It’s *time* we talk about LGADs

B. Raciti | FCC Meeting, 23rd April 2026

LPNHE
PARIS

Why is timing important?

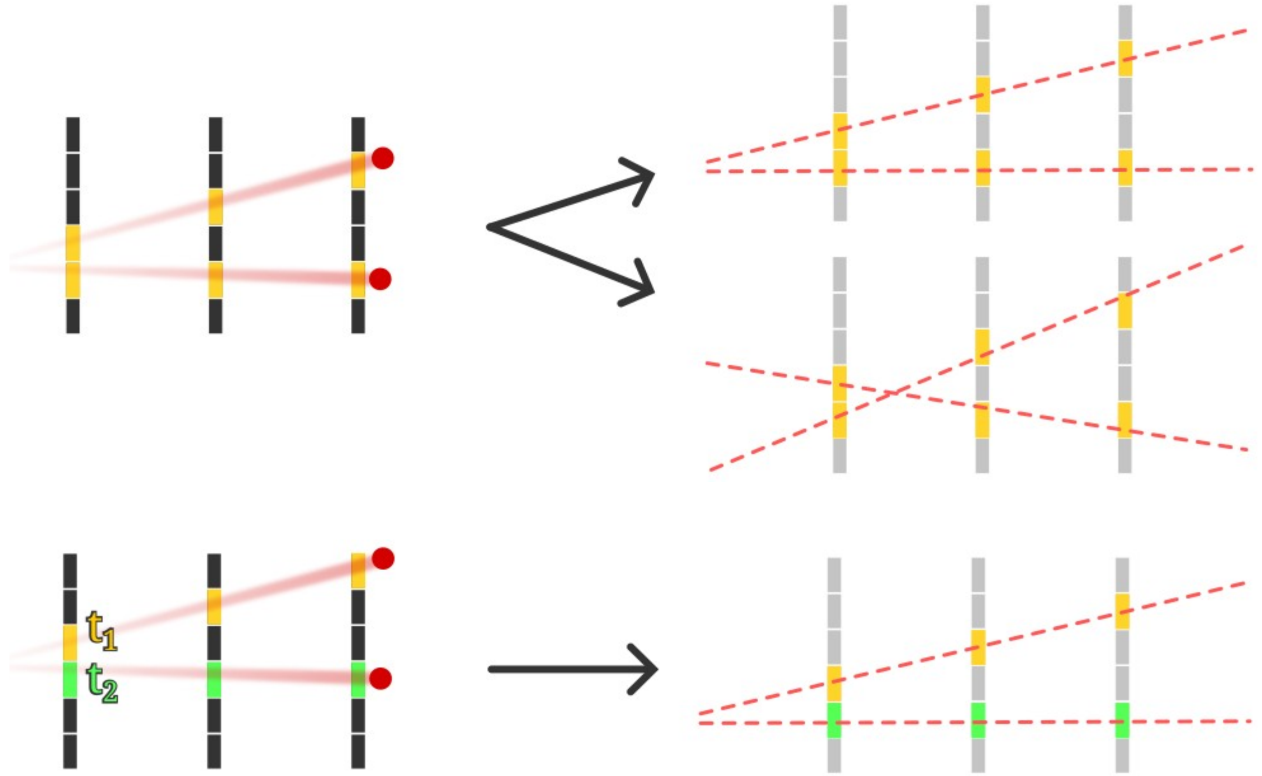
DRD3

Experiments with *increasing number of collisions* per bunch-crossing (HL-LHC, FCC-ee…):

- track **timing** to complement spatial information
  - *timing layer* → add “timestamp” to each track
  - *4D tracking* → timing at each point along the track

