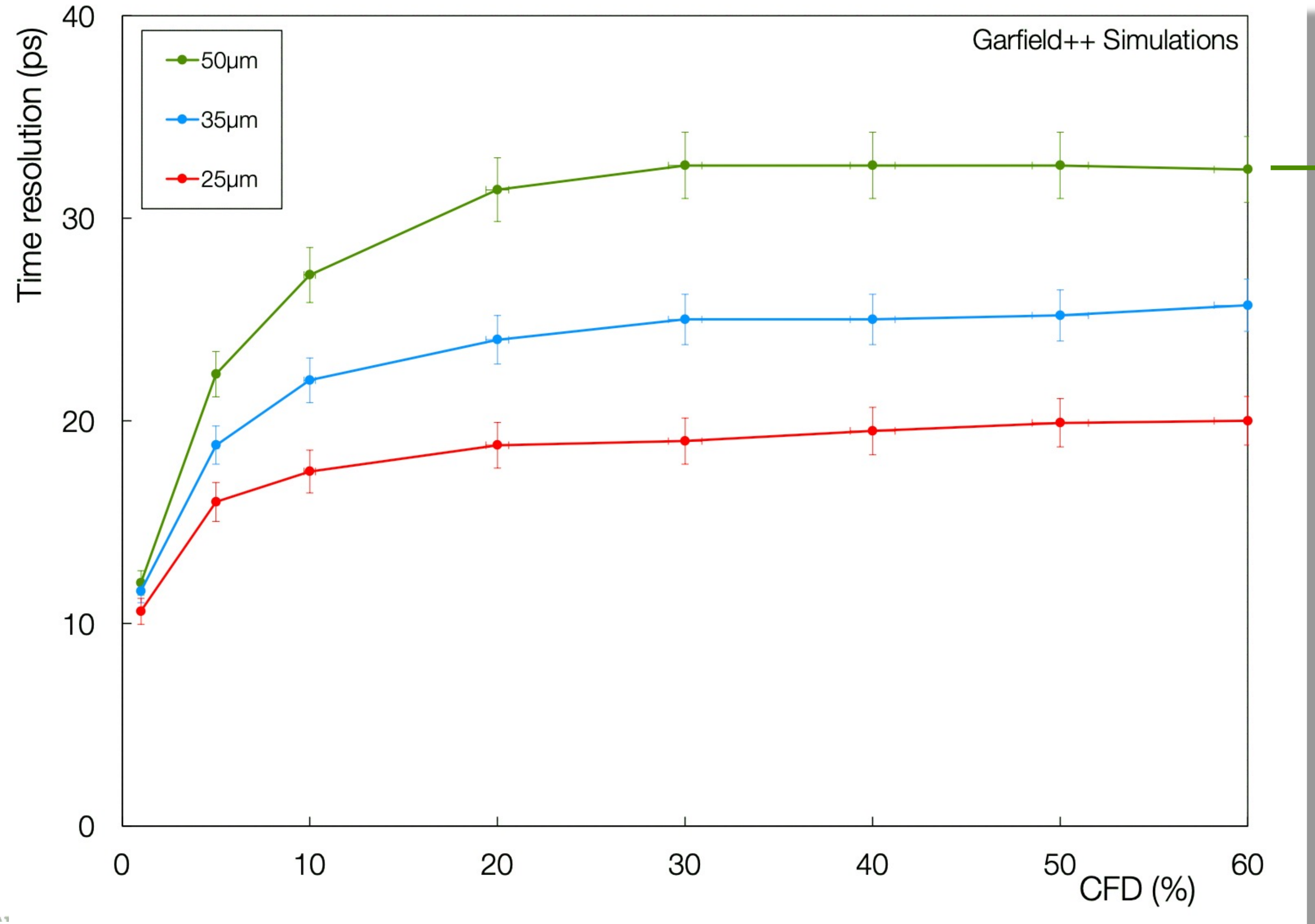
↓

most mature silicon detector technology for timing applications

50 µm: time resolution ~30 ps

→ Already envisioned for the detector upgrades at the HL-LHC both in ATLAS and CMS for 2026

MOTIVATIONS



Already envisioned for the detector upgrades at the HL-LHC both in ATLAS and CMS for 2026

ALICE 3 Timing Layers need an even better time resolution ~**20 ps**

A **thinner** LGAD design could match the requirements

TESTED LGADs

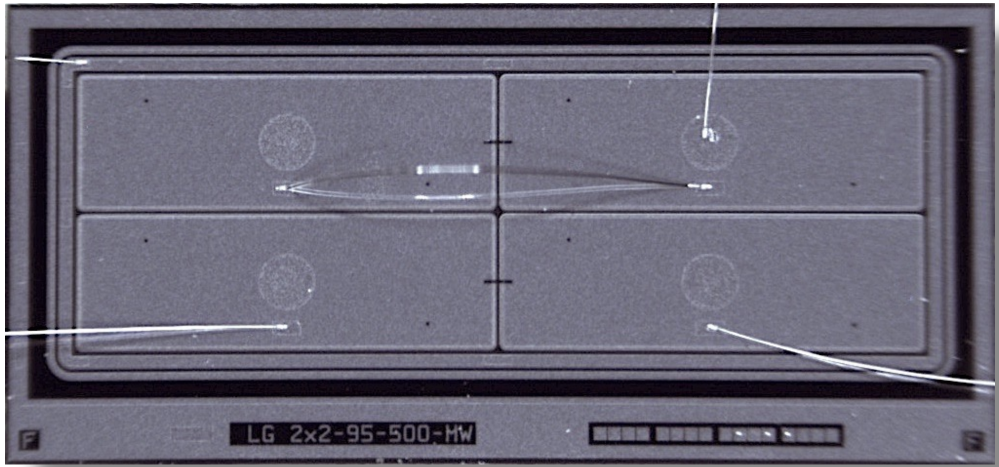
First very thin LGAD prototypes produced by FBK

50 µm-thick HPK LGAD

With known resolution

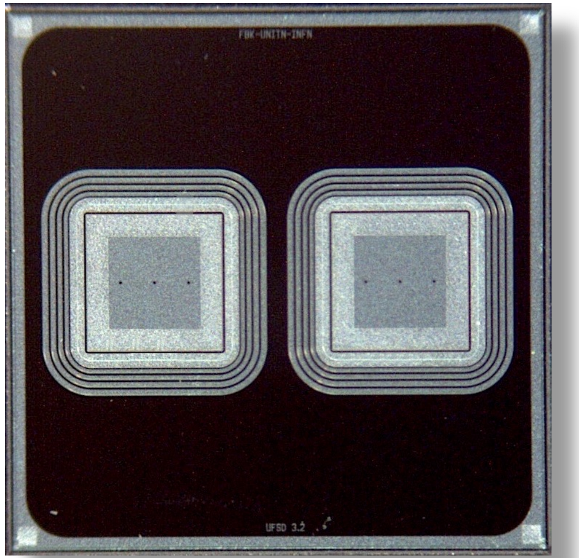
- Comparison
- Results confirmation

1x3 mm²

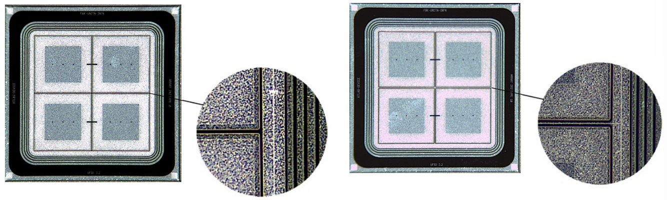


25 µm and 35 µm-thick FBK single channel

1x1 mm²



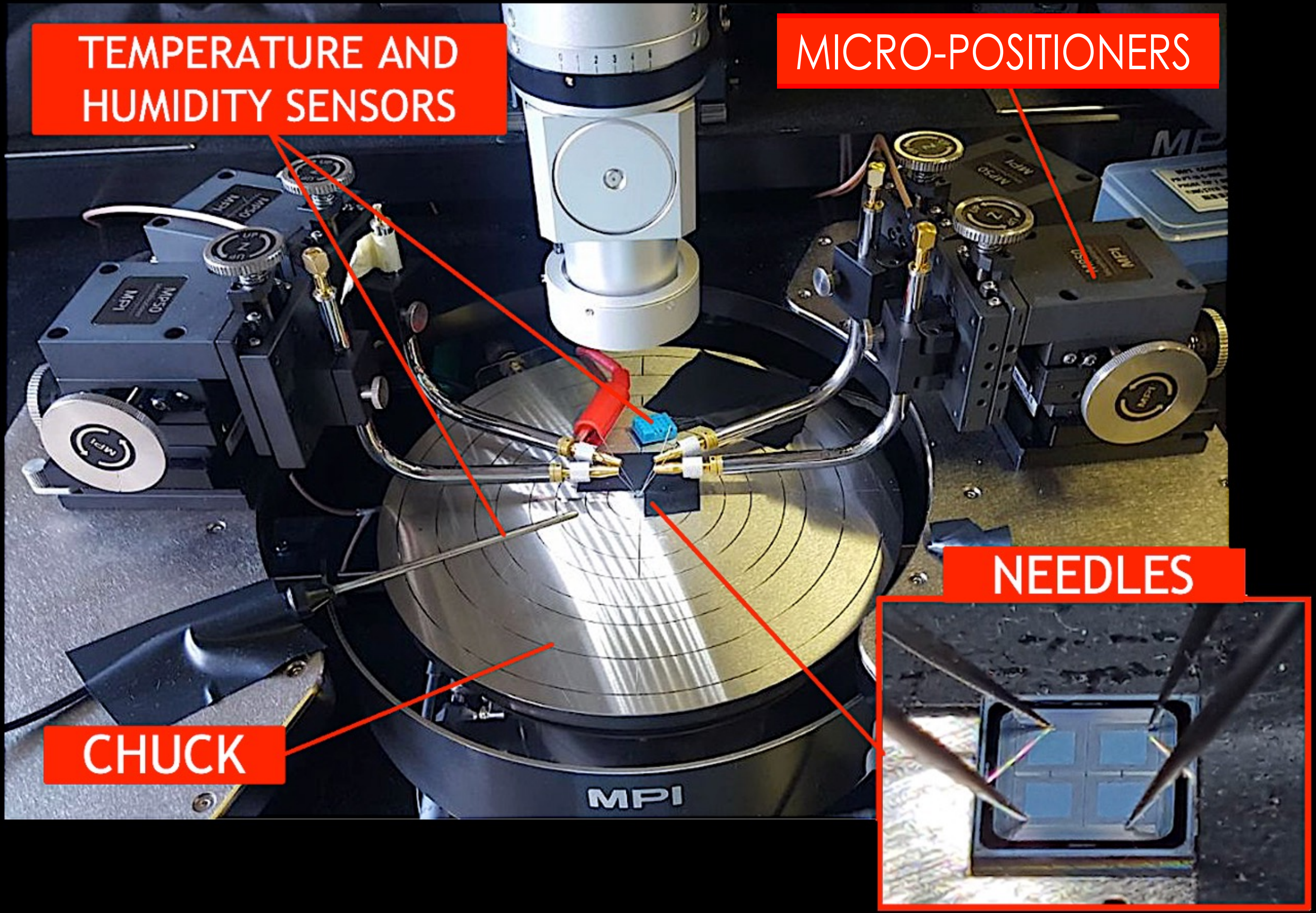
Matrices **1.3x1.3 mm²**



IV

CV

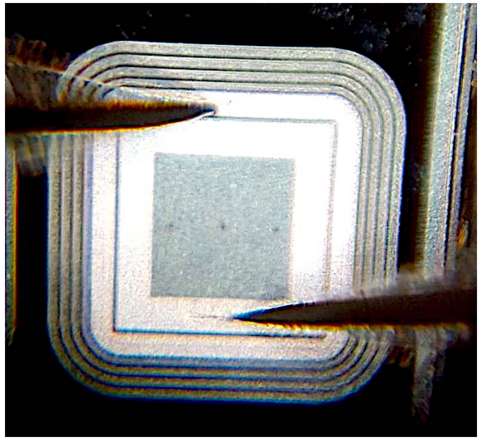
ELECTRICAL CHARACTERIZATION

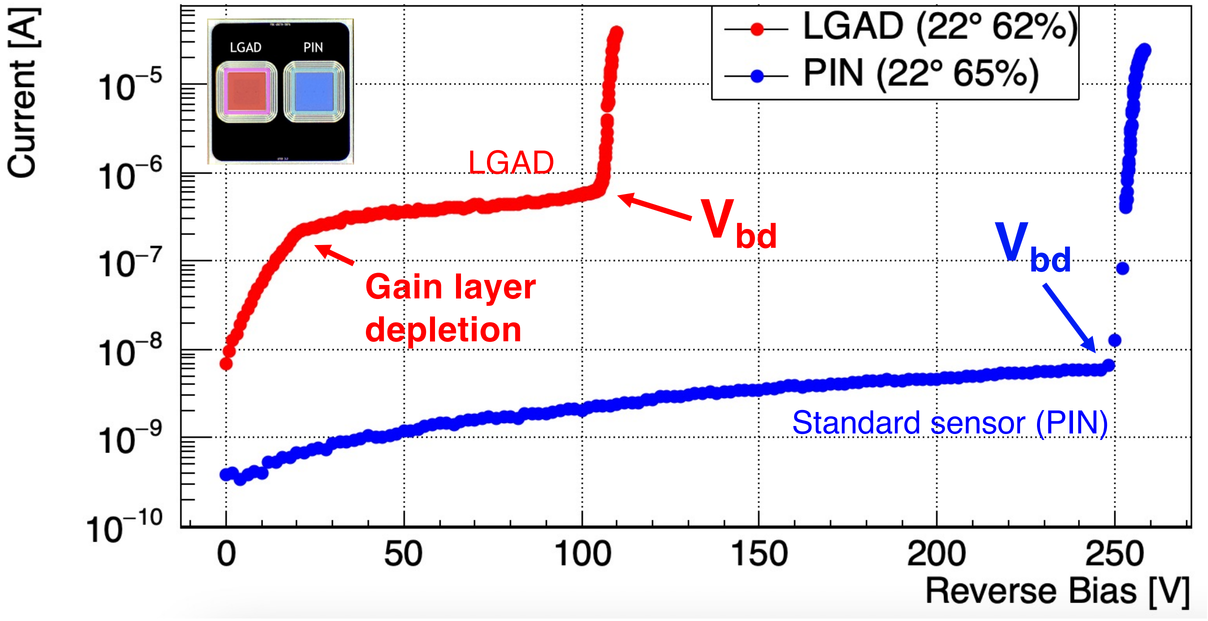


IV

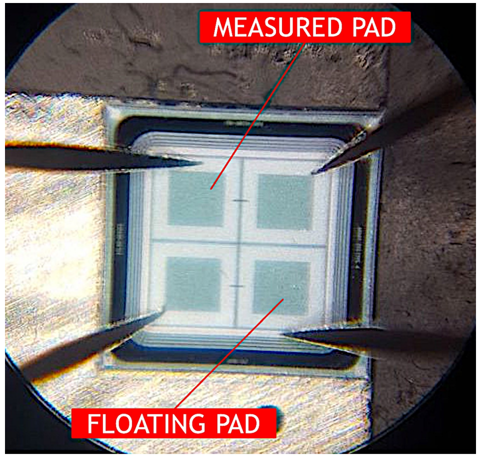
CV

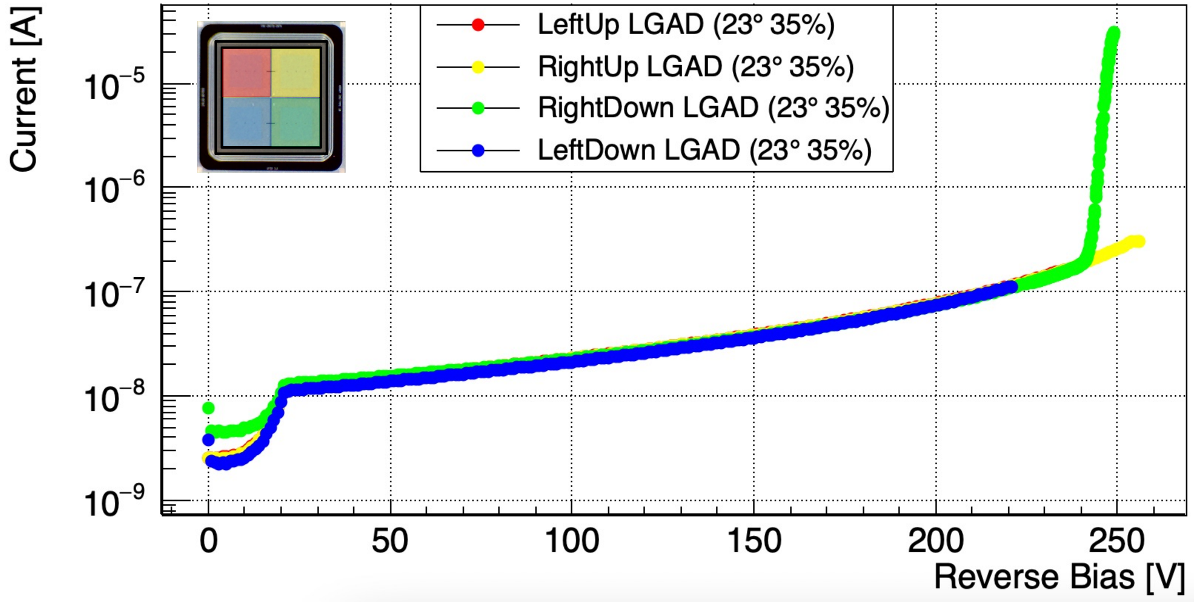
PIN-LGAD



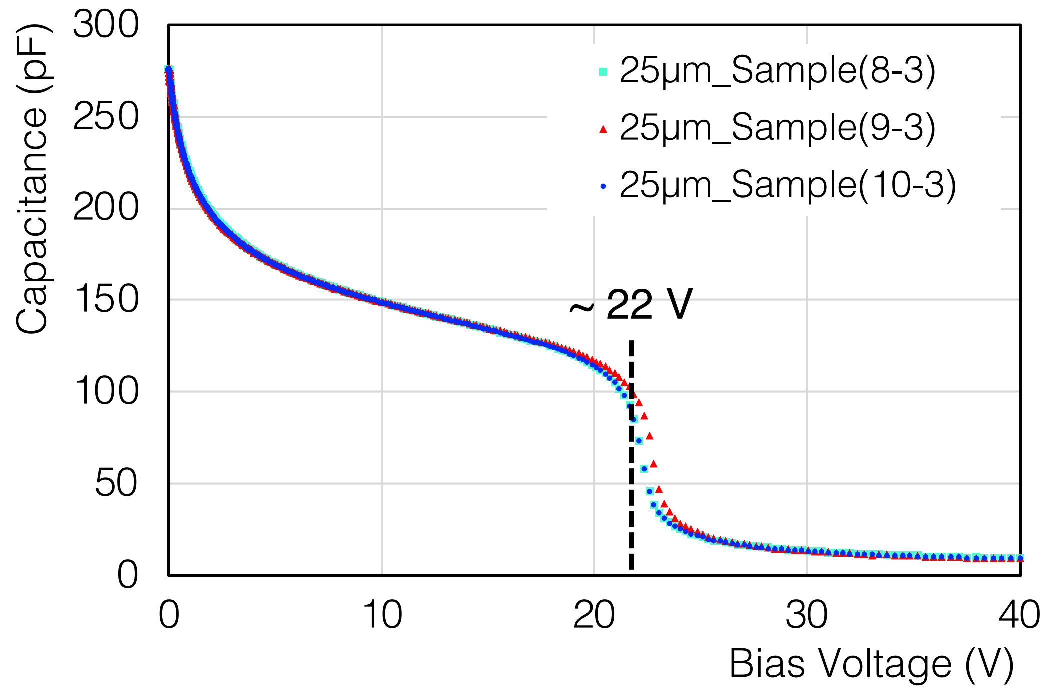


MATRIX

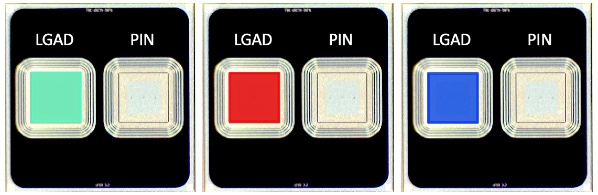


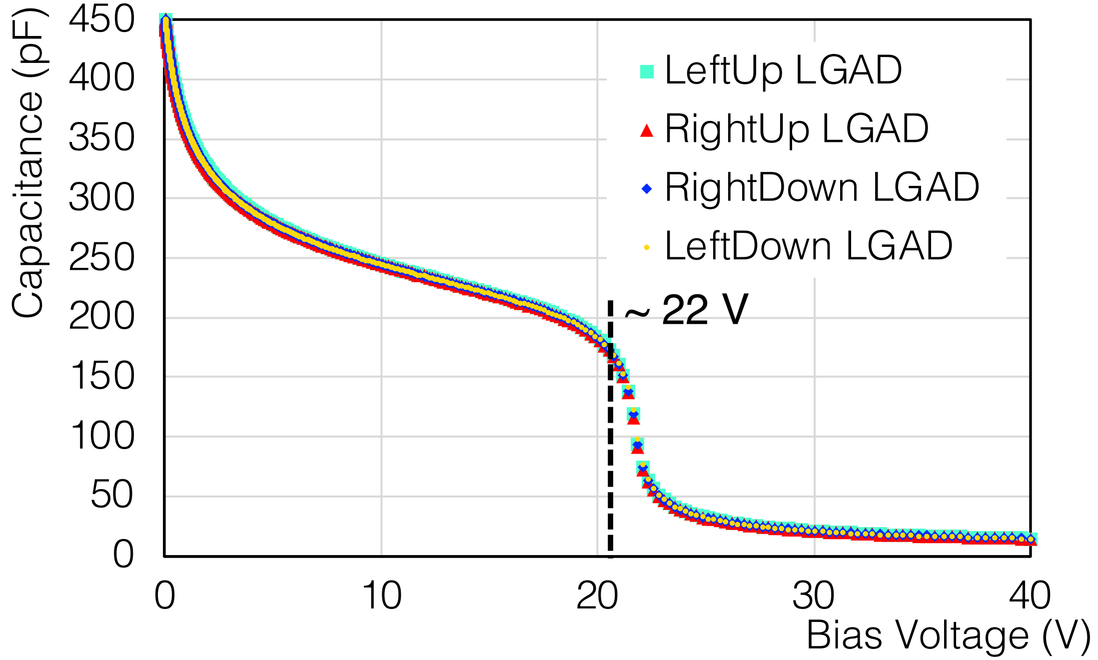


- Breakdown V
- Voltage interval of operation
- Evaluate inter-pad configuration

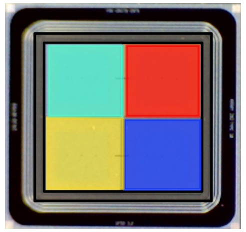


Sensors with the same wafer (25 μm)