high occupancy regime

high occupancy regime with 4D tracking



possibility 1

possibility 2

one obvious option

PhD Thesis, M. Senger

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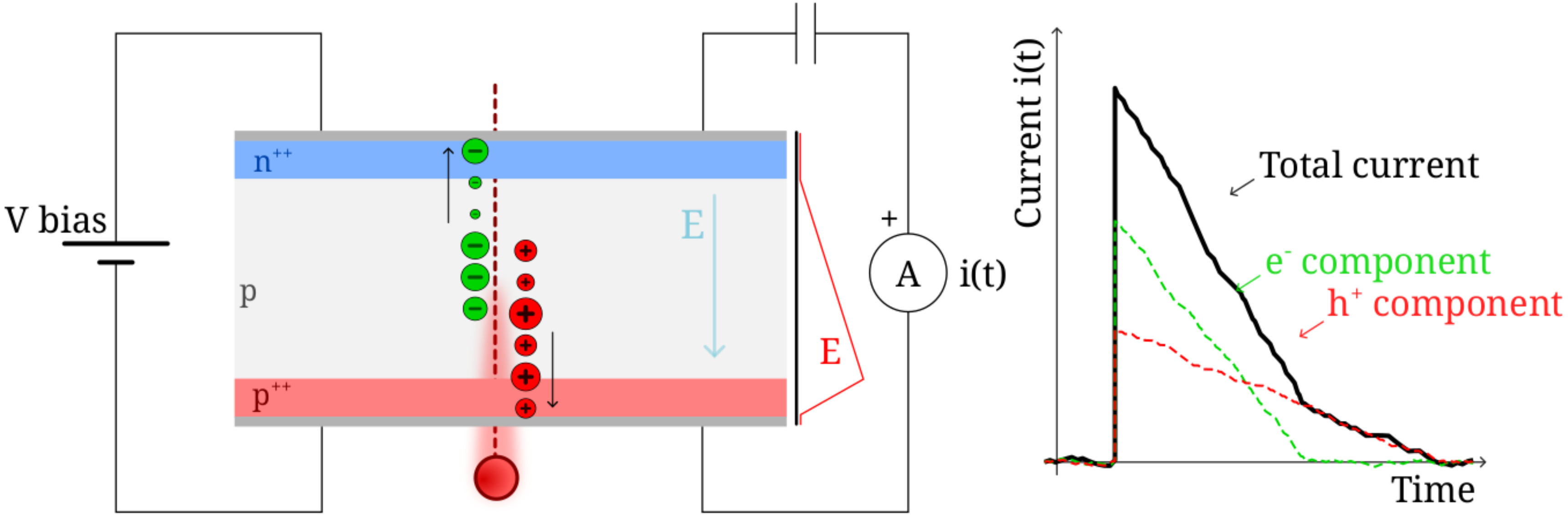
What can we use for timing (in silicon)?

Precise timing requires **fast** and **intense** current signals:

- more *charge* needed… thicker sensors?



PhD Thesis, M. Senger

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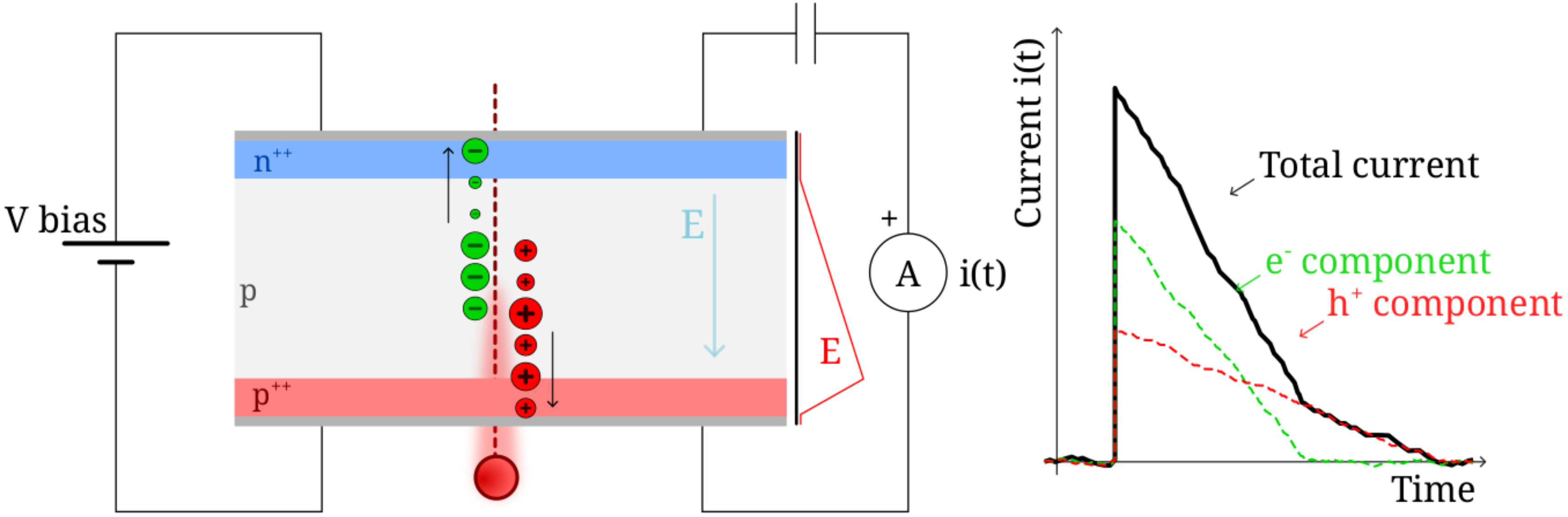
Precise timing requires **fast** and **intense** current signals:

- more *charge* needed… thicker sensors?
  - more drift time = slower signal → standard silicon sensors are not fit for the job