Pads of a same matrix



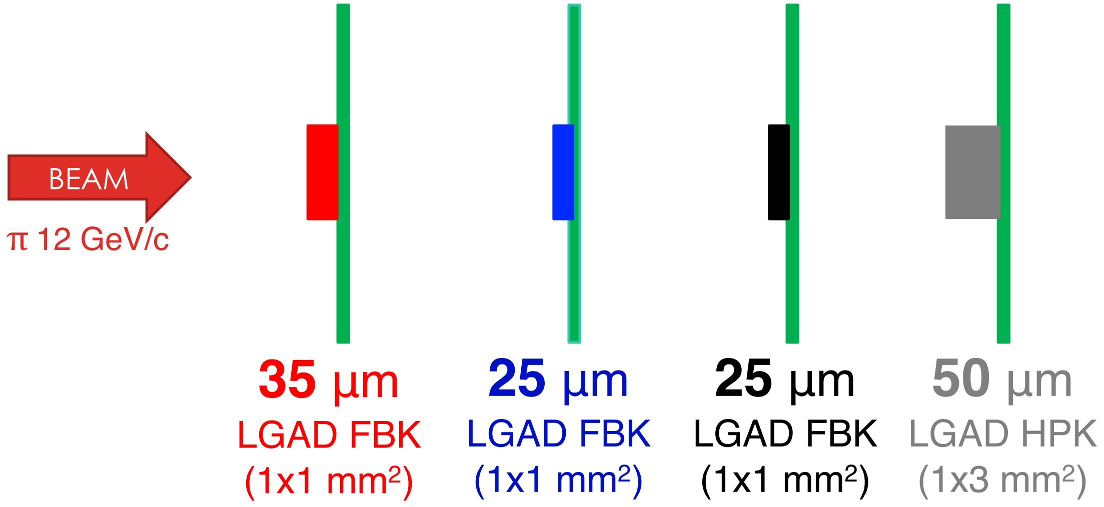
Totally negligible non-uniformities

IV

CV

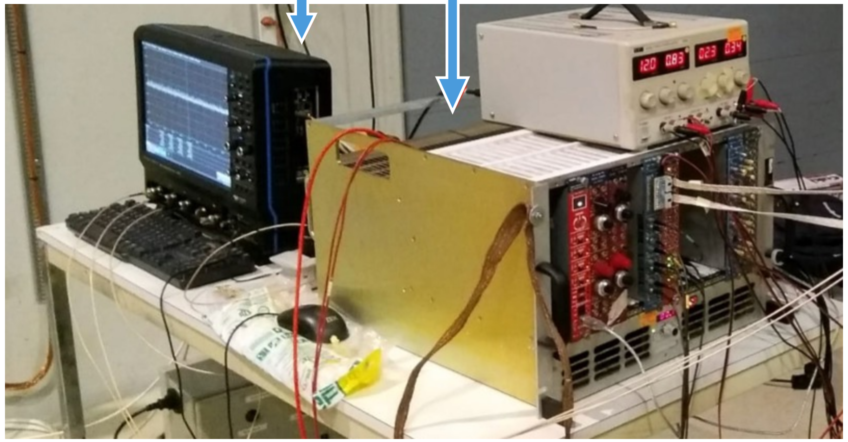
- Gain layer depletion V
- Full depletion V
- Connected to the doping profile

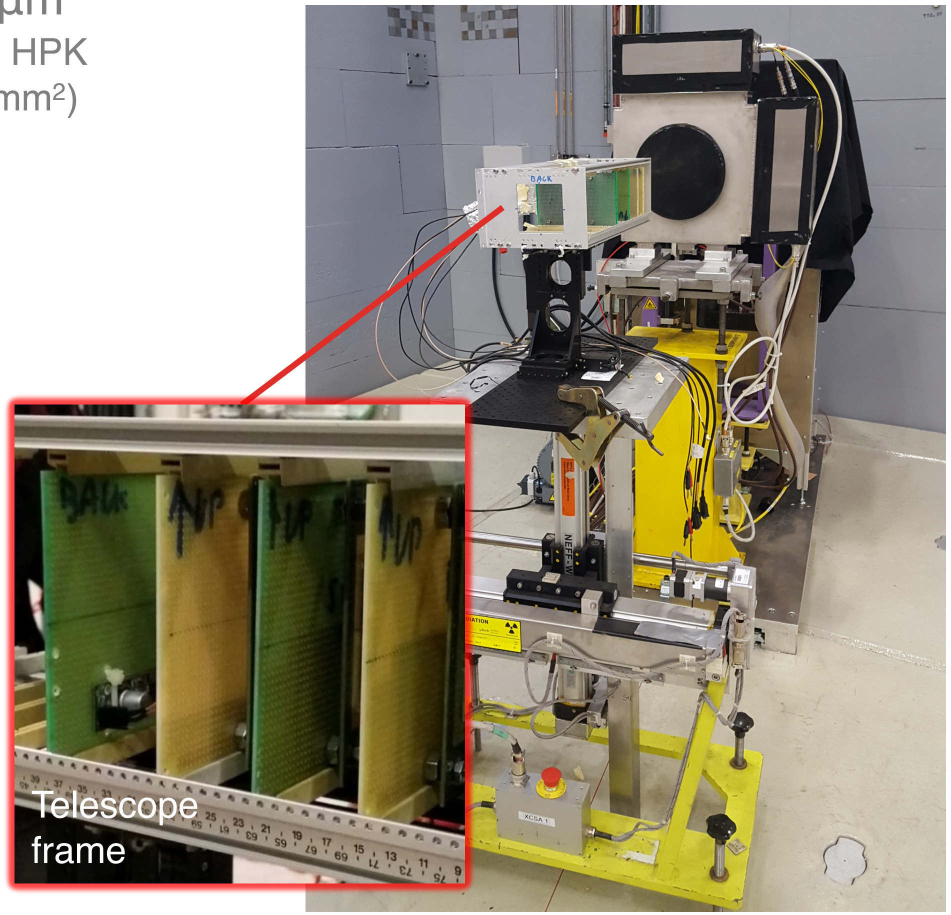
TEST BEAM SETUP



LeCroy WaveRunner 9404M-MS
Sampling rate: 20 GS/s
Time discretization: 50 ps

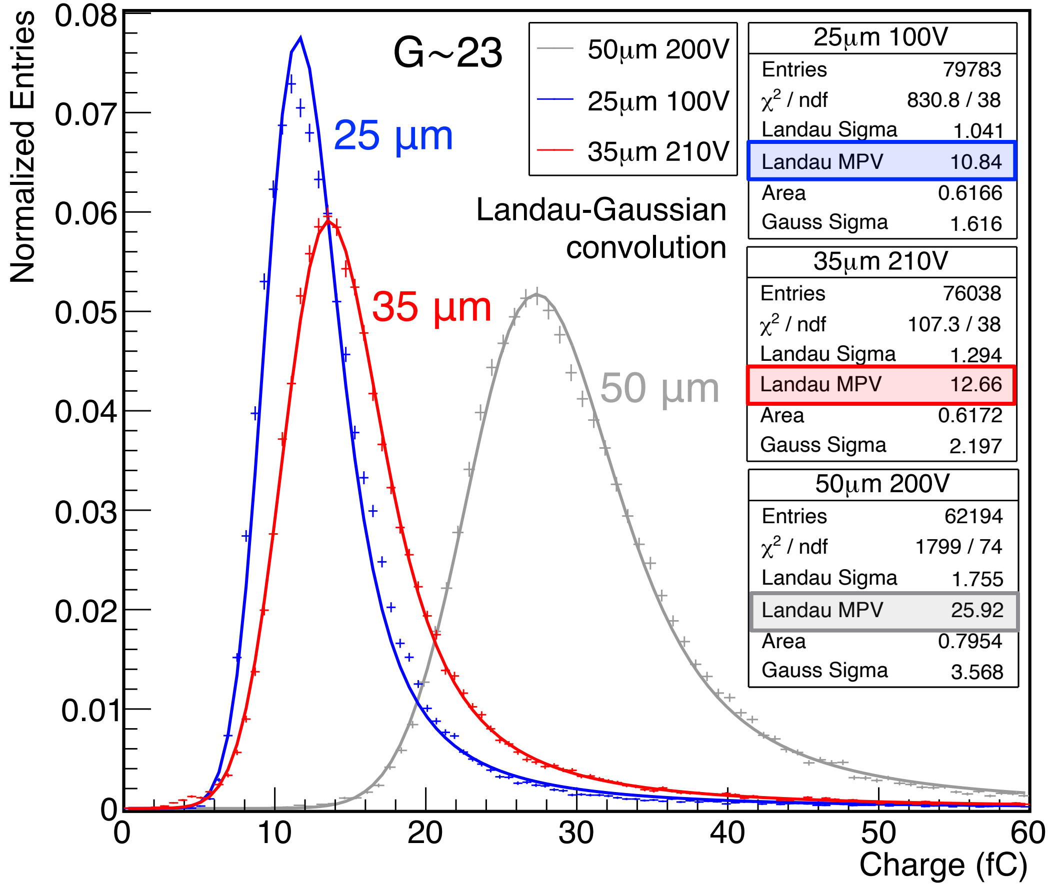
CAEN power supply



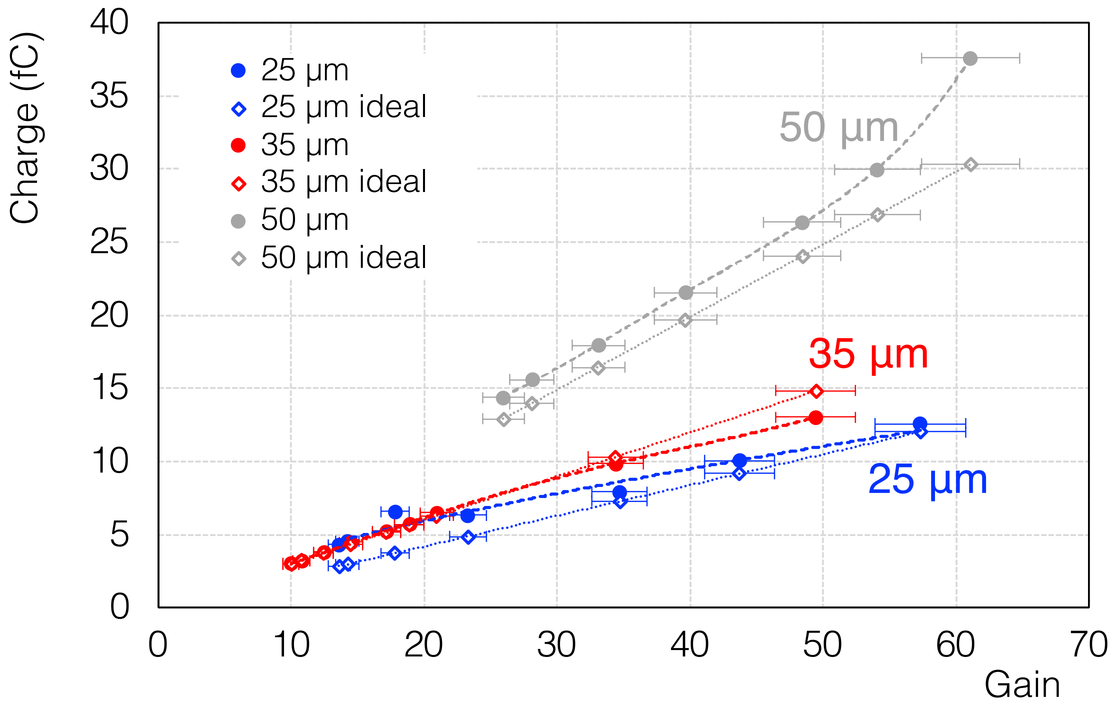


CHARGE DISTRIBUTIONS

Charge MPV increases with the thickness



Measured Charge MPV vs Ideal

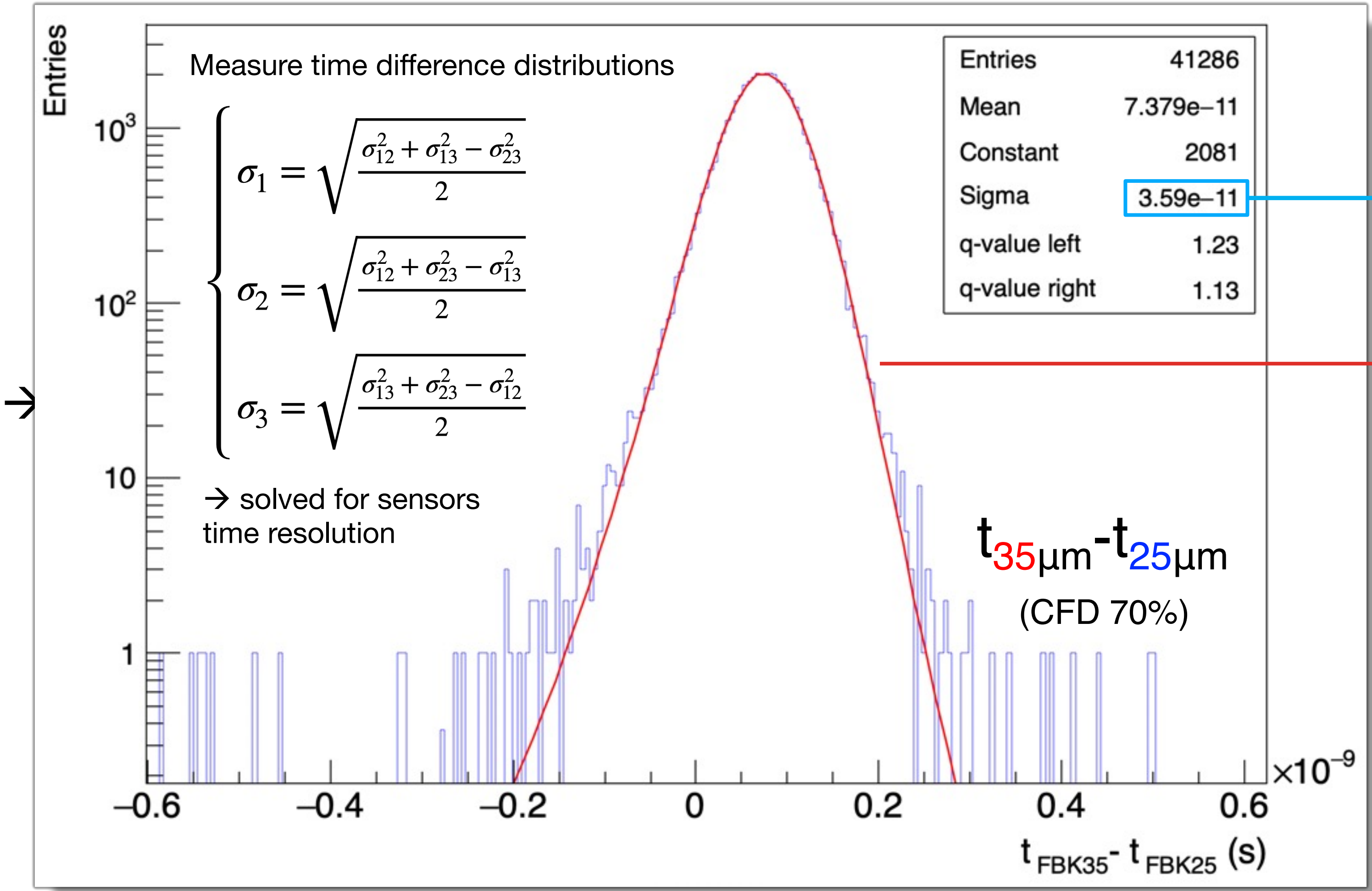


Ideal Charge = $Charge_{PIN}$ x $Gain_{meas}$

→ results are in good agreement with the expected values

DATA ANALYSIS FOR THE TIMING PERFORMANCE

Constant fraction discrimination (CFD) technique



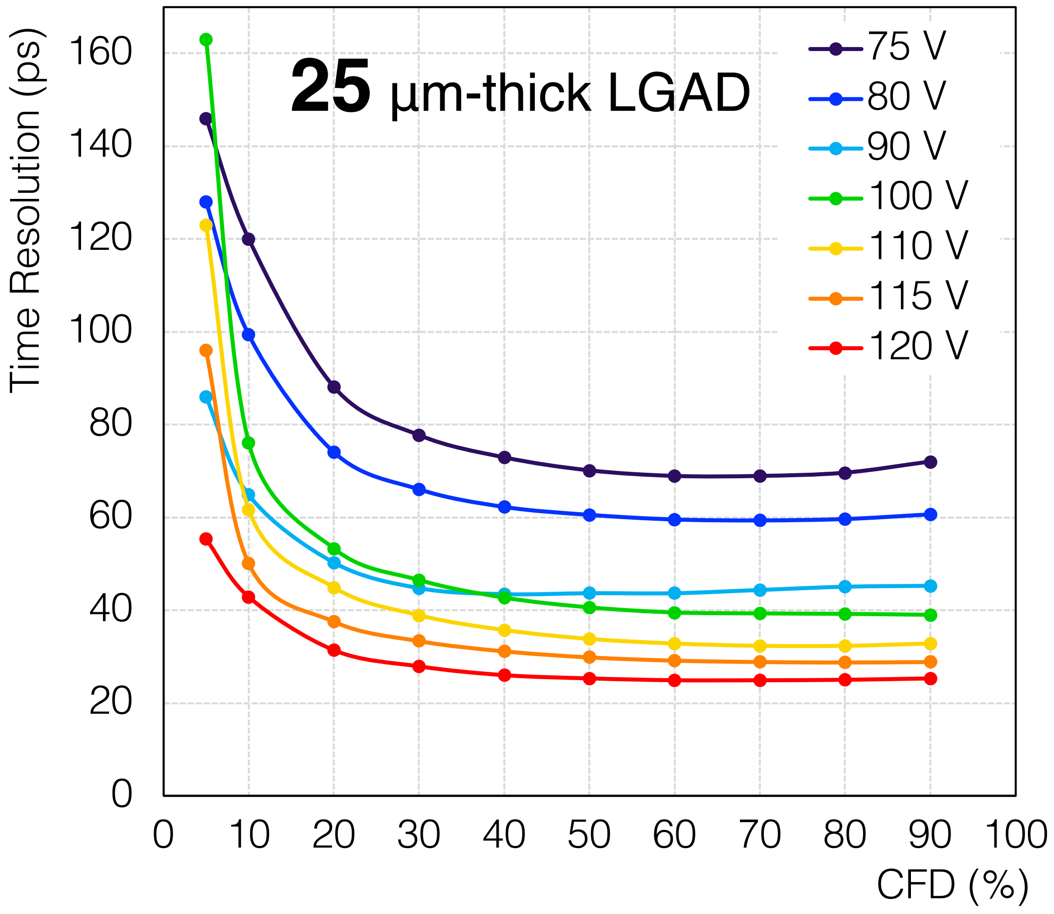
Measurements in full bandwidth (4 GHz) → Smoothing to remove high frequency noise → 1 GHz

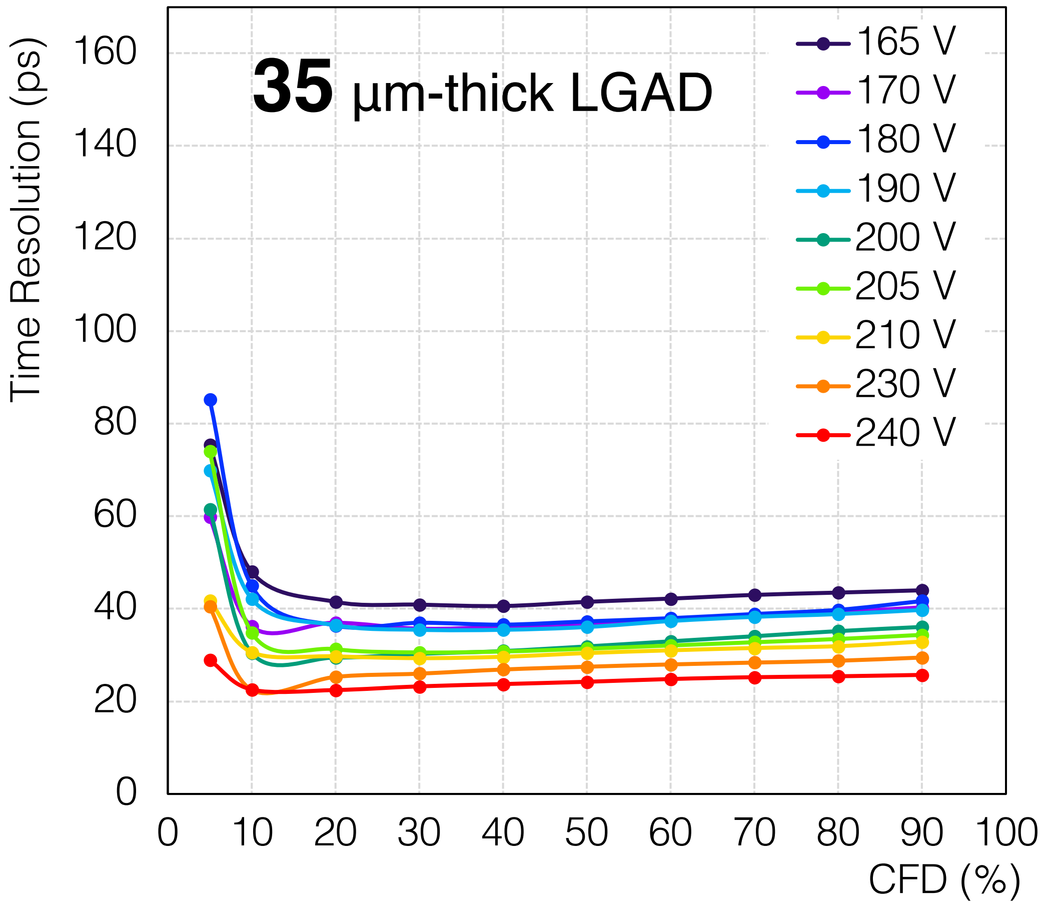
Difference between the threshold crossing time of each couple