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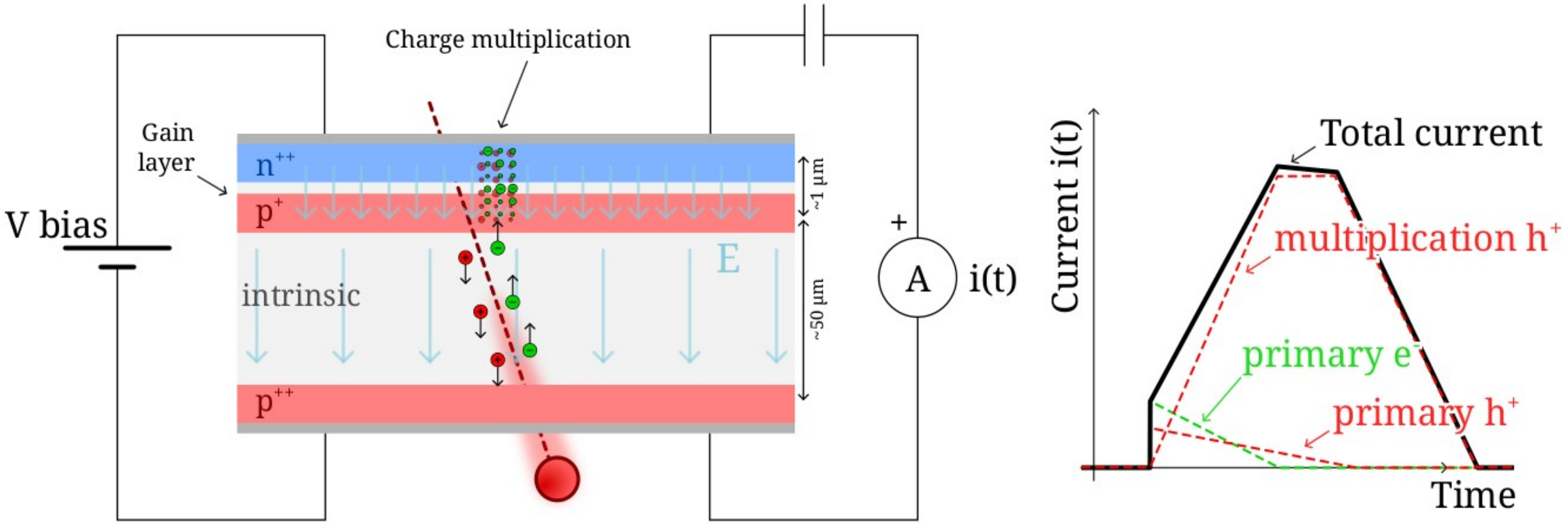
What is an LGAD?

Low Gain Avalanche Diodes (LGADs) are silicon sensor with **internal gain**:

- thinner sensors → smaller collection time = faster signals!

Charge multiplication achieved by **impact ionization** (avalanche process):

- additional p^{+} doped layer (N_A ~10^{16} atoms/cm^3) under the n^{++} layer → *$E \geq 300$ kV cm^{-1}*
- **gain factor** of ~10 → better SNR without increasing shot noise and power consumption