Asymmetric q-Gaussian fit

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

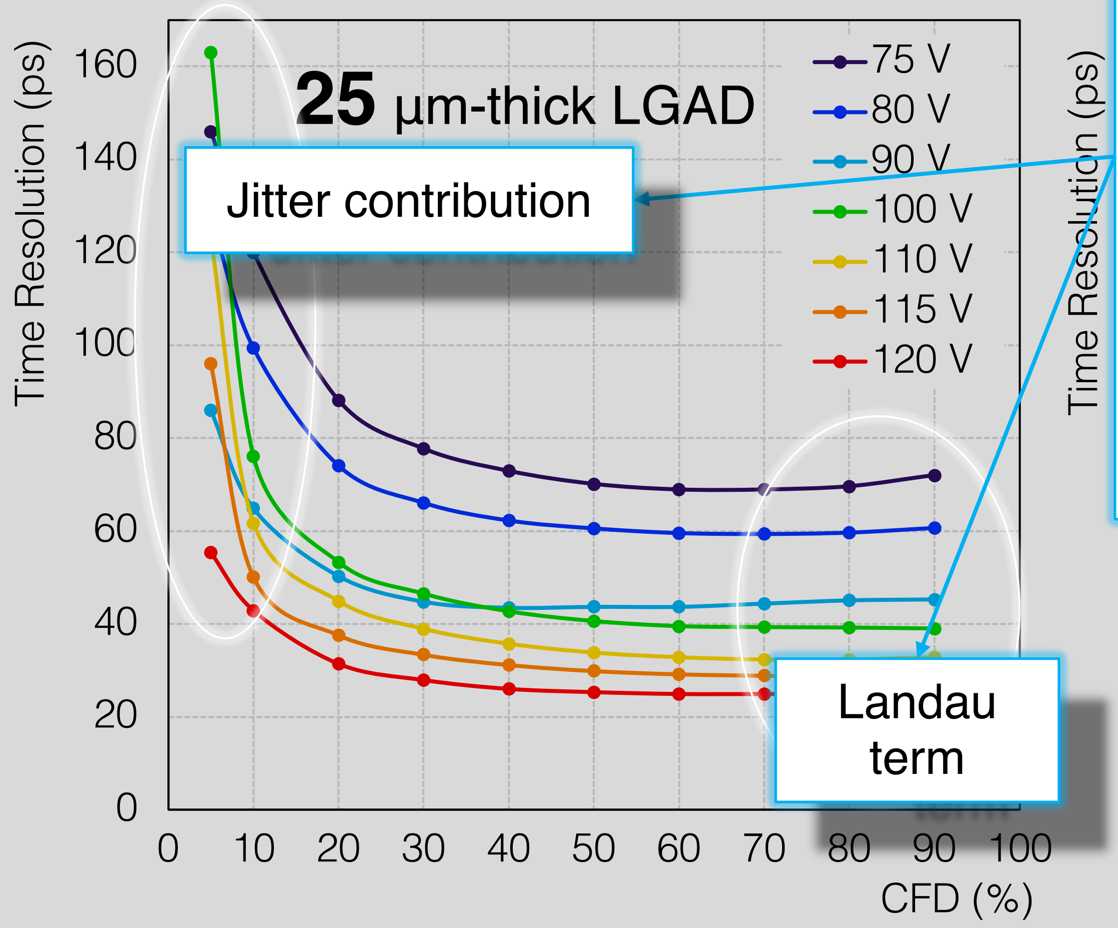
TIMING PERFORMANCE

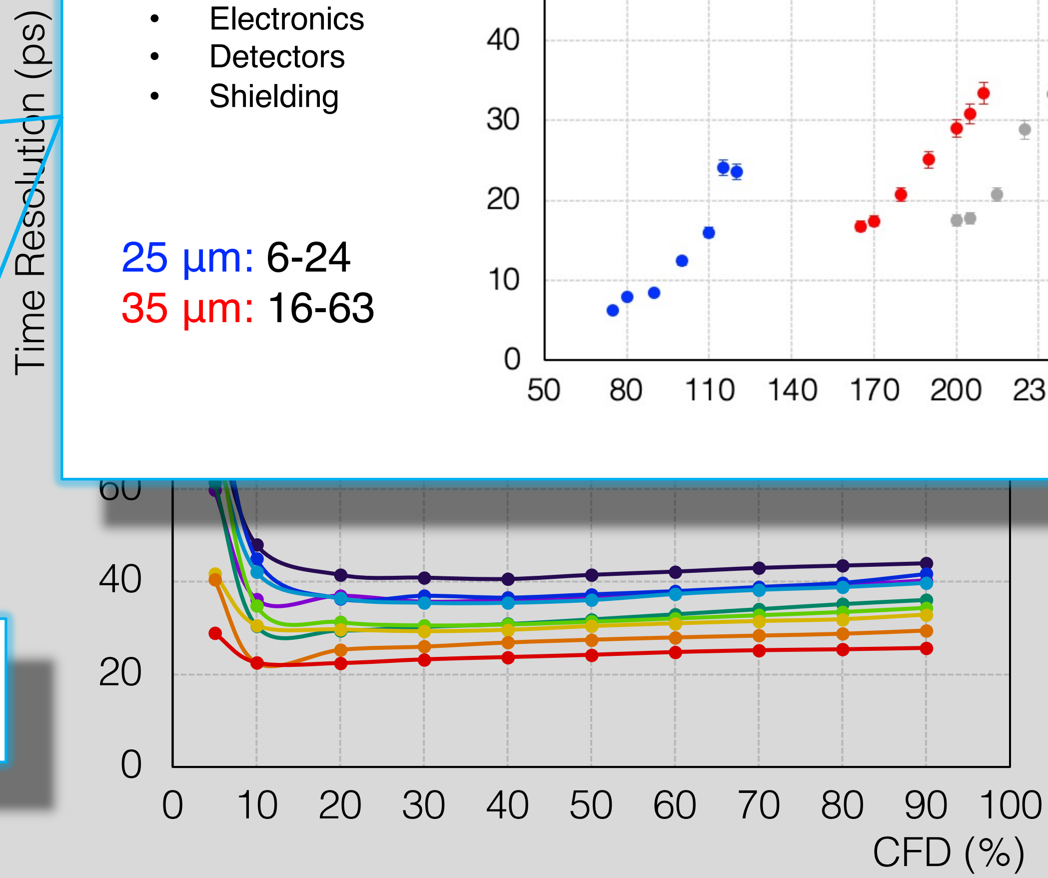




Trend and values of **50 µm** LGAD **totally in agreement** with previous results

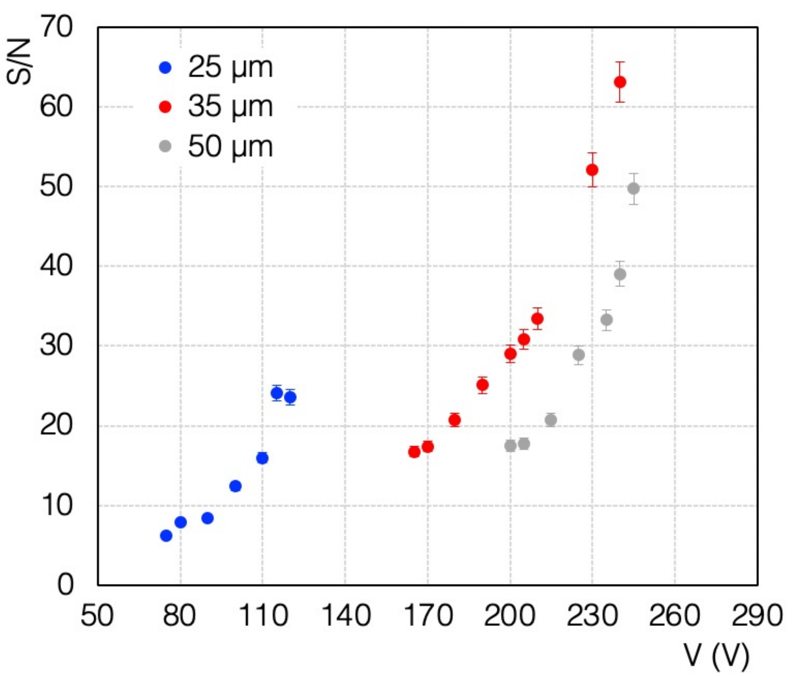
TIMING PERF





- Thickness
- S/N
  - Electronics
  - Detectors
  - Shielding

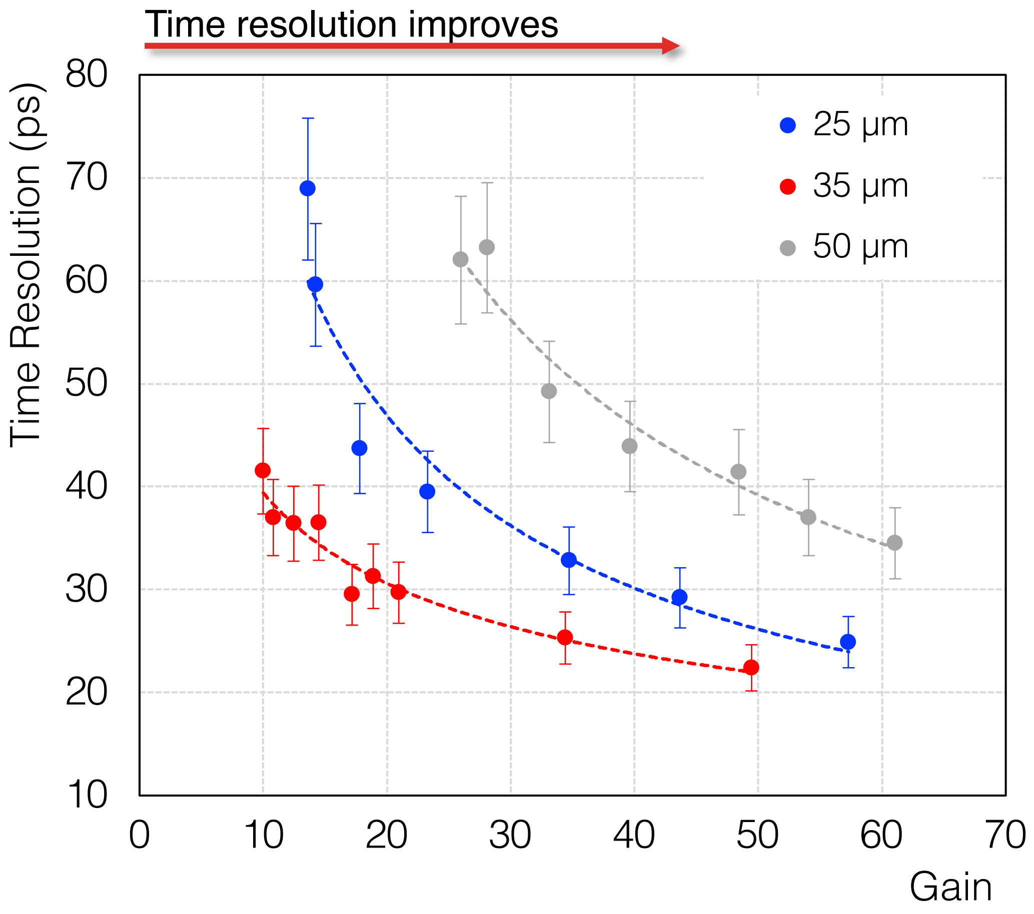
25 µm: 6-24
35 µm: 16-63

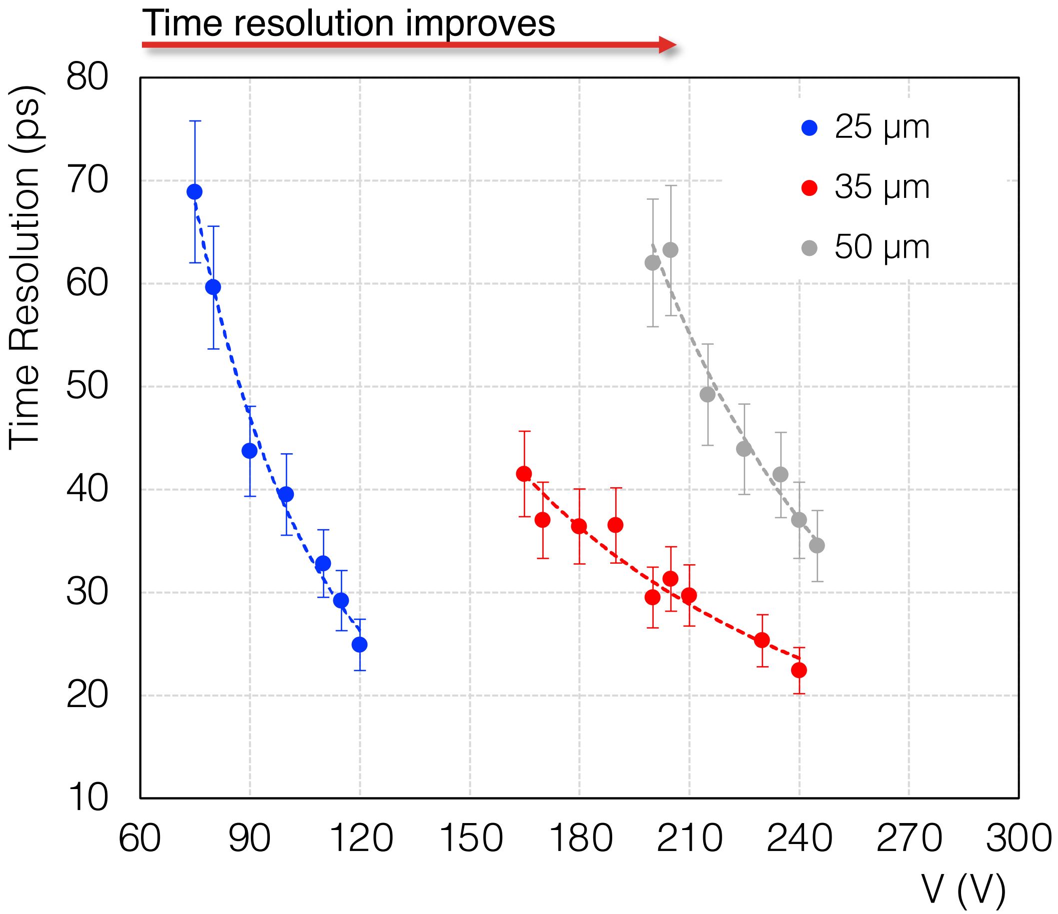


Trend and values of **50 µm** LGAD **totally in agreement** with previous results

TIMING PERFORMANCE

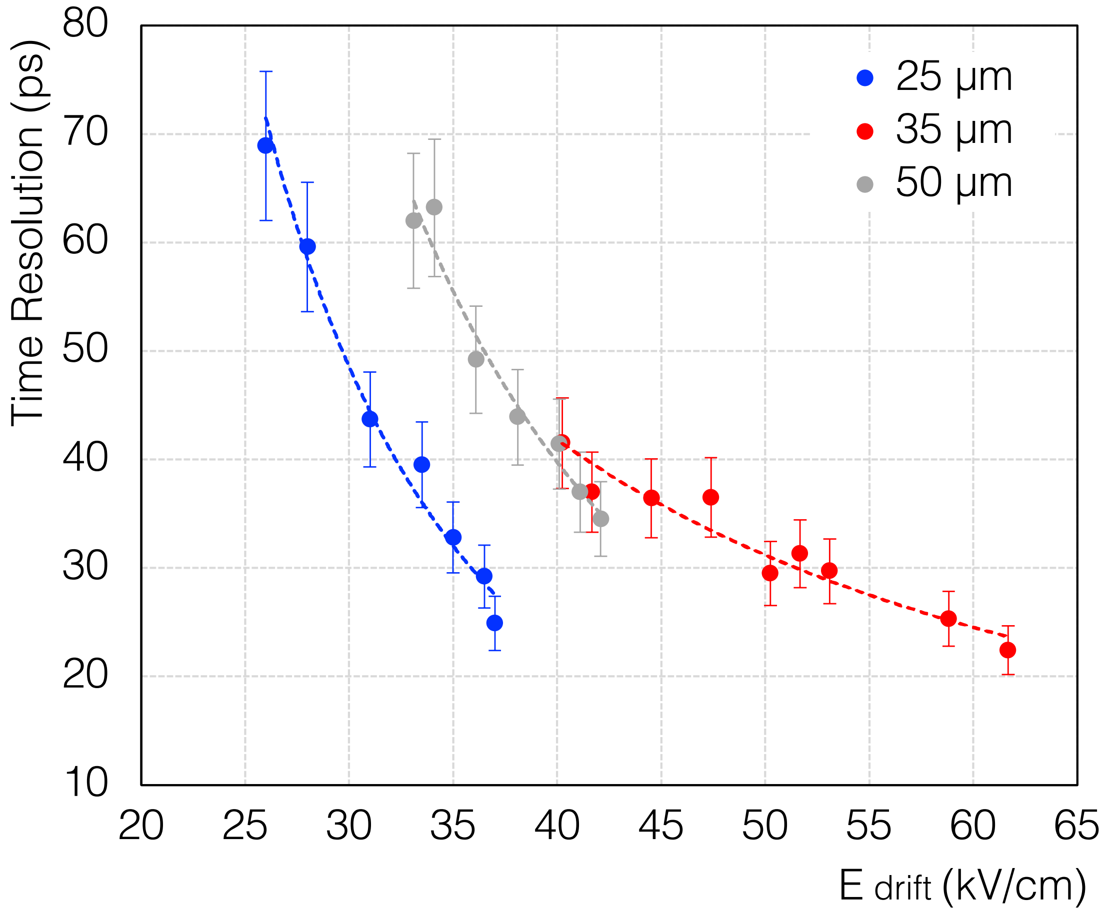
- 50 µm LGAD → ~34 ps confirms previous results
- Better values for thinner detectors (↘ Landau term)
- 25 & 35 µm are compatible within the uncertainties ~25 ps & 22 ps
  ↳ worse S/N, not optimized wafer production



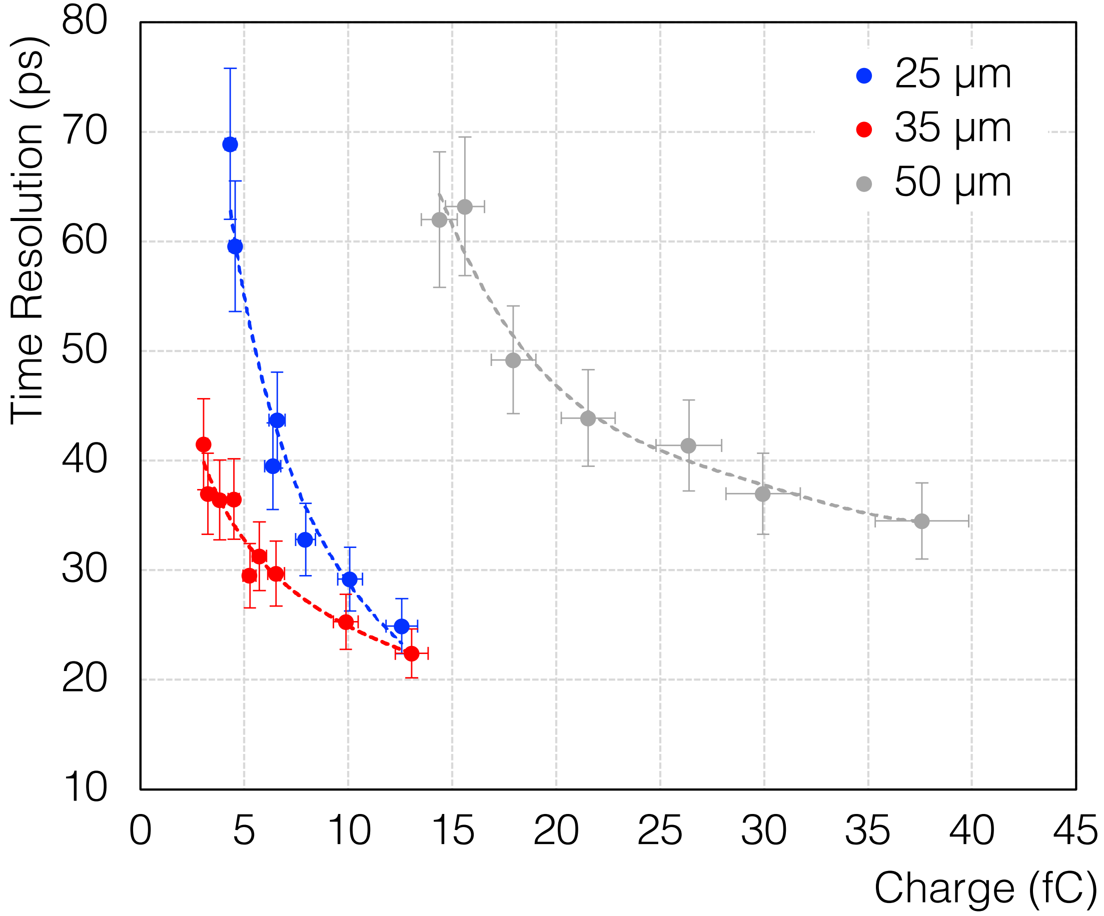


TIMING PERFORMANCE

DRIFT ELECTRIC FIELD



CHARGE



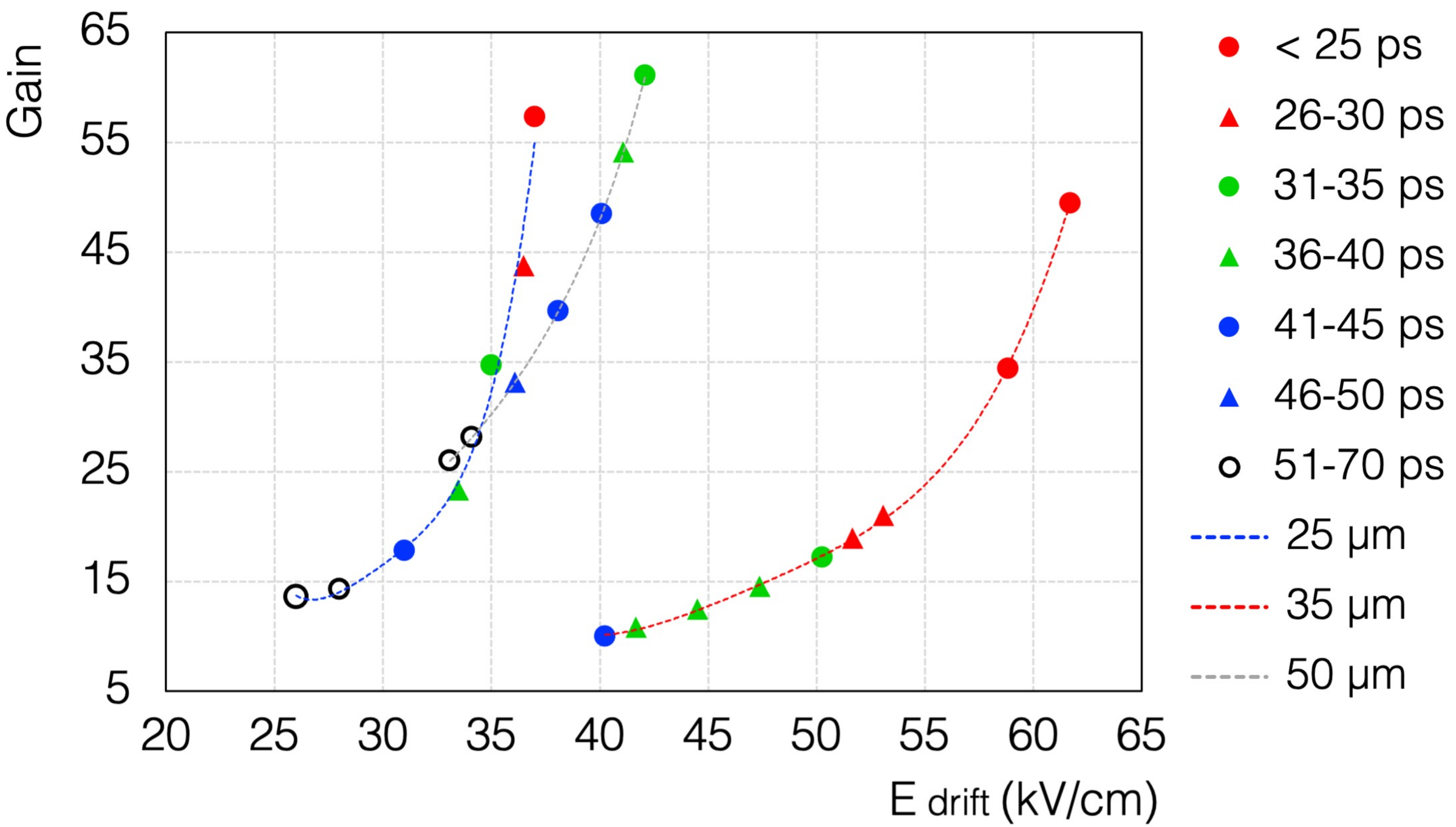
*E_{drift} → Electric field inside the silicon bulk (drift region)

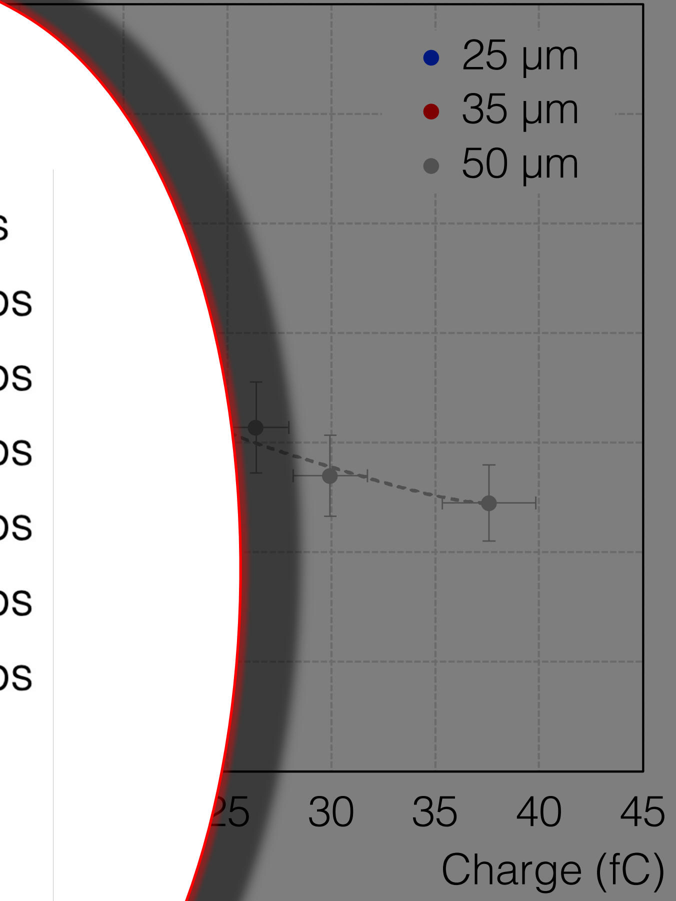
→ extracted from the data considering V and Thickness (*Weightfield simulation for the 25 µm*)

TIMING PERFORMANCE

CHARGE

To obtain a good time resolution, a combination of both high **gain** and **drift electric field** is necessary





CONCLUSIONS

First 25 and 35 μm thick FBK LGAD sensors were tested for the first time in a beam test setup

50 μm **(reference)** sensor in line with expectations → 34 ps

- Experimental setup and analysis procedure have been validated

Thinner detectors:

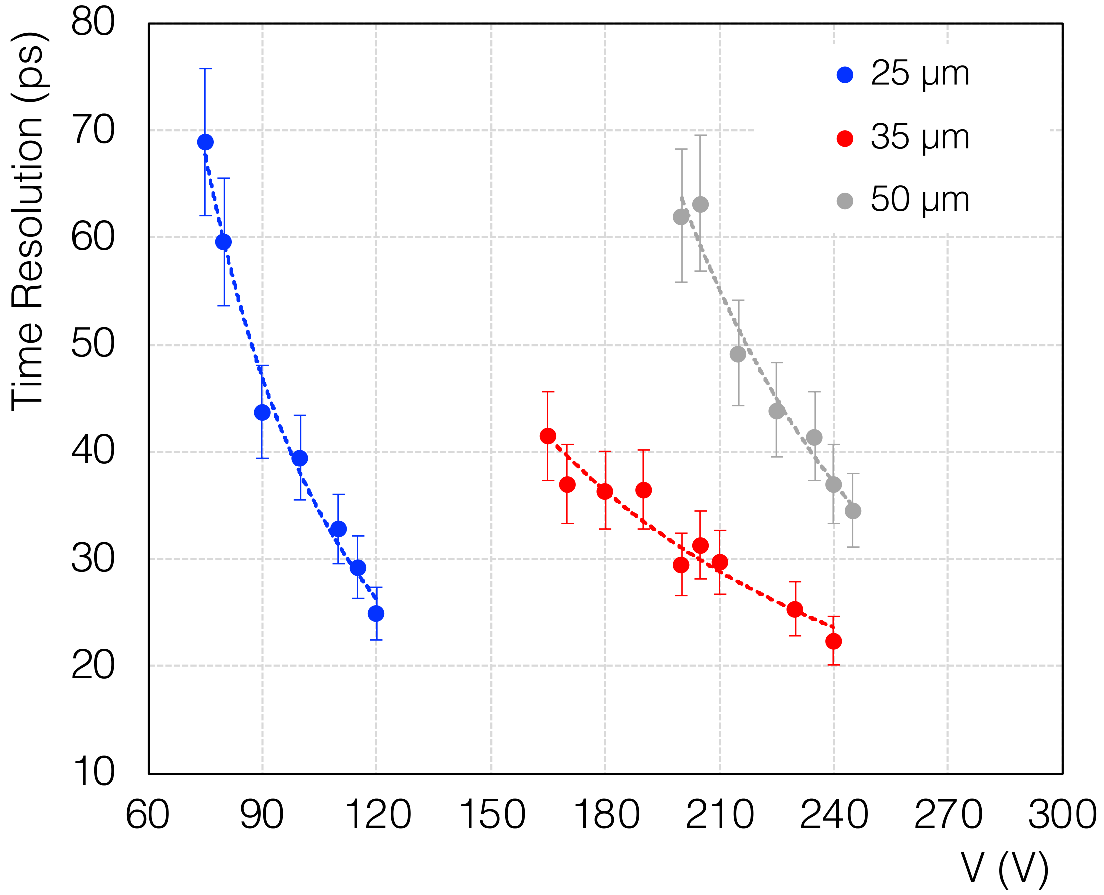
25 μm → 25 ps at 120V

- Slightly worse than simulations (maybe due to fabrication design)

35 μm → 22 ps at 240V

- in agreement with MC simulations

Both → Improved time resolution with thinner LGAD detectors

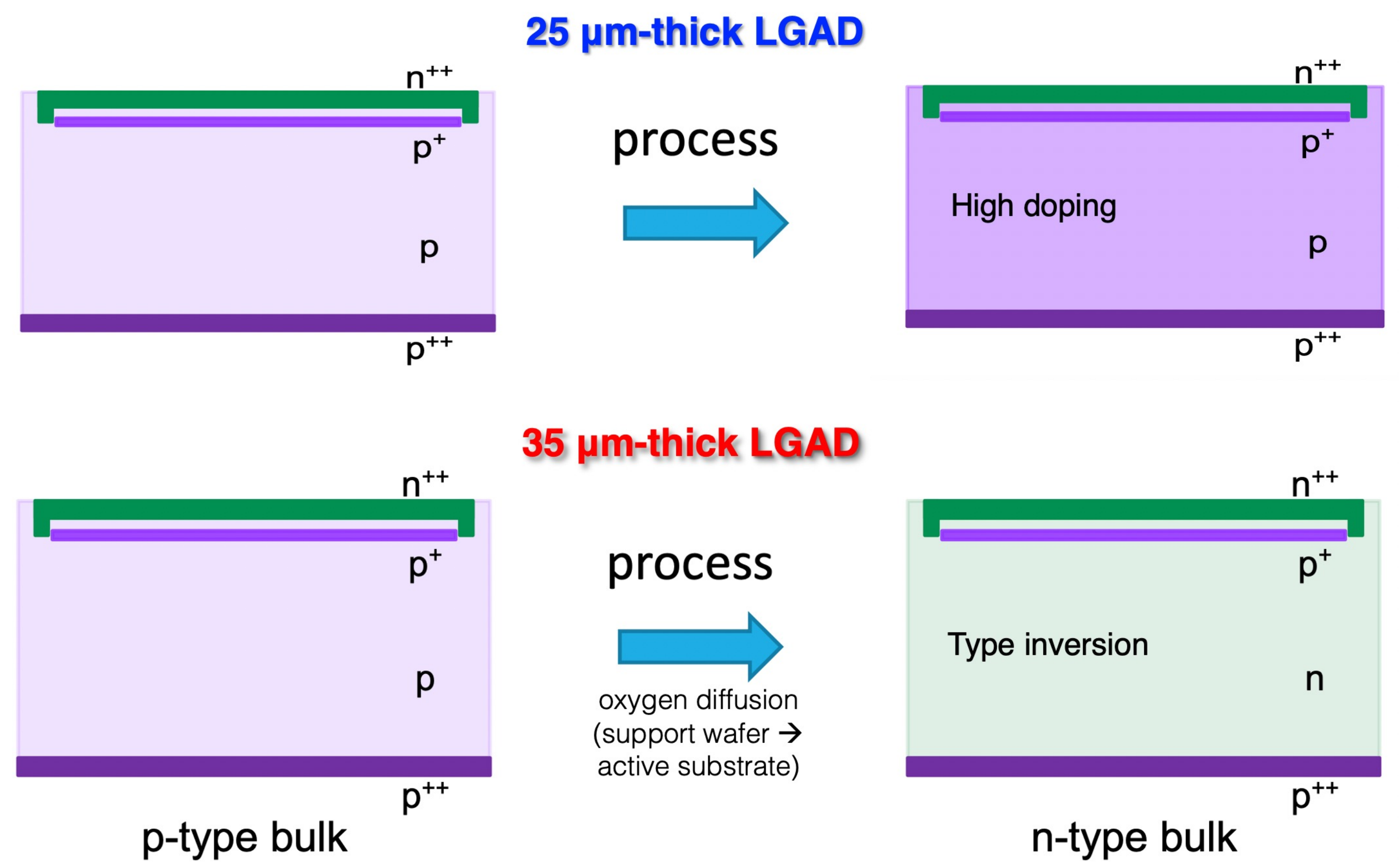


BACKUP SLIDES

ACTIVE THICKNESS

throught C-V measurement

Difficulties in the wafer production → Different doping concentrations



25 µm

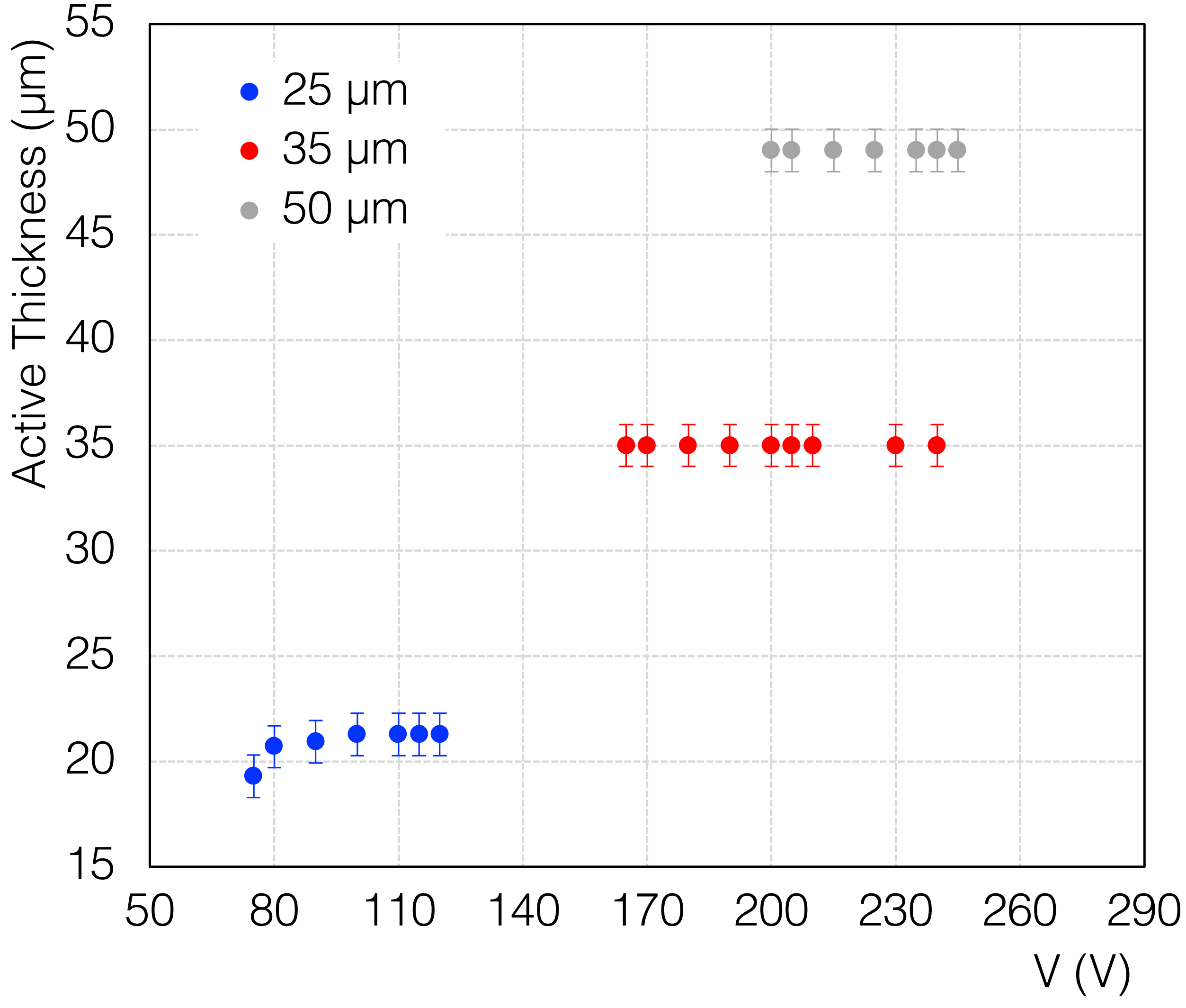
Low resistivity due to high doping of the bulk, which results in a higher E near the junction

- → is still depleting and reaches a plateau at around 100V
- → lower final active thickness

50 µm, 35 µm

are independent on the V measurements range

→ only info on the total depletion V from CV



ACTIVE THICKNESS

throught C-V measurement

25 µm

Low resistivity due to high doping of the bulk, which results in a higher E near the junction

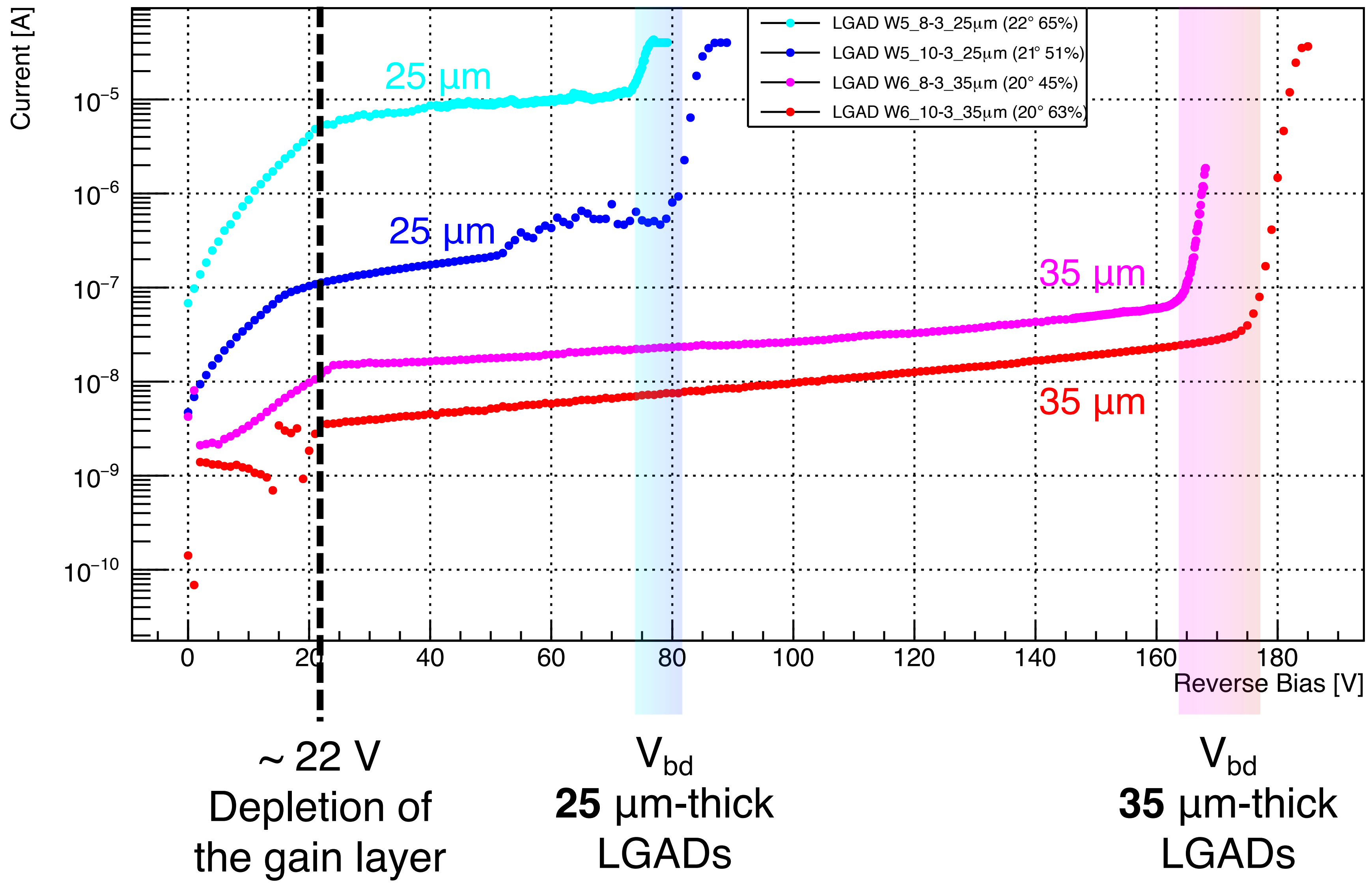
- → is still depleting and reaches a plateau at around 100V
- → lower final active thickness

50 µm, 35 µm

are independent on the V measurements range

→ only info on the total depletion V from CV

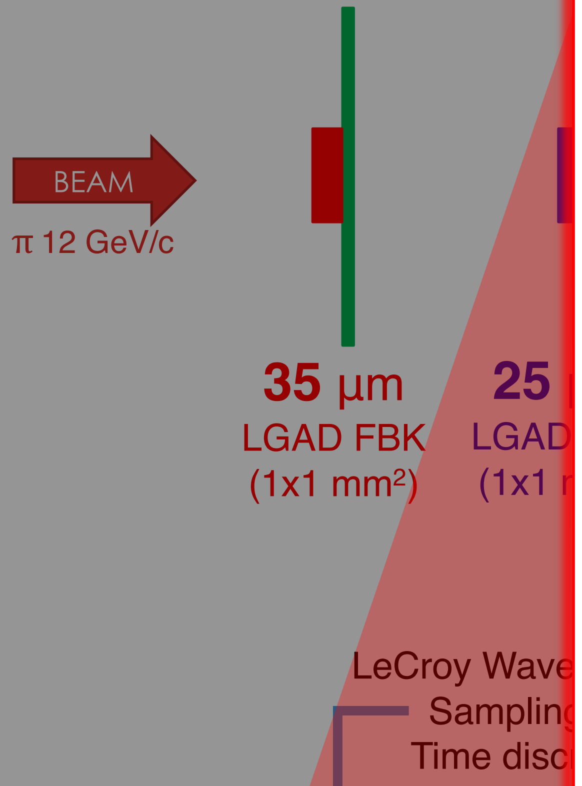
Comparison between 25 and 35 µm-thick LGADs

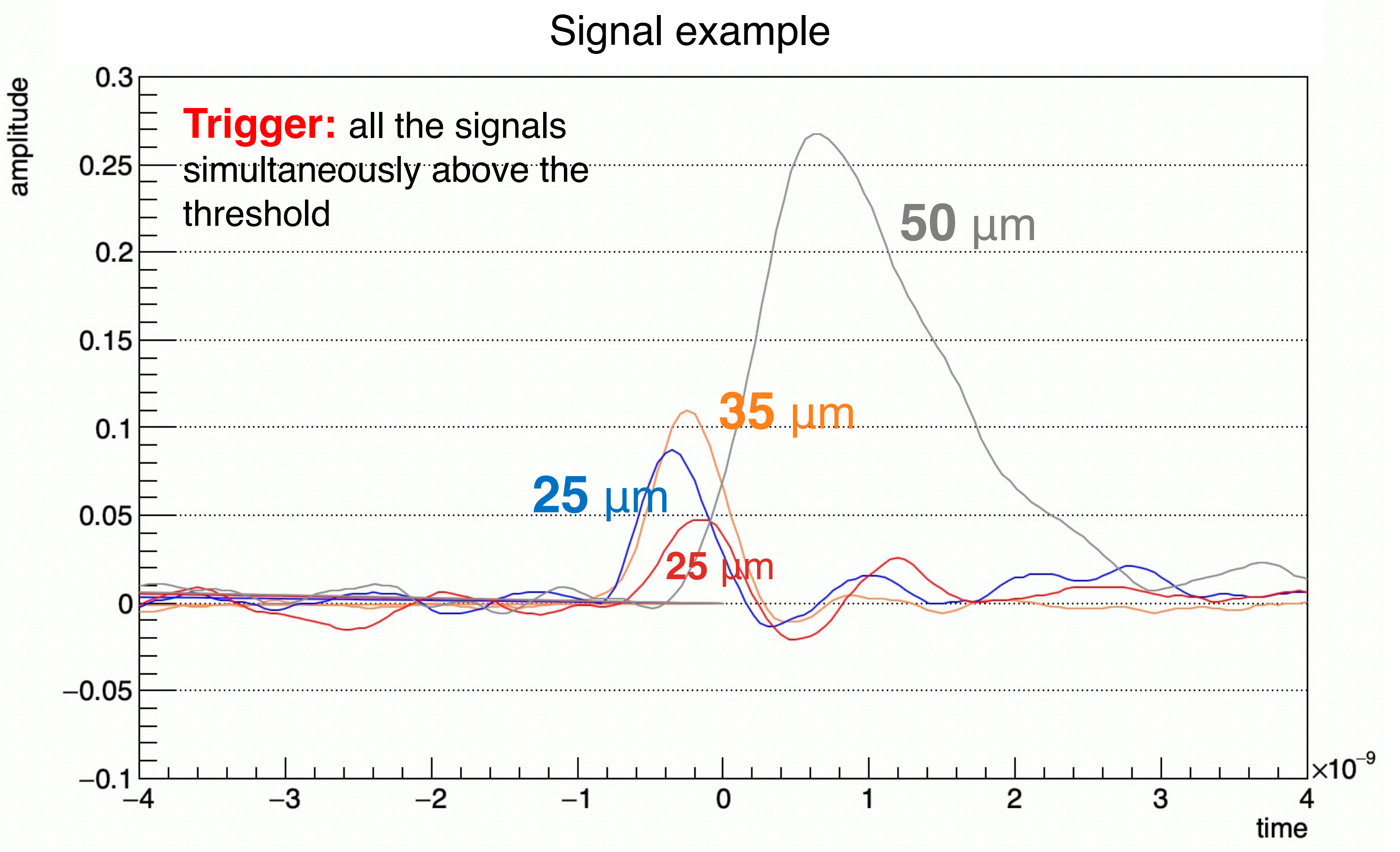


IV

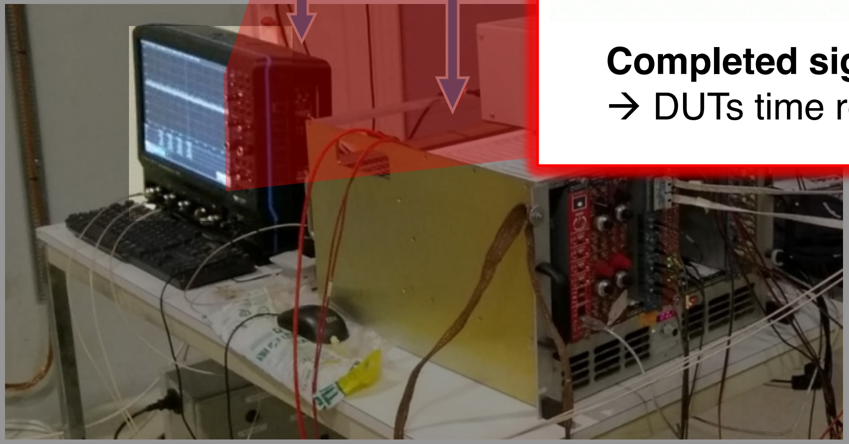
CV

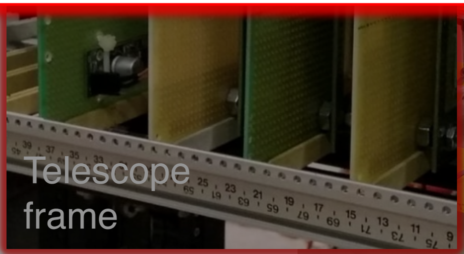
- Breakdown V
- Voltage interval of operation
- Evaluate inter-pad configuration