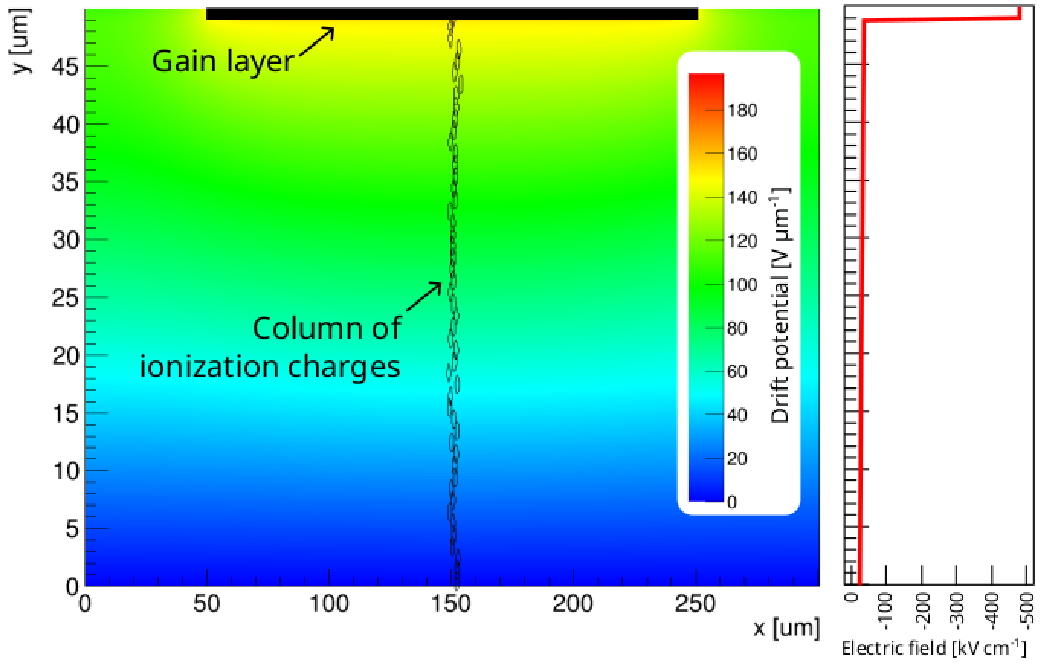


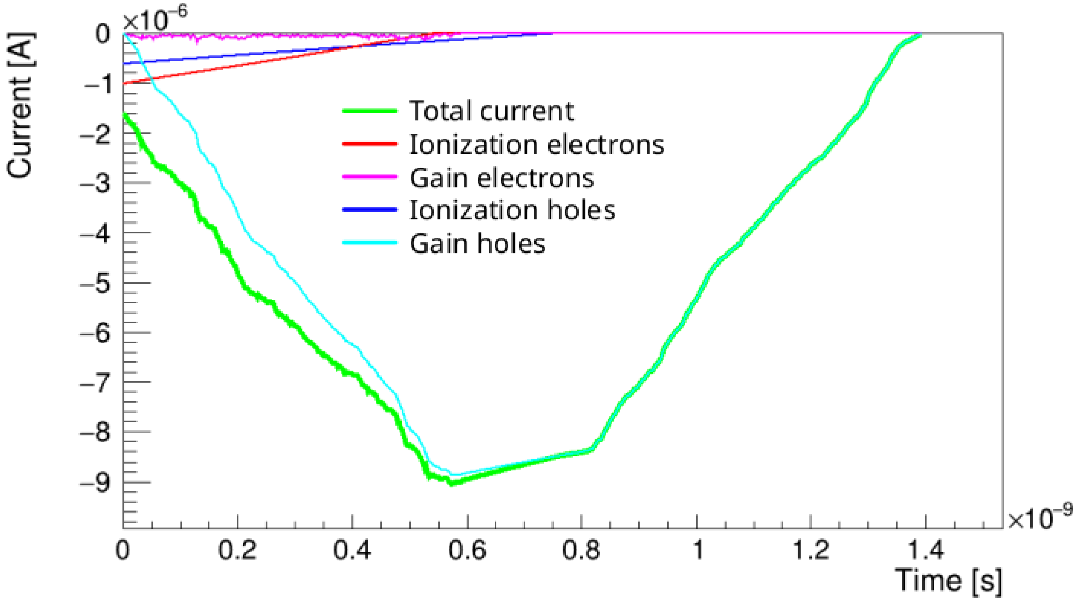
PhD Thesis, M. Senger

How does an LGAD work?

E increases linearly along sensor thickness → abrupt step at gain layer initiates **multiplication**:

- *ionization* e^-/h^+ contribute as for standard silicon sensors
- *gain* e^- are immediately collected, don't contribute to signal
- *gain* h^+ are produced by e^- reaching the high-field region in gain layer → generate most of the signal





PhD Thesis, M. Senger

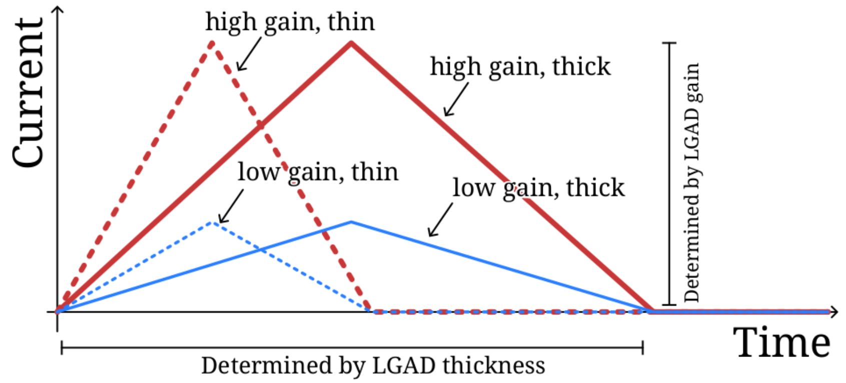
How does an LGAD work?

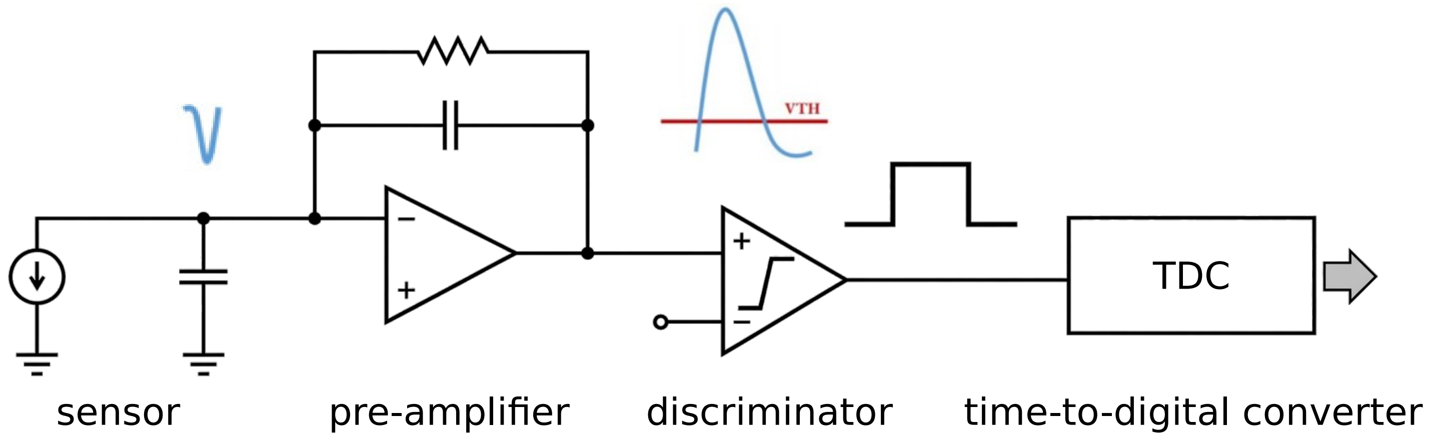
Looking at the signals **shape**:

- amplitude ∝ *gain* and pulse duration ∝ *thickness*
- rise time = e^- drift time through sensor thickness → **slew rate**
  - *thinner sensors* = steeper signals, but increased junction **capacitance** affects time resolution (σ_t)
  - *high gain* increases slew rate, but impacts **SNR** and **power consumption** (higher V_{bias})

Signals are digitized in the TDC → Time-of-Arrival (ToA) and Time-over-Threshold (ToT):

- **σ_t < 30 ps** with 50 µm thick *standard* LGADs with 1.3 mm pitch
  - designs from IHEP and USTC
- target for HL-LHC, but **BIG** pixels!





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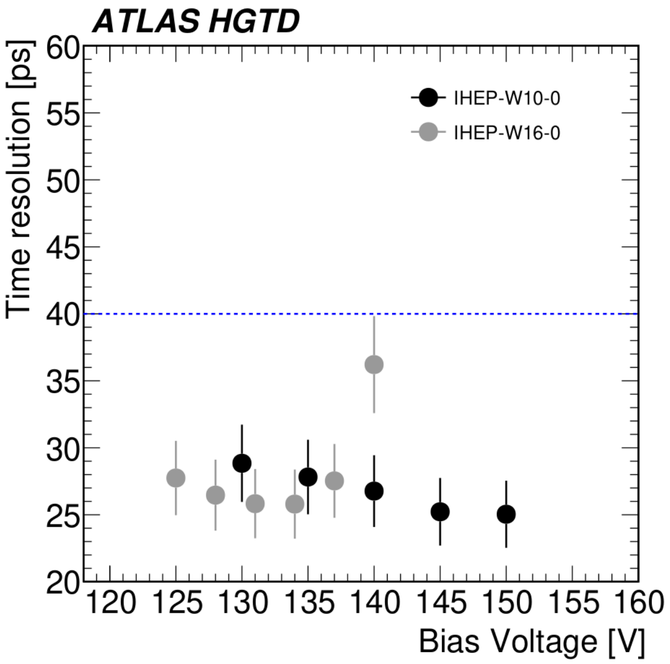
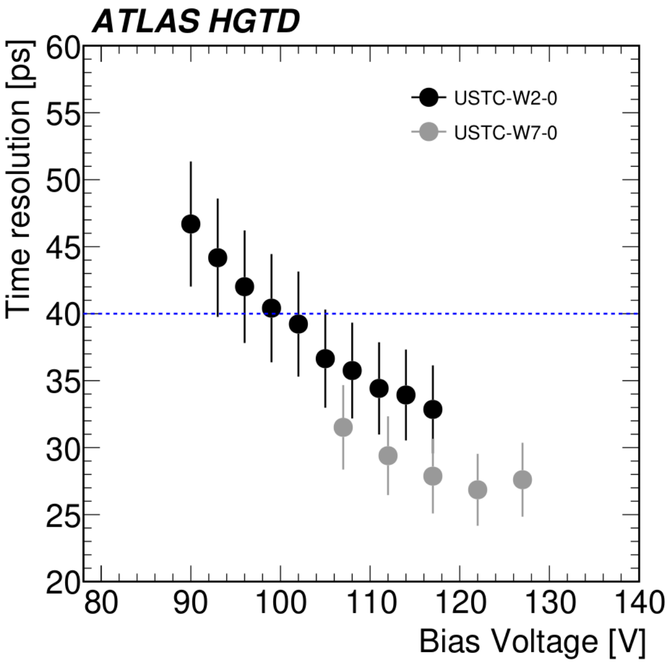




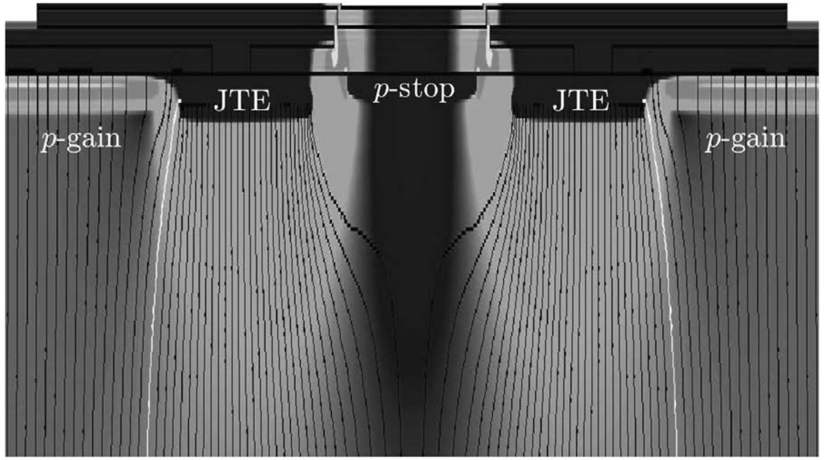
[arXiv:2512.01855]