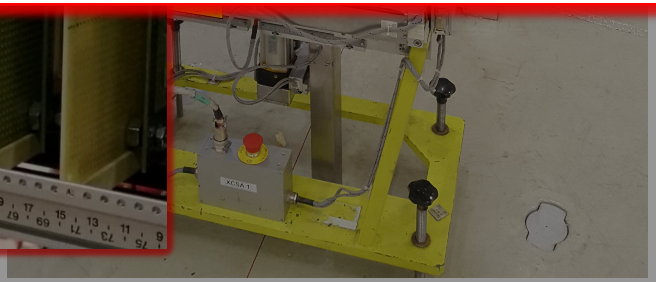




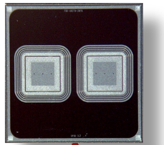
Completed signal waveforms recorded and analyzed offline
→ DUTs time resolutions without problems relates to the front-end electronics



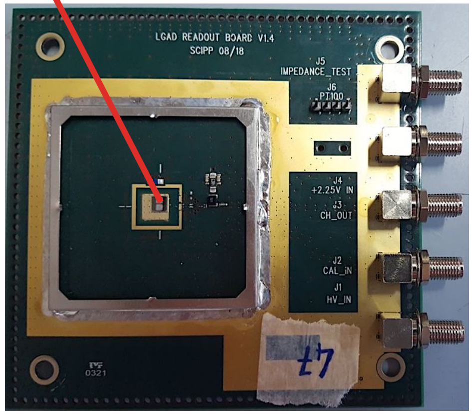




AMPLIFICATION

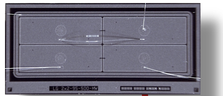


25 µm
35 µm

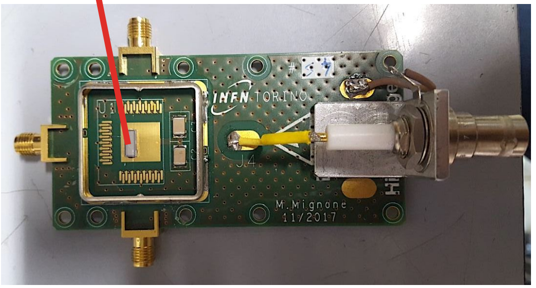


SantaCruz single-channel LGAD read-out board *V1.4 SCIPP 08/18*
$G_{amplifier}$ ~ **6**

Second stage external amplifier
+ $G_{amplifier}$ ~ **13-14**



50 µm

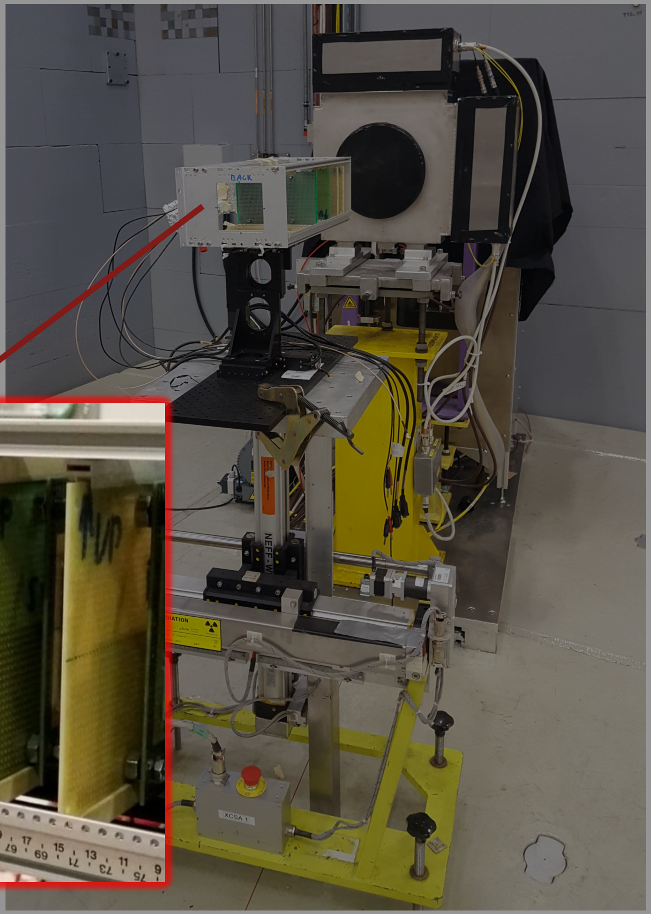


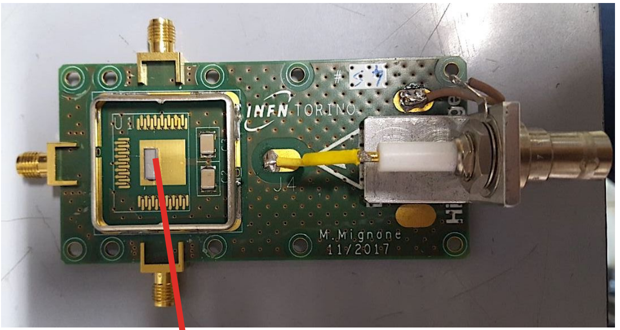
low-noise current amplifier

$G_{amplifier}$ ~ **196**

TEST BEAM SETUP

50 µm
LGAD HPK
(1x3 mm²)



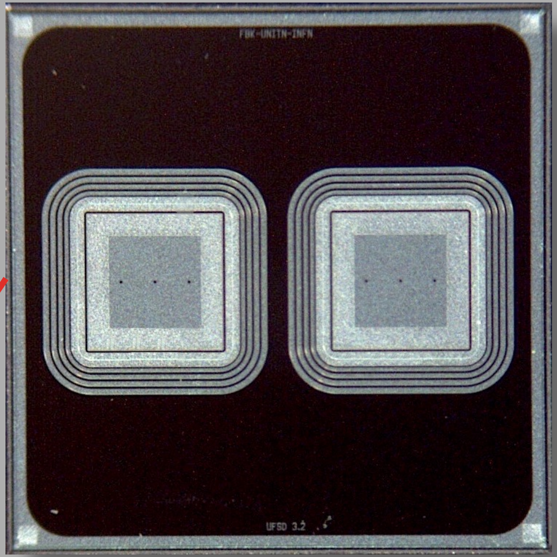


low-noise current amplifier

$G_{amplifier}$ ~ **196**

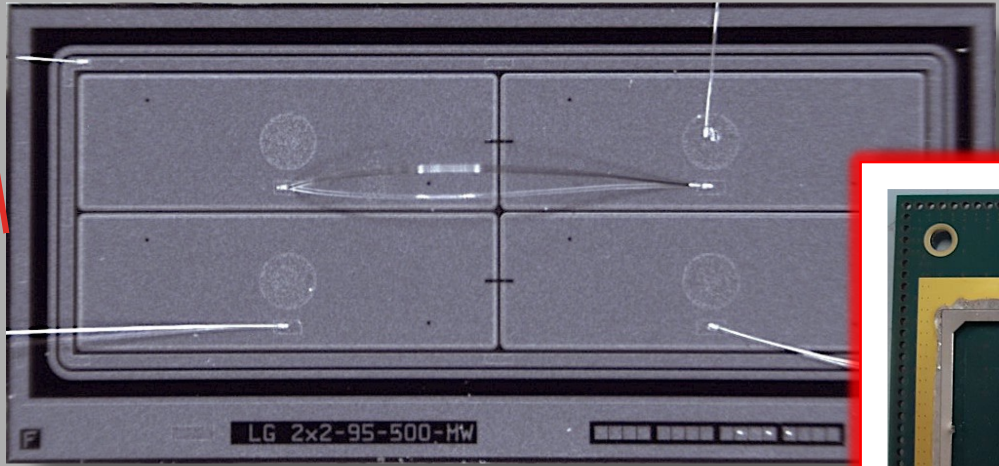
First very thin LGAD prototypes produced by FBK

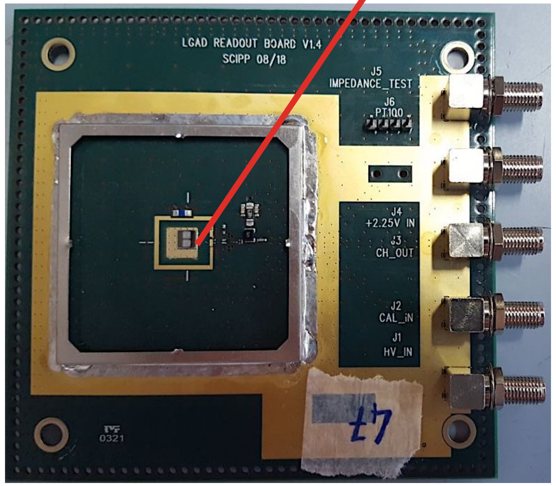
25 µm and
35 µm-thick FBK
single channel



50 µm-thick HPK LGAD

1x3 mm²





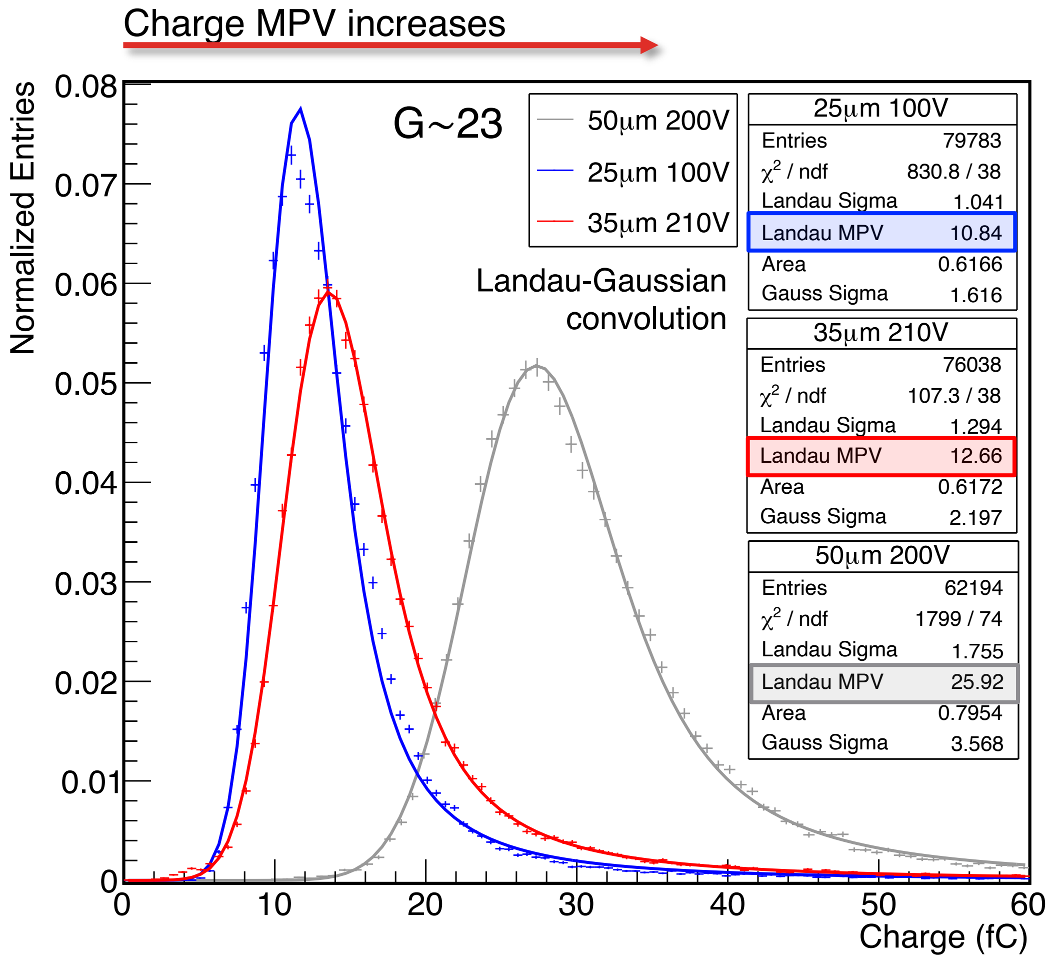
SantaCruz
single-channel LGAD
read-out board *V1.4*
SCIPP 08/18

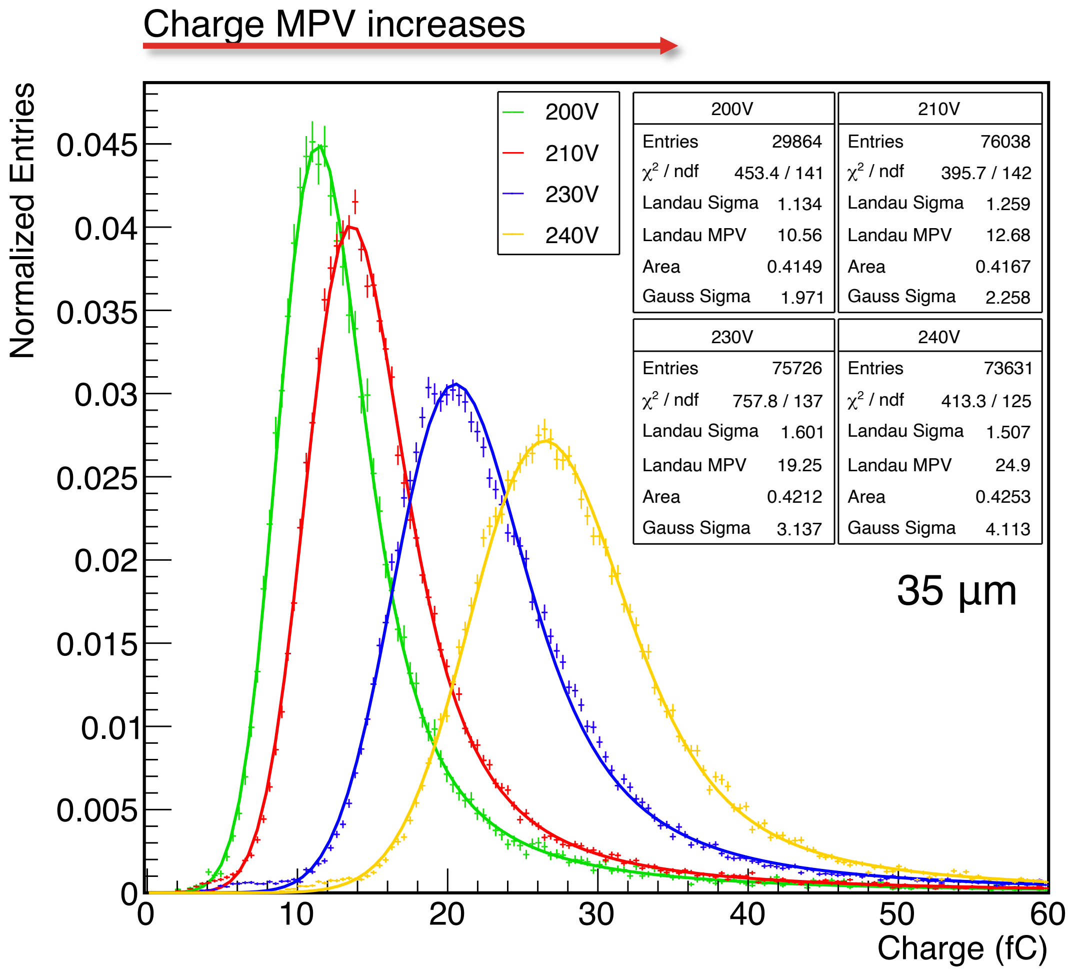
$G_{amplifier}$ ~ **6**

Second stage external amplifier

$G_{amplifier}$ ~ **13-14**

CHARGE DISTRIBUTIONS



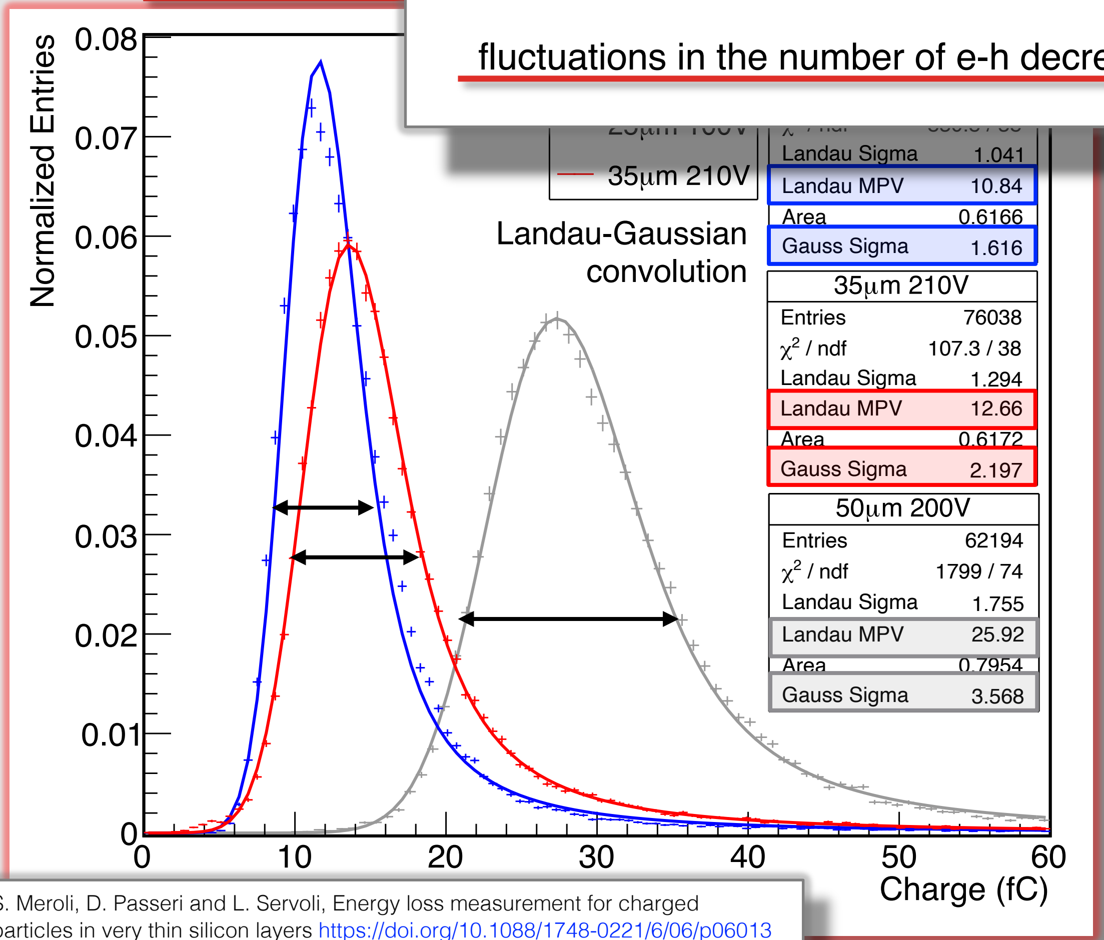


CHARGE DISTRIBUTIONS

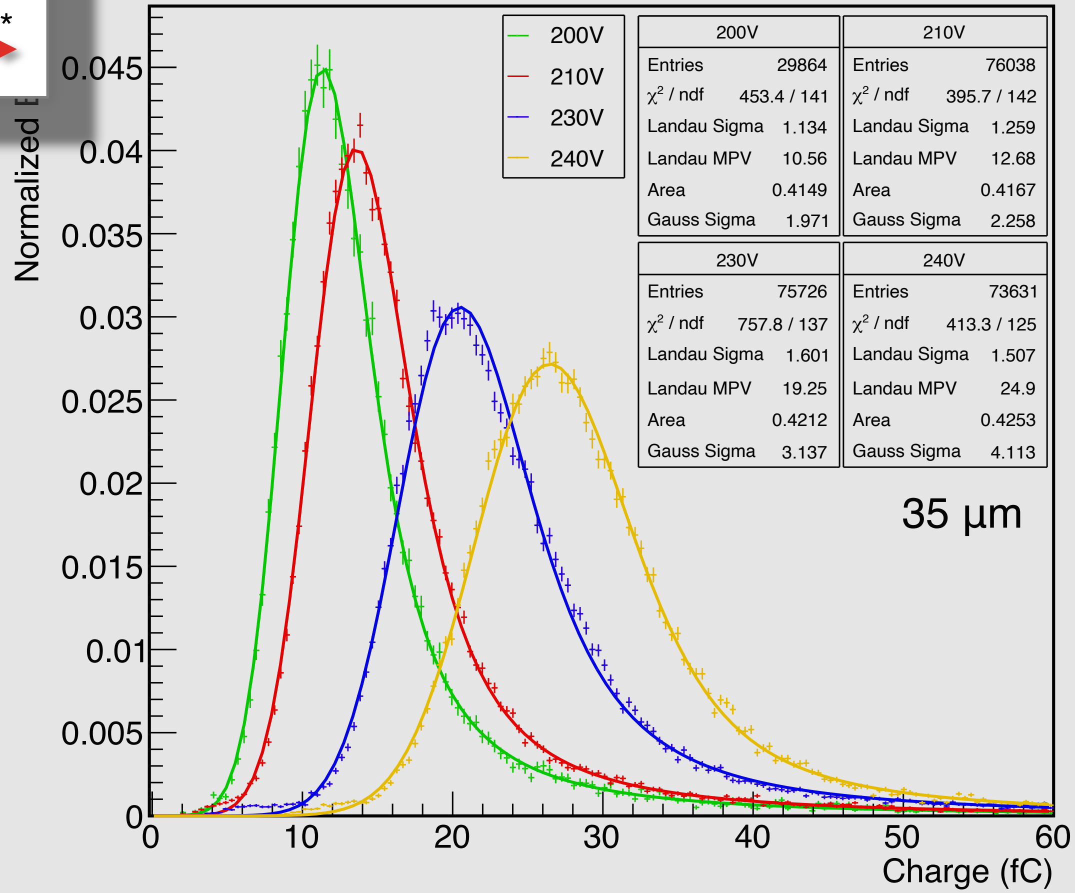
Width of the distribution
MPV

fluctuations in the number of e-h decreases *

Charge MPV inc



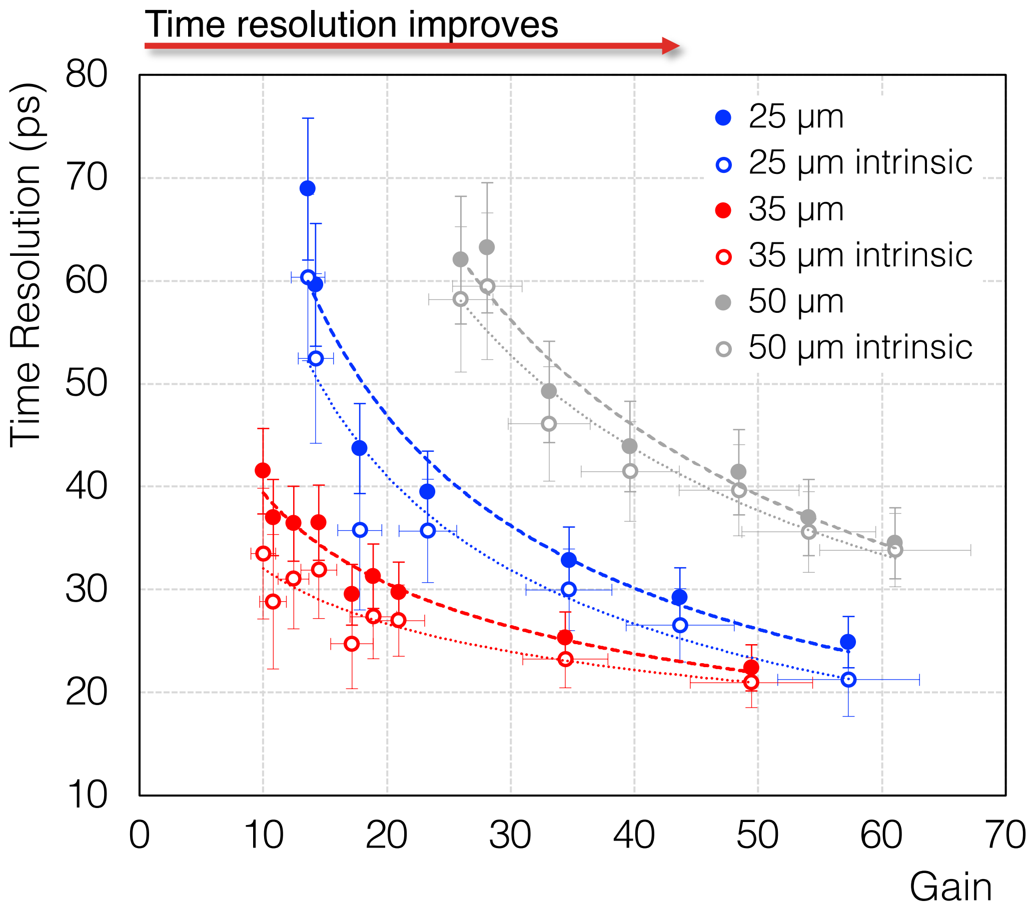
Charge MPV increases

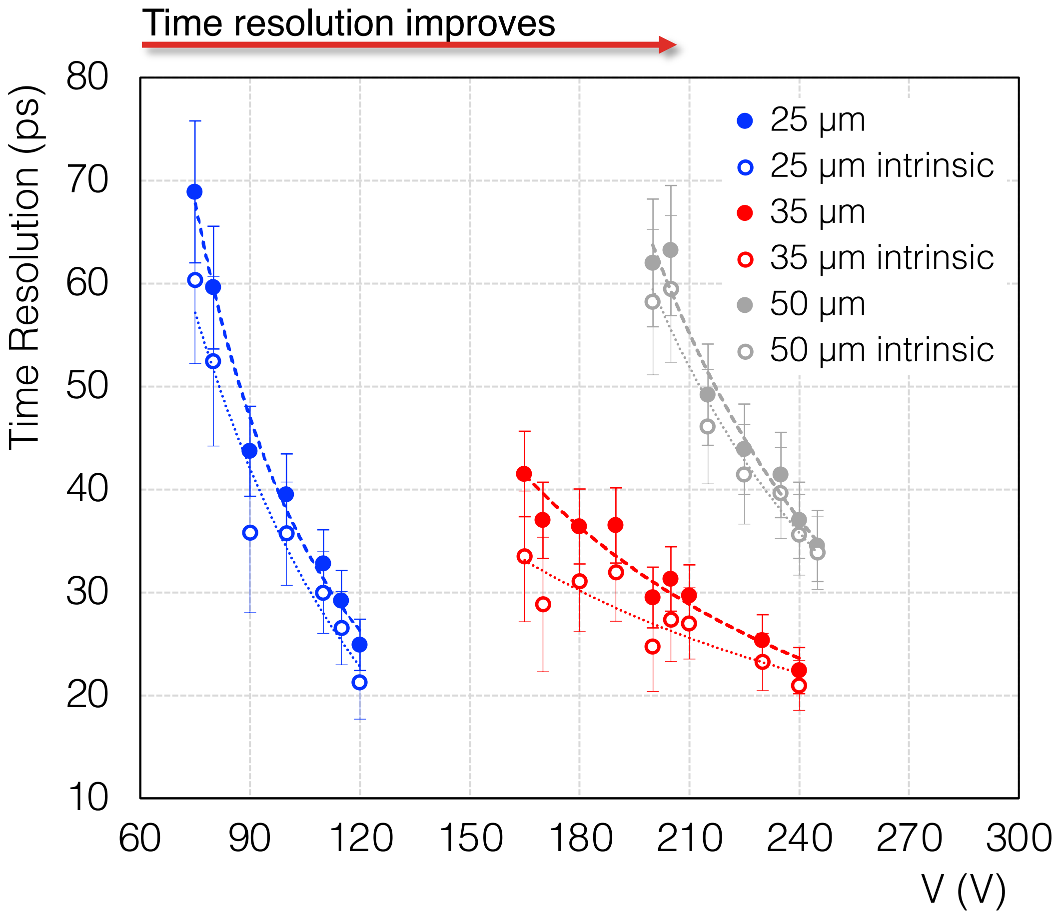


* S. Meroli, D. Passeri and L. Servoli, Energy loss measurement for charged particles in very thin silicon layers https://doi.org/10.1088/1748-0221/6/06/p06013
W.RieglerandG.AglieriRinella,Timeresolutionofsiliconpixelsensors https://doi.org/10.1088/1748-0221/12/11/p11017

TIMING PERFORMANCES

- 50 µm LGAD ➞ ~34 ps confirms previous results
- Better values for thinner detectors (↘ Landau term)
- 25 & 35 µm are compatible within the uncertainties ~25 ps & 22 ps
  - ↳ worse S/N, not optimized wafer production





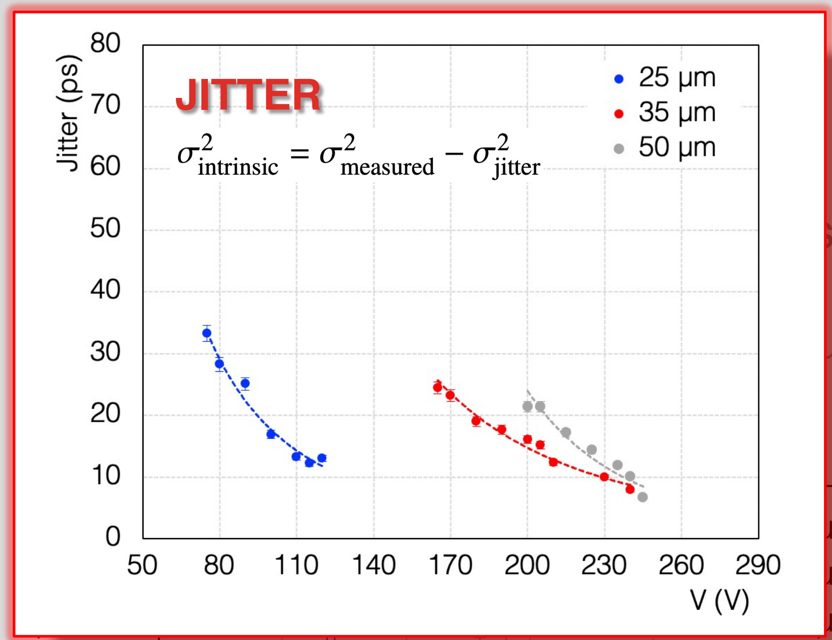
PERFORMANCES

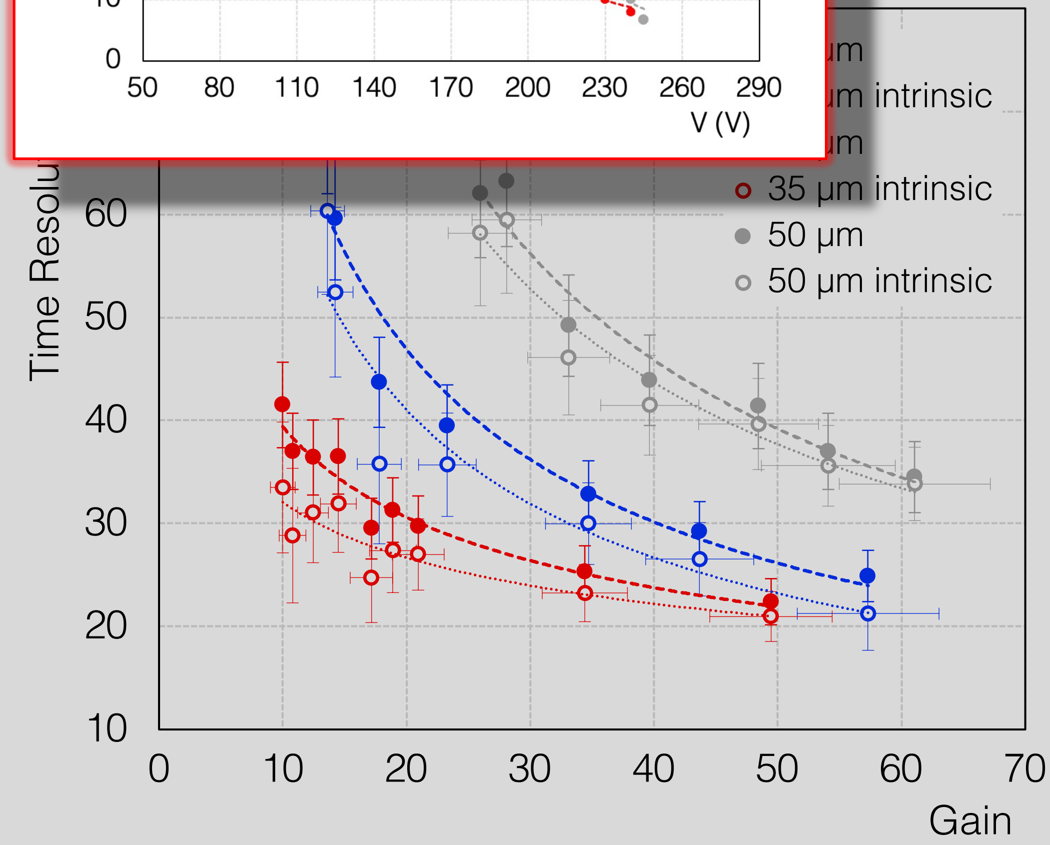
previous results

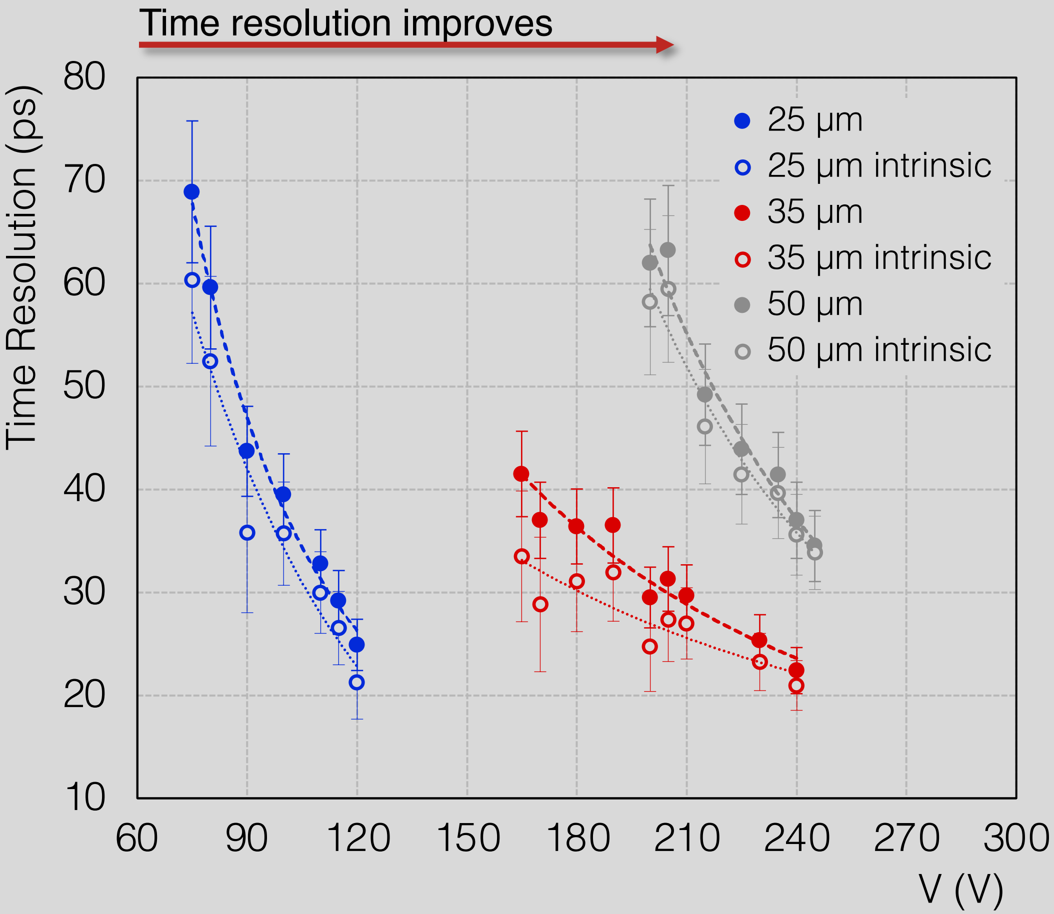
s (↘ Landau term)

the uncertainties ~25 ps & 22 ps

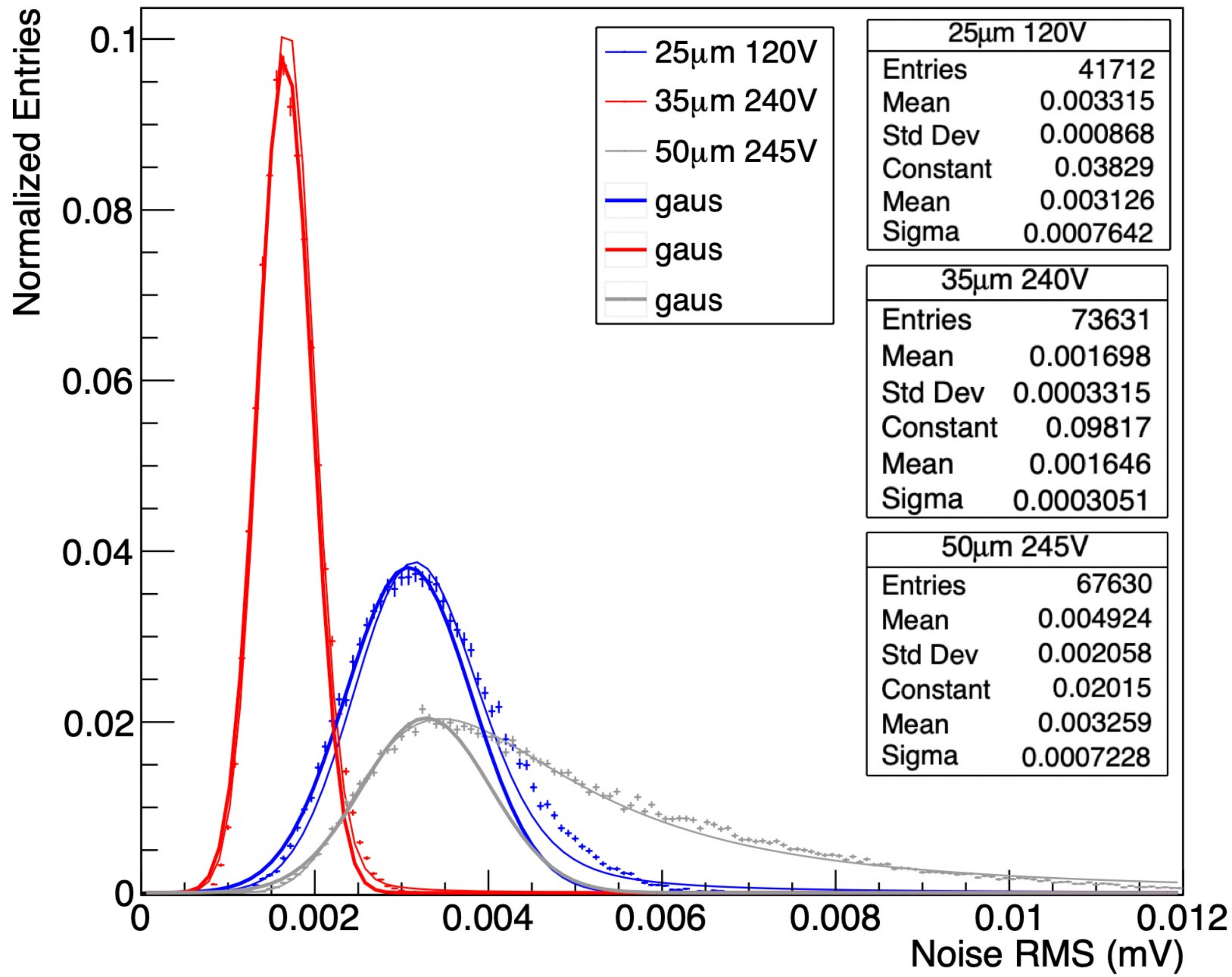
uction





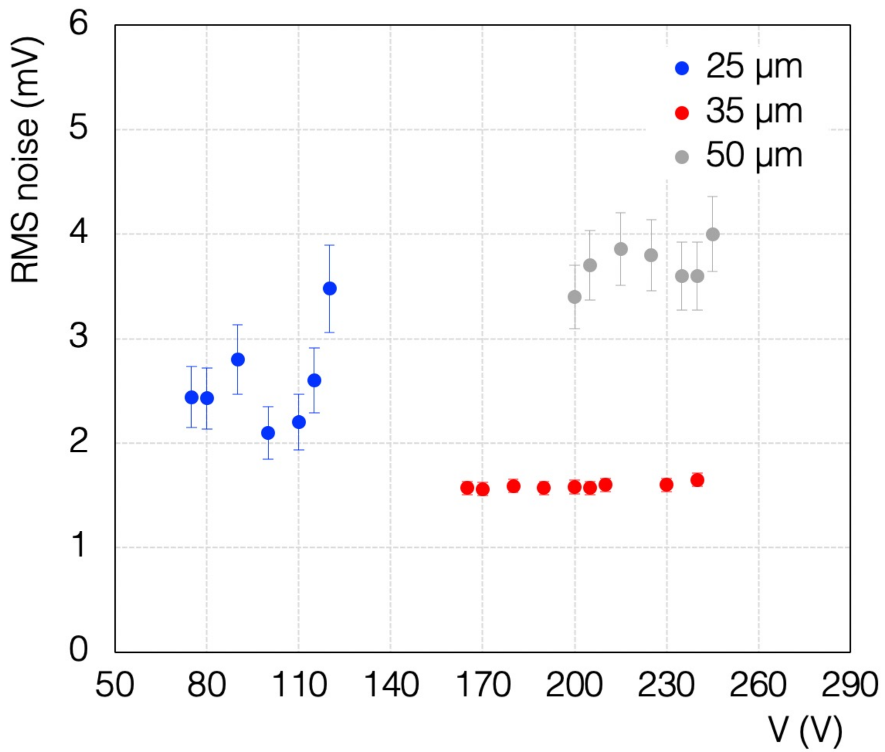


NOISE RMS



Extracted considering a time window before the signals

- More Gaussian distribution for the thinner sensors
- Lower for the 35 µm LGAD
- Stable MPV between 1-4 mV



50 μm (reference) sensor in line with expectations → **34 ps**

- Experimental setup and analysis procedure have been validated

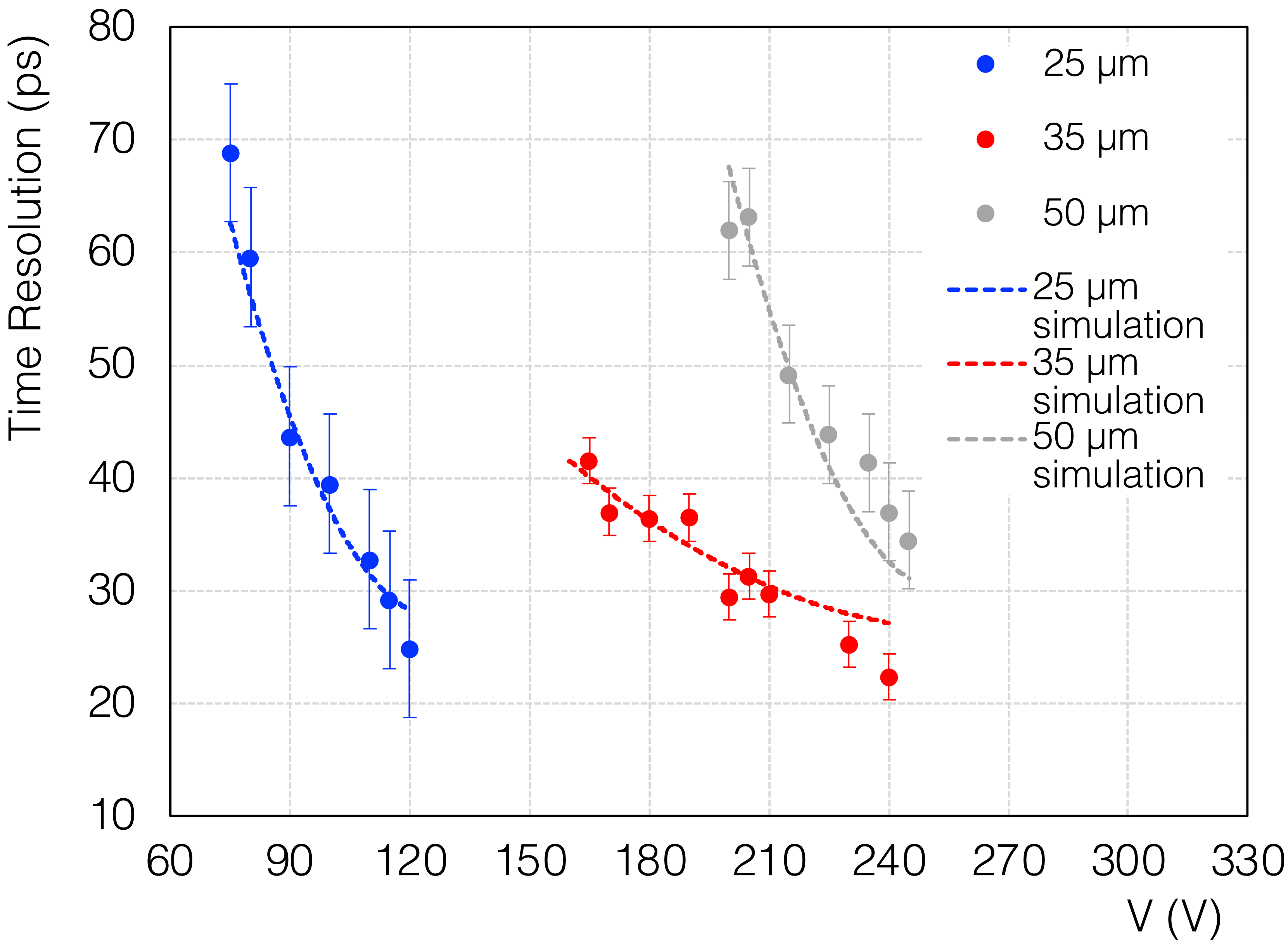
Thinner detectors:

- **25 μm → 25 ps** at 120V
  - Slightly worse than simulations (maybe due to fabrication design)
- **35 μm → 22 ps** at 240V
  - in agreement with MC simulations
- **Both → Improved** time resolution **with thinner LGAD** detectors

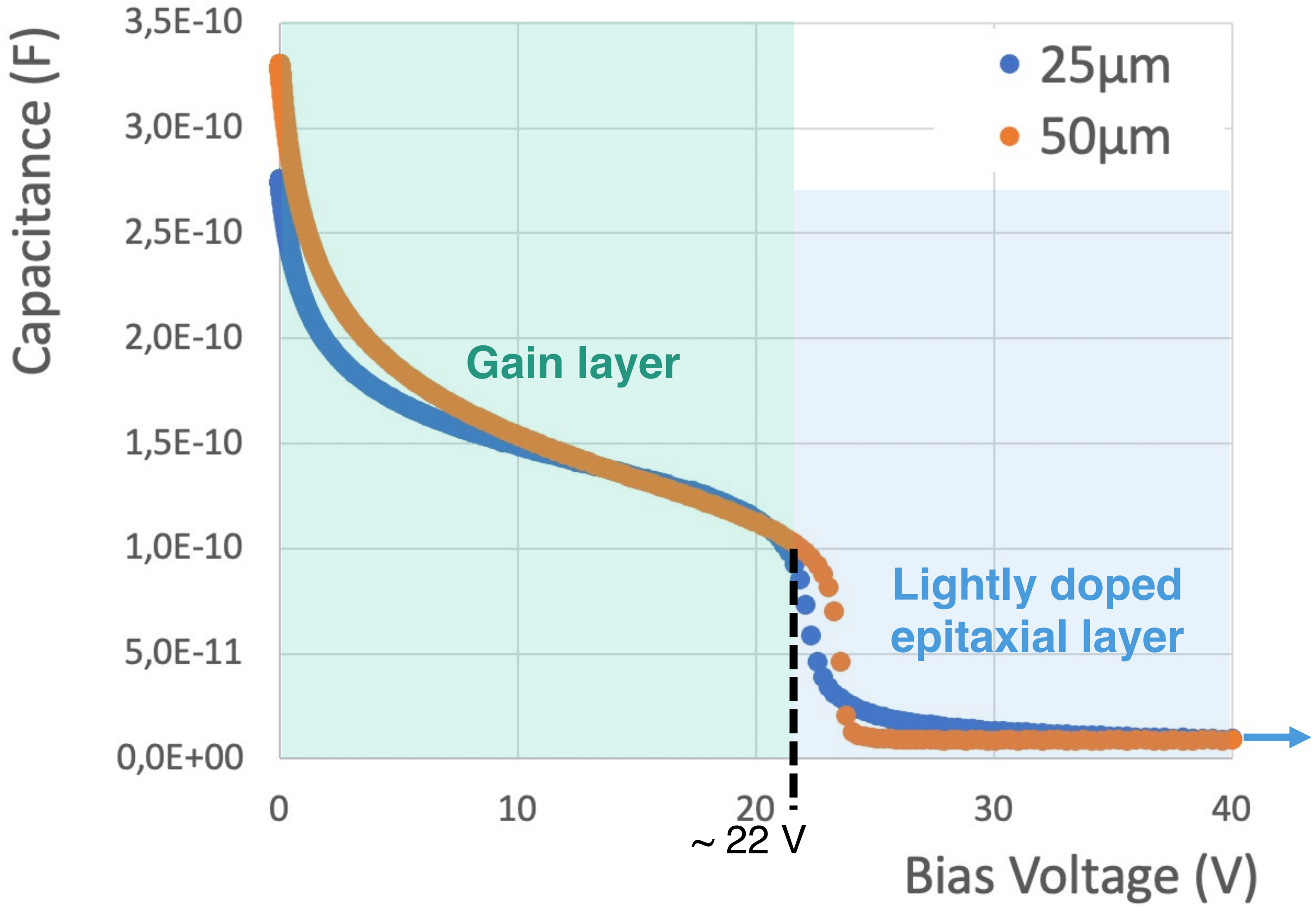
FUTURE PLANS

- **We are in contact with FBK** to continue the **R&D** focused on the design of LGADs optimized for the TOF system requirements
  - Validate the results on 25 µm
    - ⇢ maybe considering a new production with the **right doping concentrations**
  - Eventually study the timing performance of **even thinner sensors**
- **Beam tests 2022**
  - Two slots in July and November

WEIGHTFIELD SIMULATIONS



CV example for **25** and **50 µm-thick** LGADs

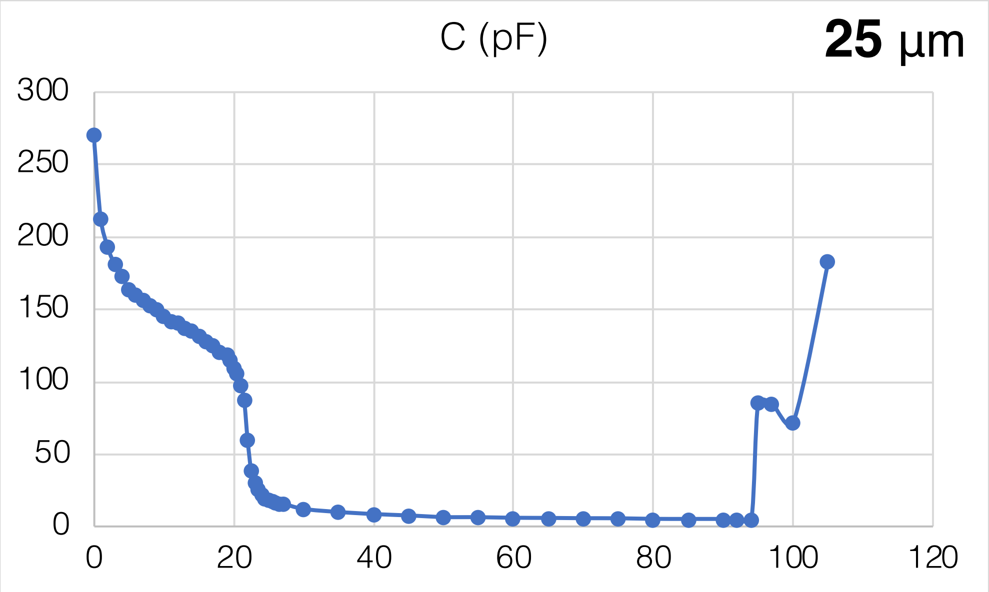


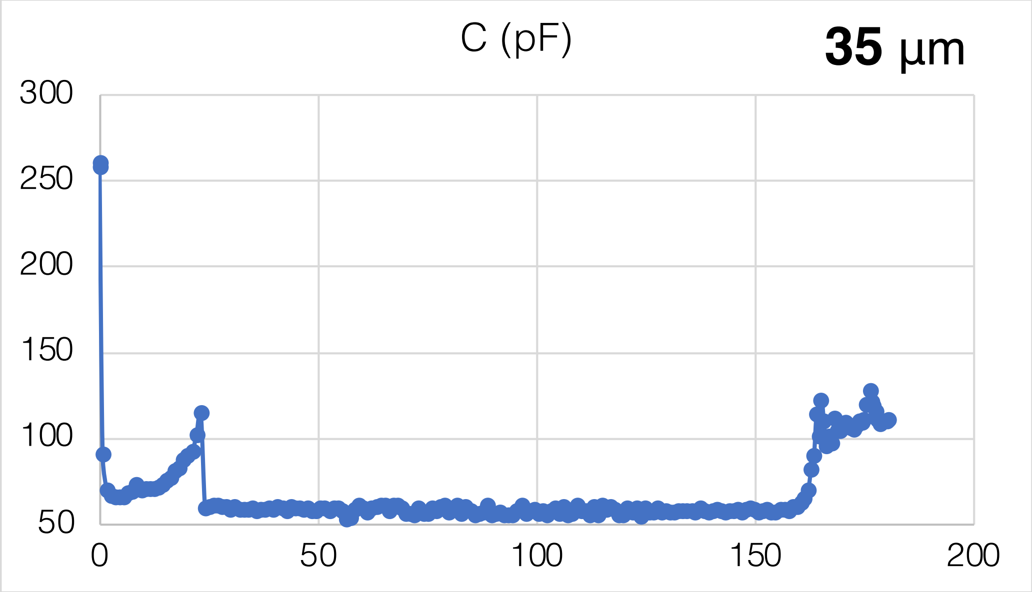
Asymptotic behaviour to fully depleted LGAD capacitance

IV

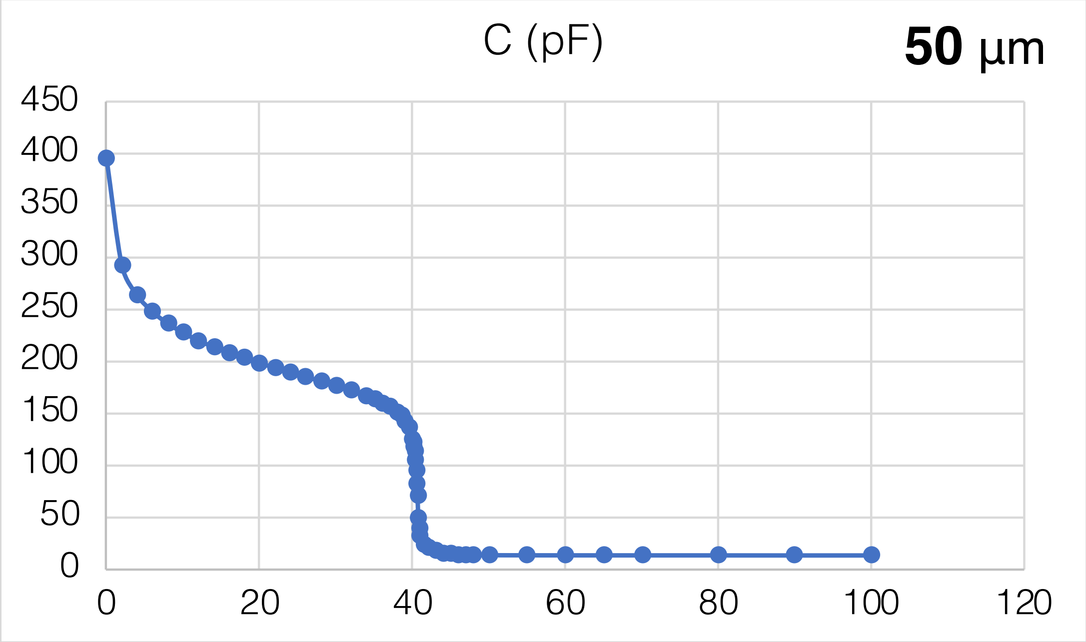
CV

- Gain layer depletion V
- Full depletion V
- Connected to the doping profile



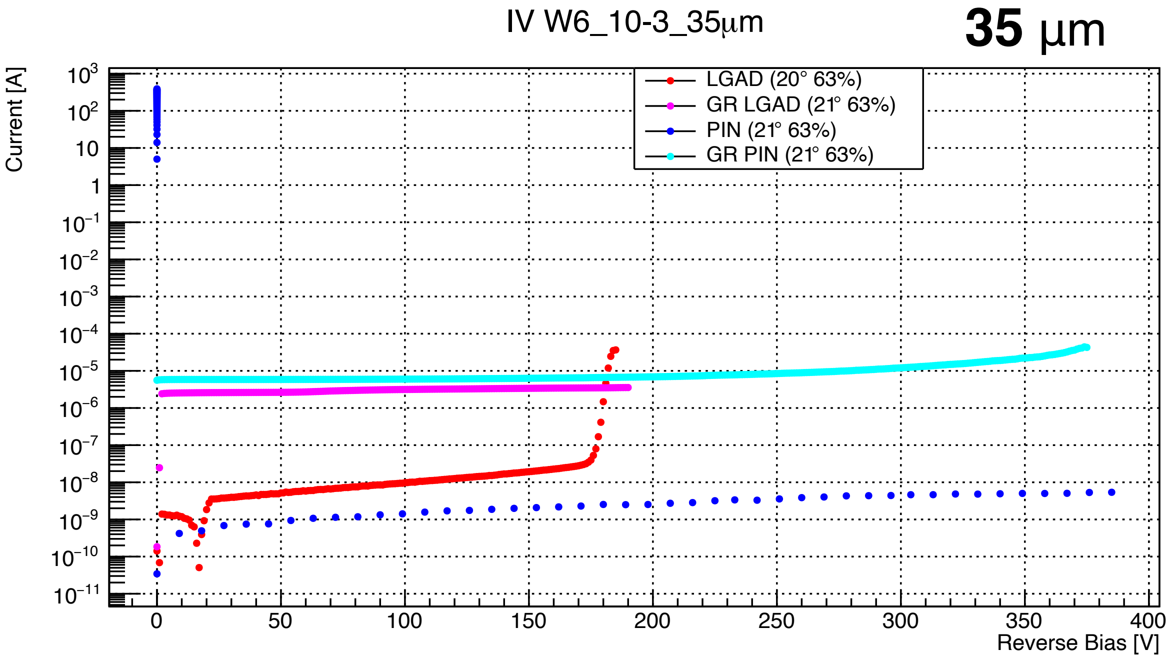


CAPACITANCE-VOLTAGE CHARACTERISTICS

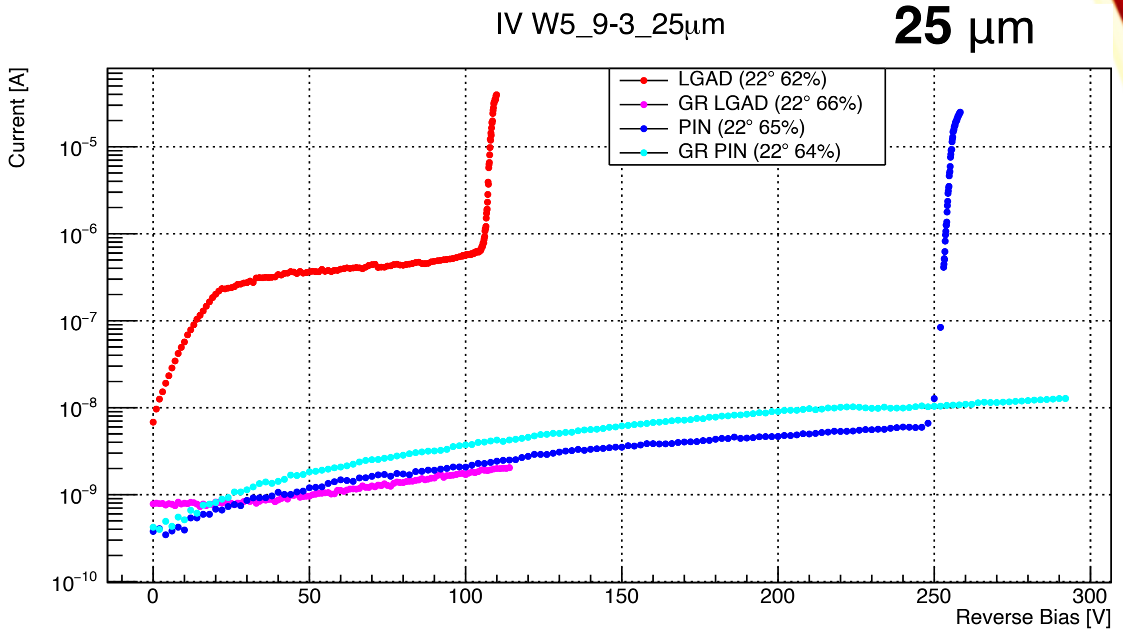


CURRENT-VOLTAGE CHARACTERISTICS

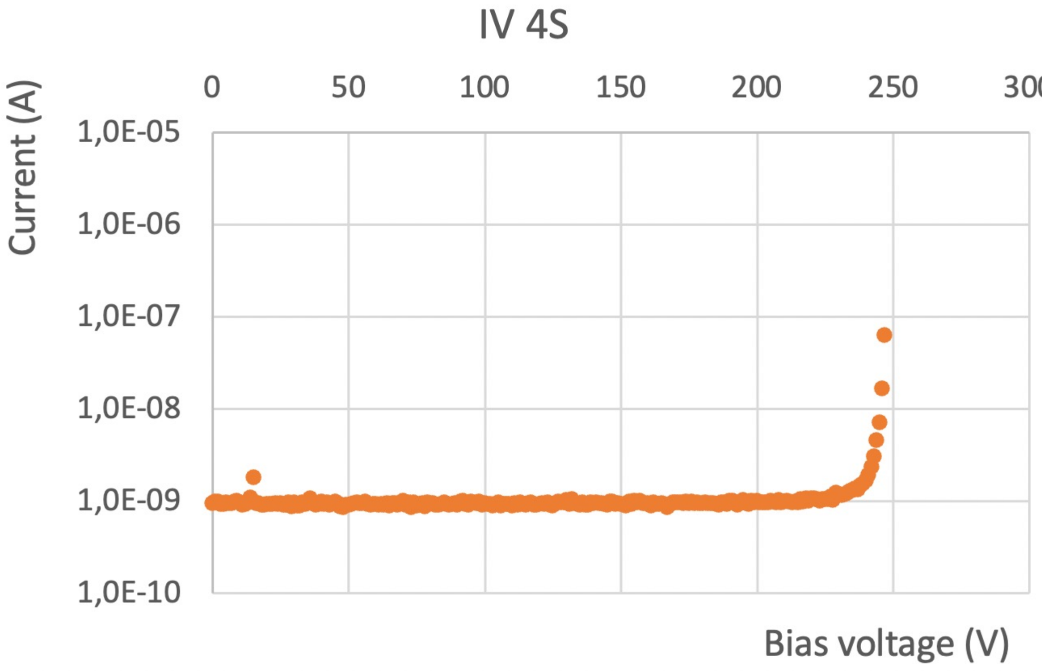
35 µm



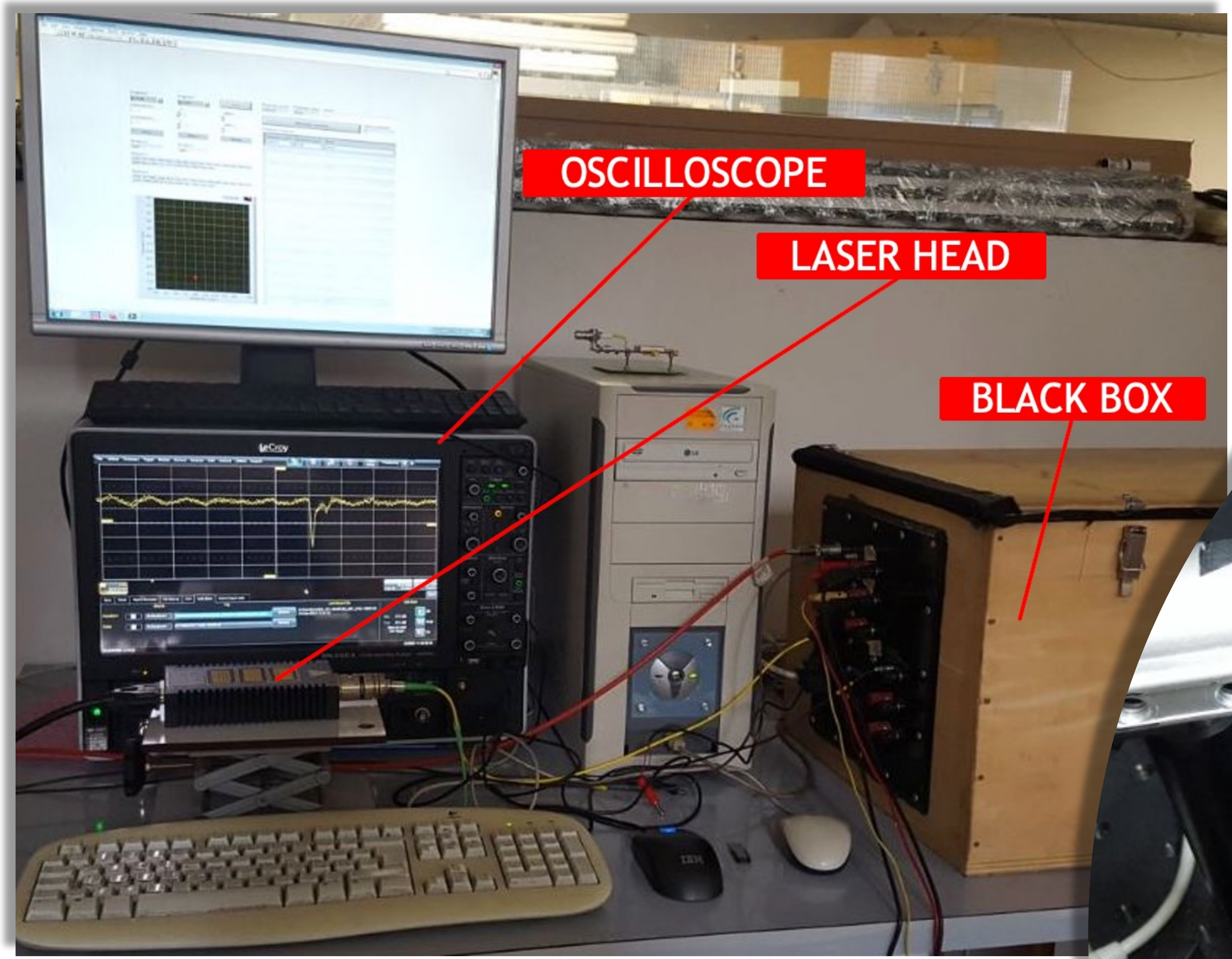
25 µm

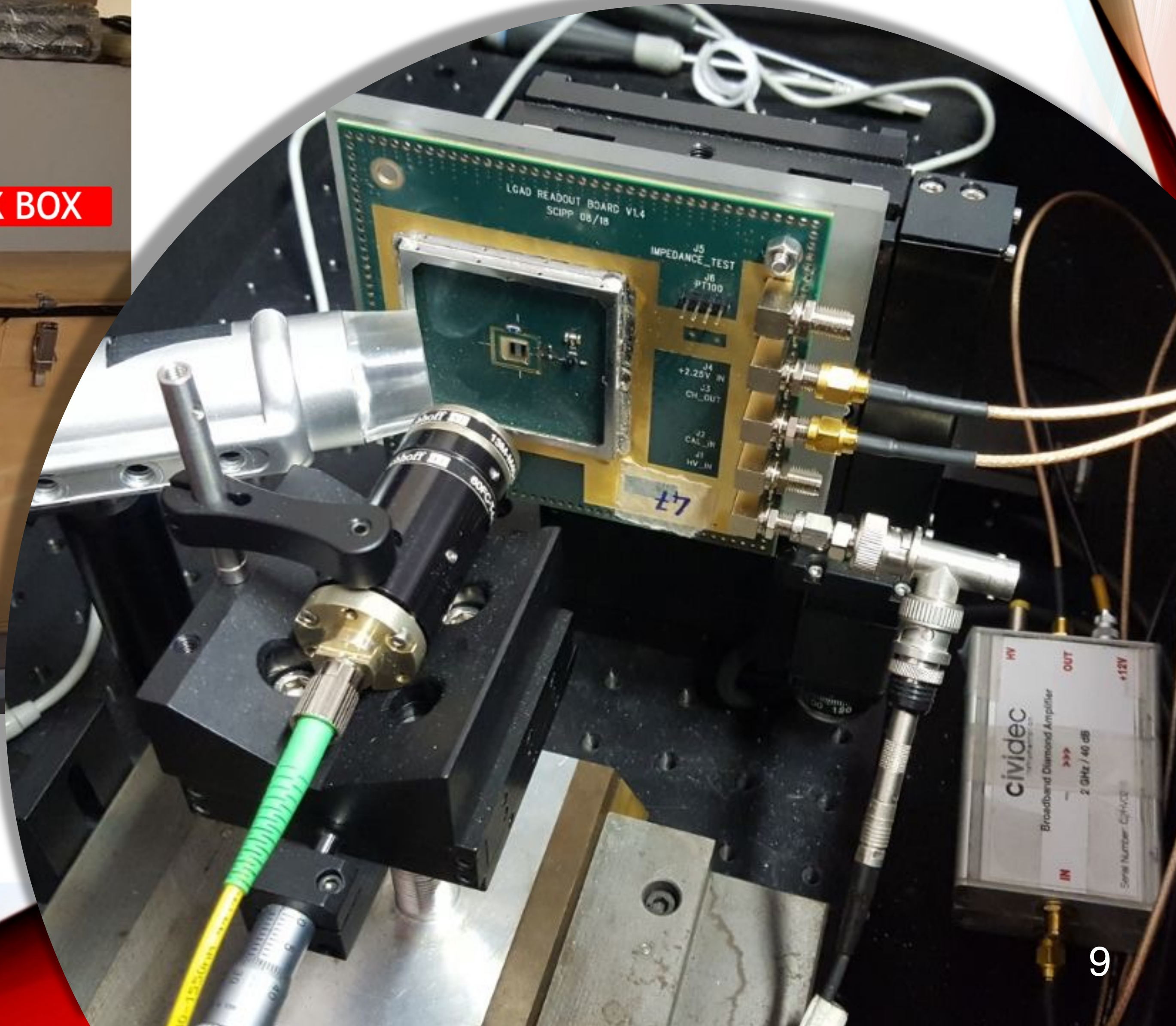


50 µm



PERFORMANCES STUDY

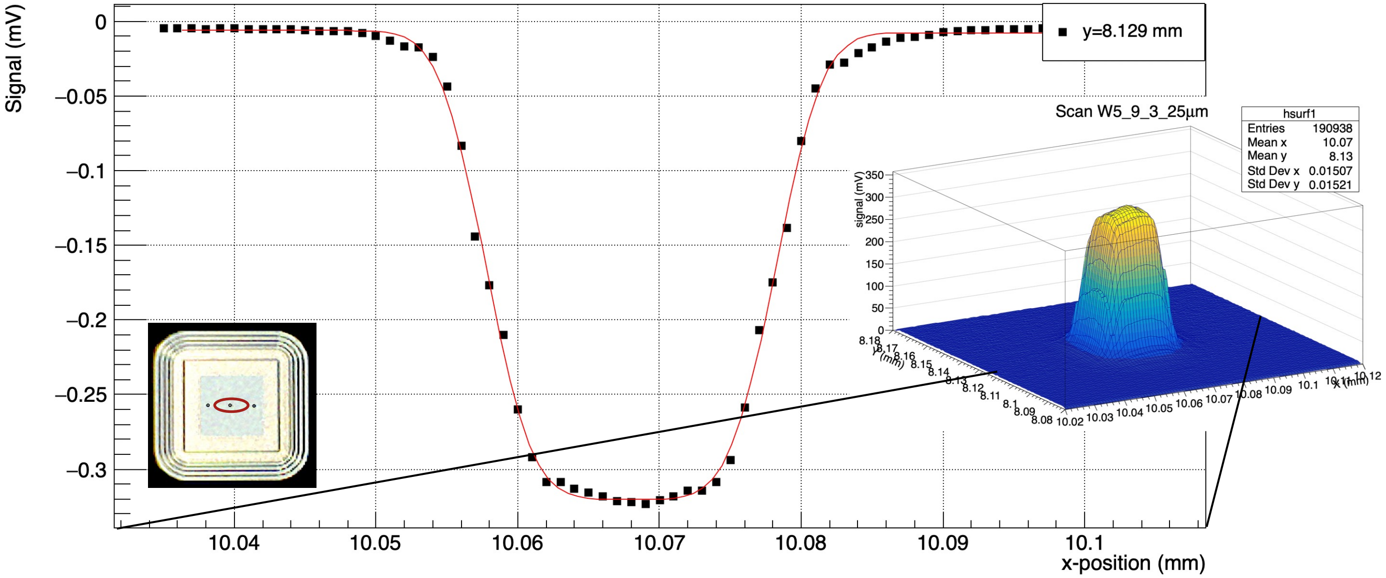


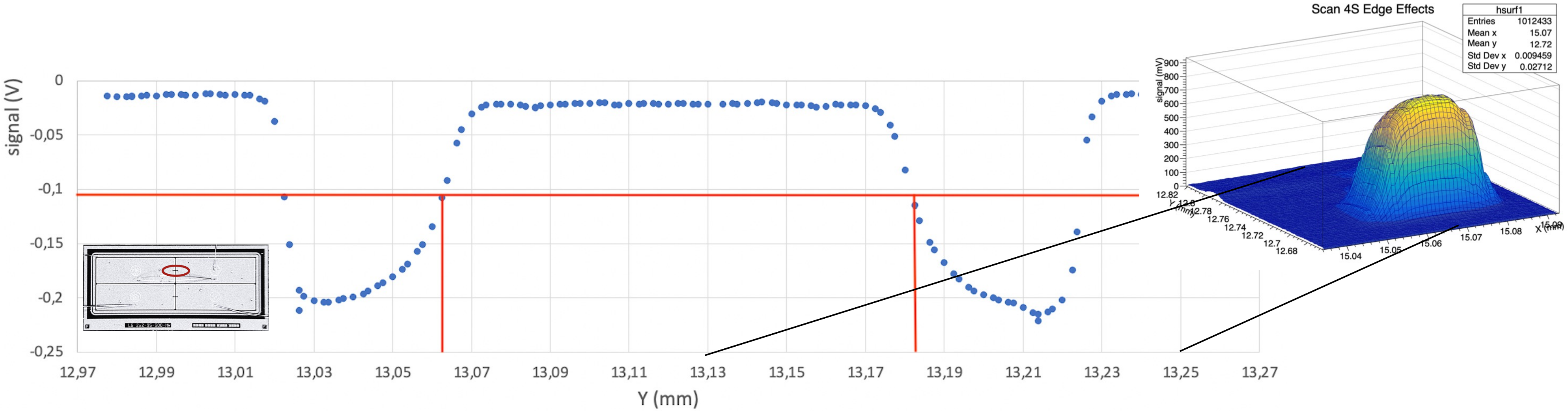


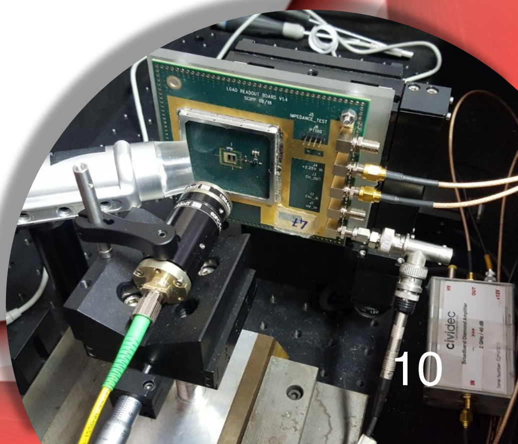
PRELIMINARY TESTS
through automatic scans

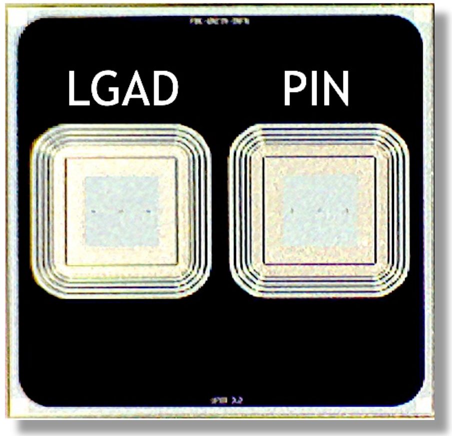
- ➢ Evaluate light sensitive areas
  - Efficiency
  - Uniformity
  - Edge effects

- ➢ Extract windows and laser spot dimensions



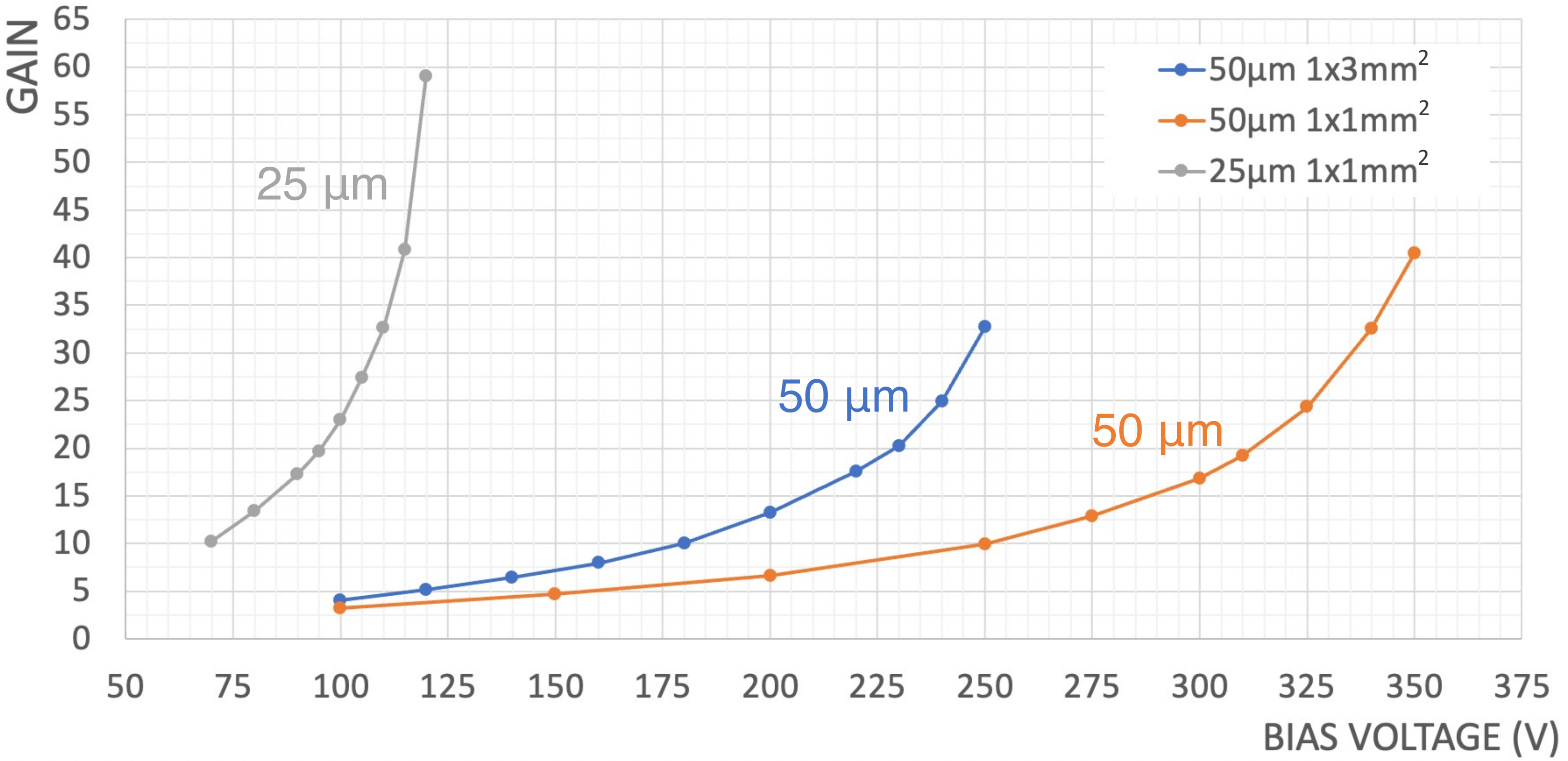






Same { Light conditions
Focusing of the spot

$$G = \frac{\text{mean charge of the LGAD}}{\text{mean charge in the reference PIN (without gain)}}$$



GAIN EVALUATION

Related to time resolution

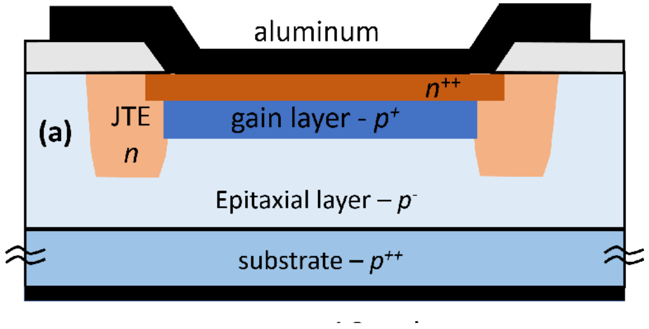
↓

Voltage in which to operate the LGAD

3 cadidates for ALICE 3 TOF

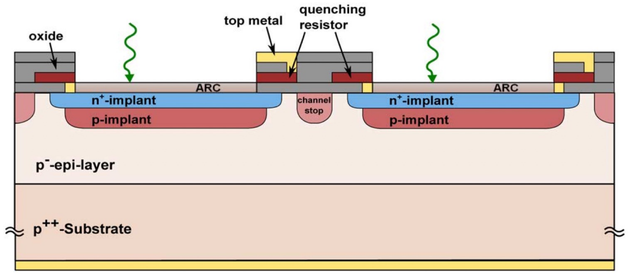
NEW SILICON TECHNOLOGIES

LGAD



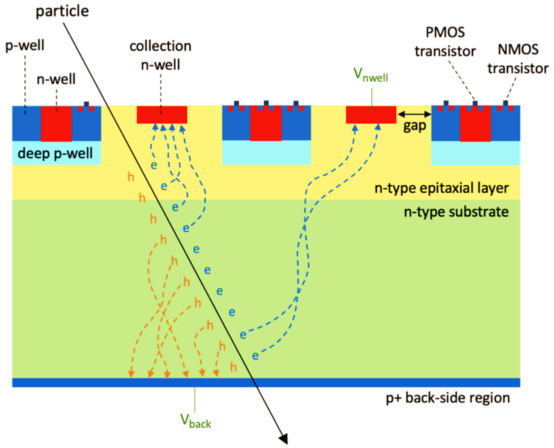
- 30-35 ps for 50 μm up to (1-2)10^{15} 1-MeV-n_{eq}/cm^2
- Recent Simulations with thinner design
  → **20 ps**

SiPM



- Only for photon detection so far
  → ~ 20 ps
- **Investigation** with **charged particles**
  → already started in Bologna

CMOS MAPS



- Low material budget
- High SNR
- Low power
- **Investigation on innovative designes**
  → required time resolution

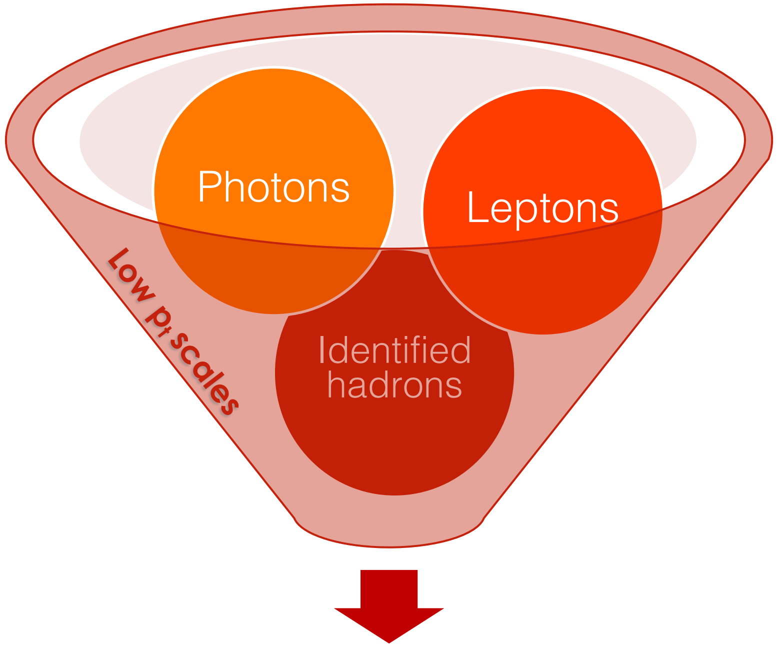
ALICE 3

- Heavy flavour and quarkonia
- Photons and low-mass dileptons
- Soft and ultra-soft photons
- Other topics

A next-generation LHC heavy-ion experiment

Specifically designed for pp, pA, AA } Luminosities **20-50×Run4**

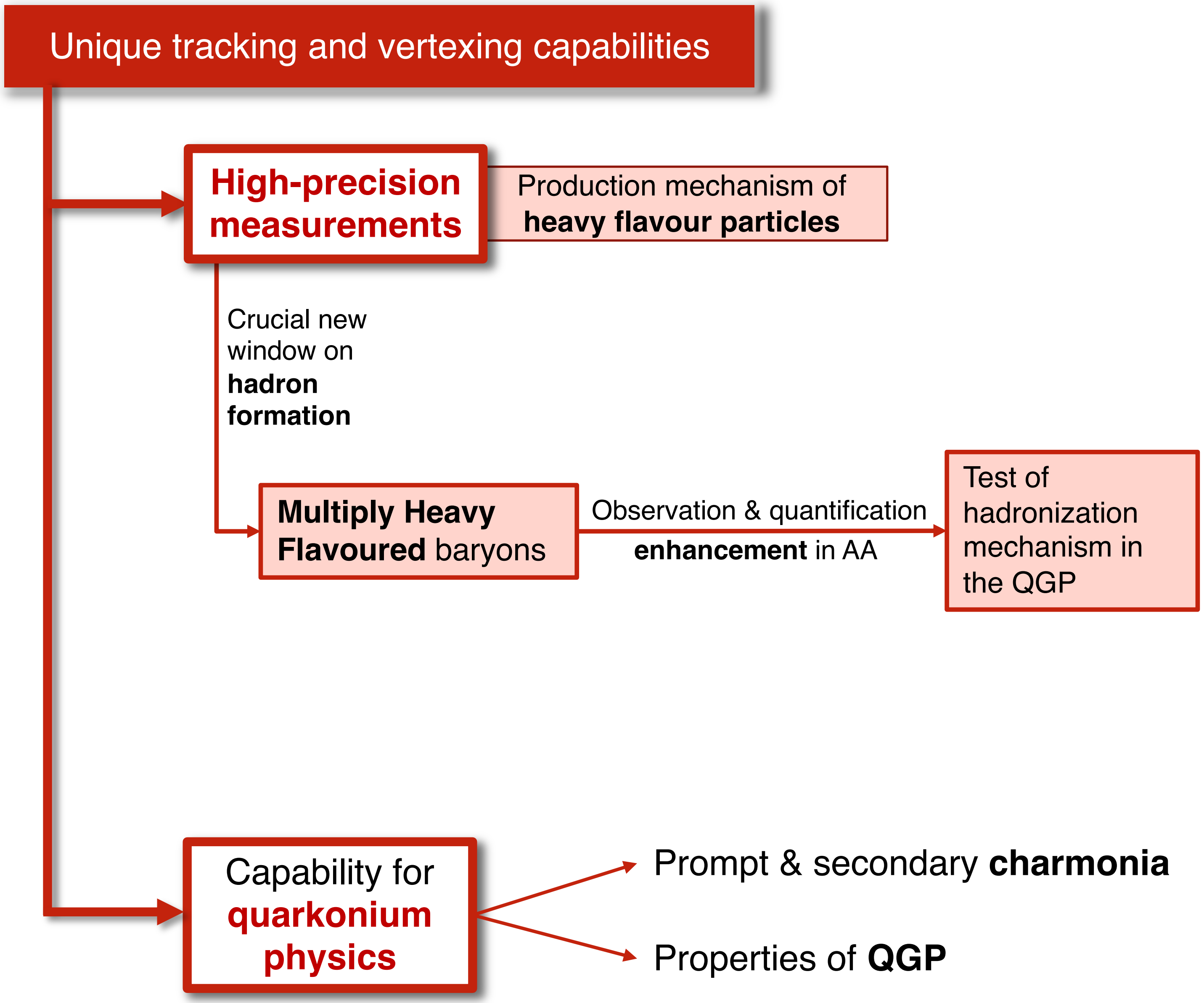
Excellent:
- PID
- **secondary vertex** finding



Significant **advances** & rich **physics program**

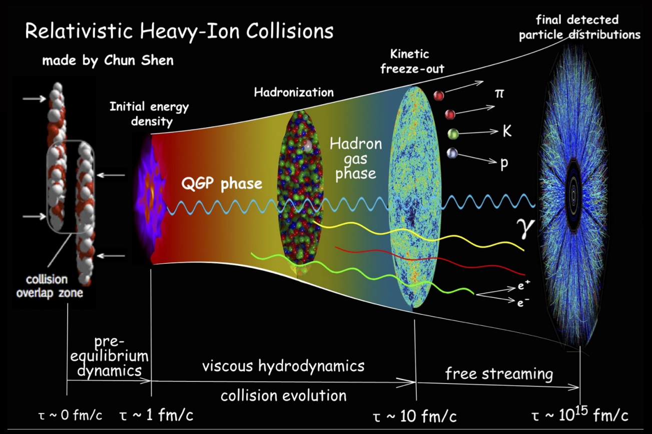
ALICE 3

- **Heavy flavour and quarkonia**
- Photons and low-mass dileptons
- Soft and ultra-soft photons
- Other topics



ALICE 3

- Heavy flavour and quarkonia
- **Photons and low-mass dileptons**
- Soft and ultra-soft photons
- Other topics

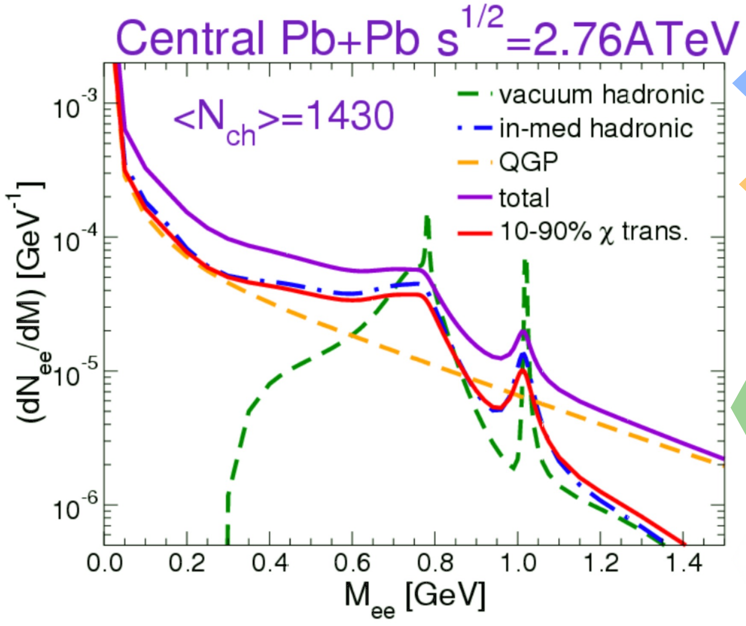


EM radiation emitted during the whole lifetime of QGP

p_T very close to the natural scale ∝ $1/R_{system}$

New approach:
Precision measurement of
- photons
- thermal di-leptons

Unique sensitivity to the early times of the deconfined system



Hadronic production via vector mesons

Thermal production from the plasma

Hadrons decays **without medium effects**

Crucial test for **chiral symmetry restoration**

ALICE 3

- Heavy flavour and quarkonia
- Photons and low-mass dileptons
- **Soft and ultra-soft photons**
- Other topics

Soft and ultra-soft photons
$p_T \sim$ 10 MeV/c

Extremely **difficult**

- Huge background from π_0 decays
- e^- bremsstrahlung

Directly connected to **charged final state** of QGP

Test the predictions on radiation in this p_T range

ALICE 3

- Heavy flavour and quarkonia
- Photons and low-mass dileptons
- Soft and ultra-soft photons
- Other topics

PUSH THE BOUNDARIES IN A NUMBER OF OTHER AREAS

⇕

Comprehensive **studies** and **simulations** to fully exploit the **physics potential**