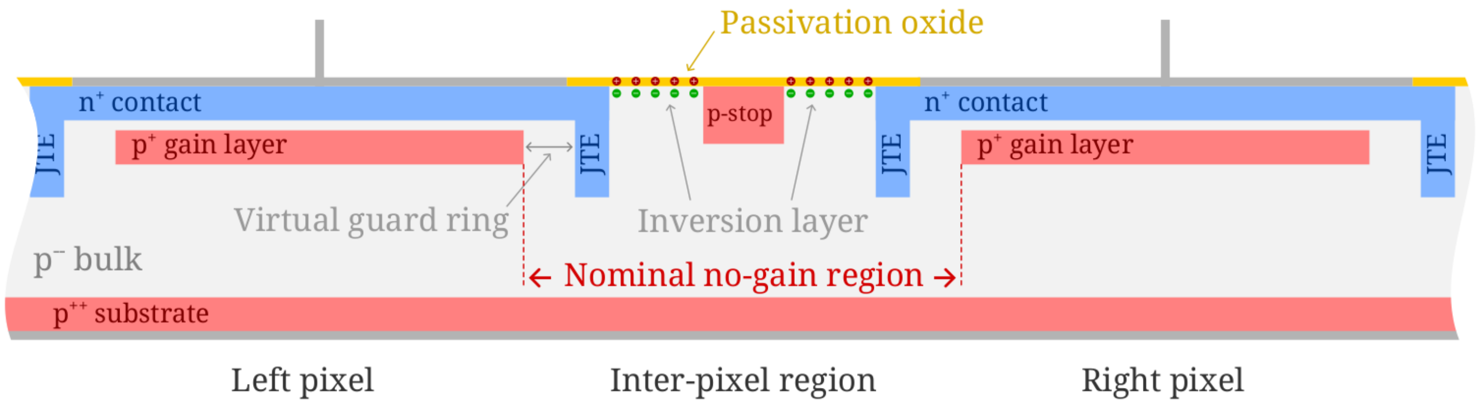
The problem: no-gain region

The **segmentation** of a *standard* LGAD requires:

- junction termination extension (JTE)
  - e^-/h^+ pairs generated between two pixels do not reach the gain layer → lateral drift time impacts σ_t
  - reduces electric field at pixel boarder
- virtual guard ring
  - separation between gain layer and JTE, and avoids premature breakdown
- p-stop to isolate pixels:
  - avoiding formation of inversion layer under oxide shorting n^+ contacts

This leads to the *fill factor problem*.





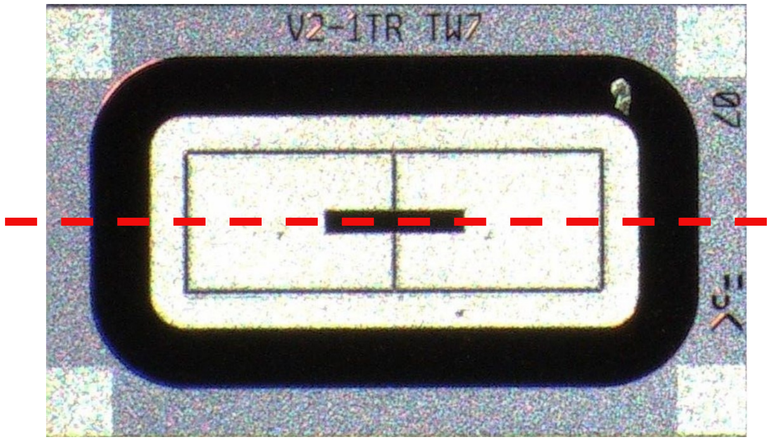
The problem: no-gain region

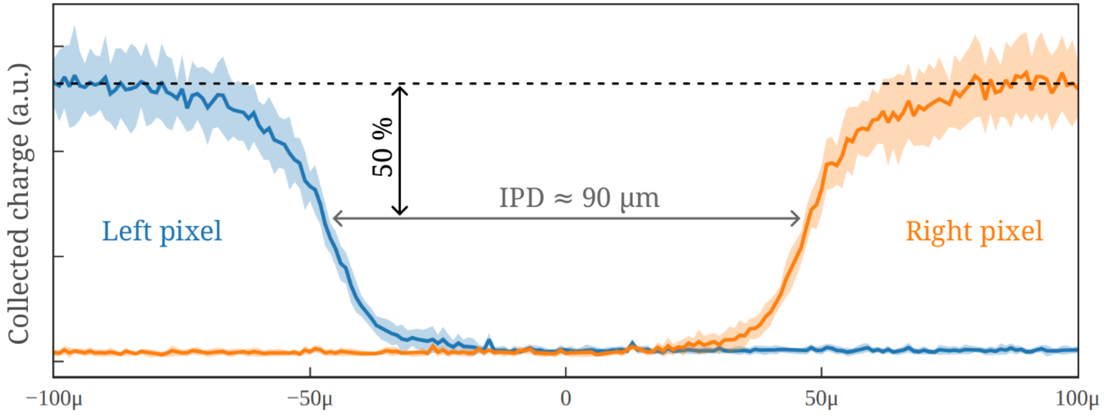
There is a *no-gain* region:

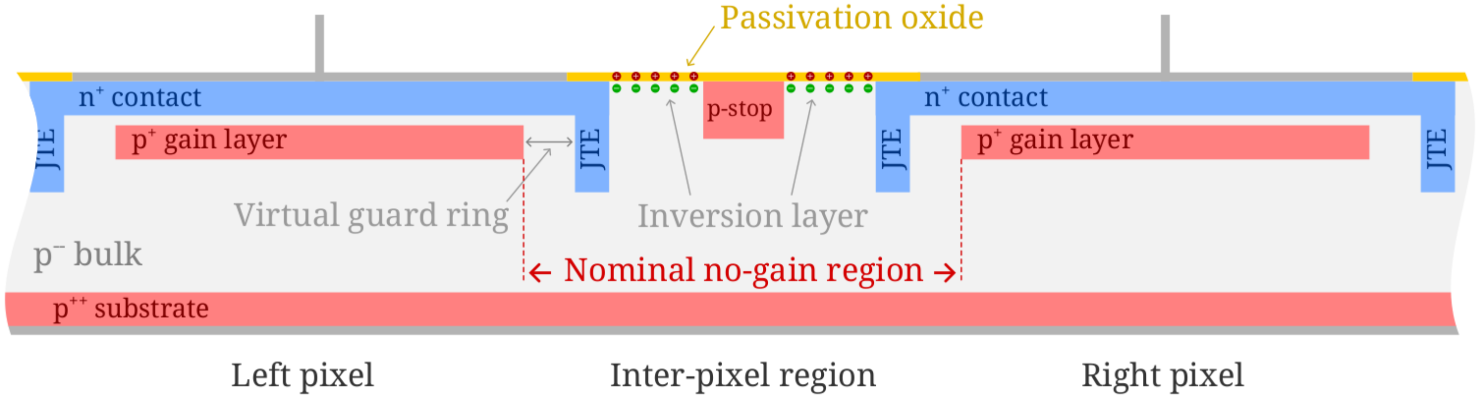
- ionization charges collected **without being multiplied** by gain layer
  - smaller signal *filtered by threshold* in the electronics
- the extent can be measured with laser in TCT

The *fill factor* must be maximized:

- to maximize detection efficiency
- A_{active} / A_{total}



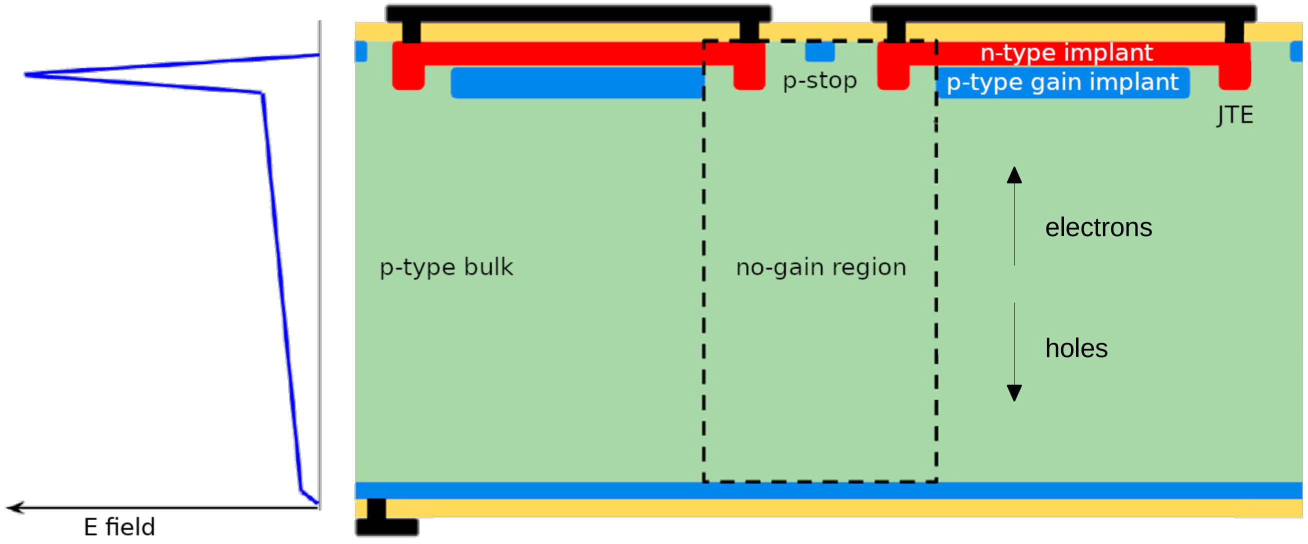




New LGAD technologies: standard LGADs

Standard LGADs, the starting point:

- **σ_t < 30 ps**
- no-gain region ranges from 20–90 µm
- initially constrained to be > 1 mm²

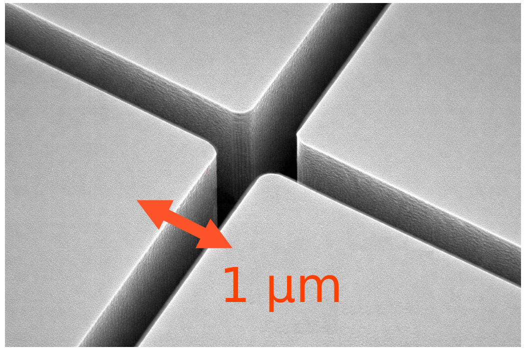


[10.3389/fphy.2024.1359179]

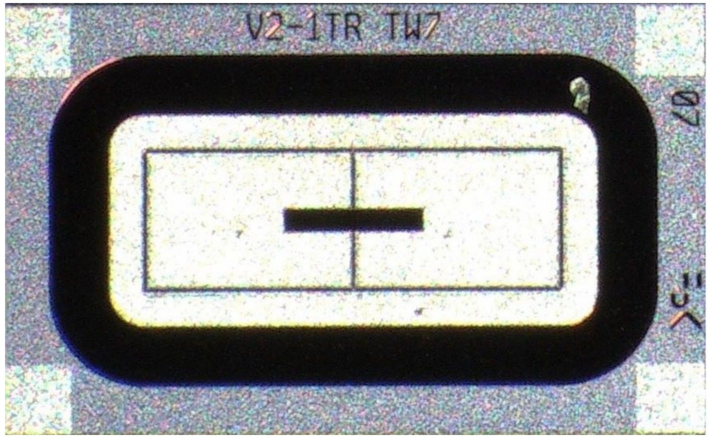
New LGAD technologies: trench-isolated LGADs

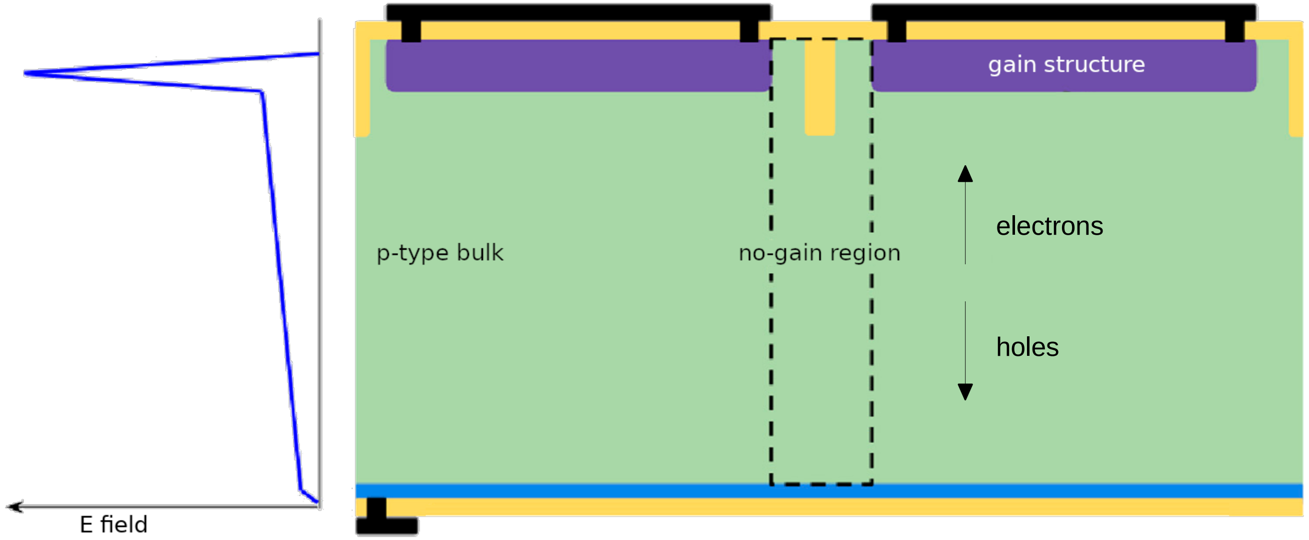
Trench-isolated LGADs: trenches etched in silicon substrate and filled with SiO_2

- replace *all structures* at pixel boarder
  - no-gain region reaches **< 5 µm**
- aspect ratio of 20:1 with < 1 µm precision (DRIE)
- formation of *inversion layer* at interface
  - conductive path shorts pixels
- *defects* at Si–SiO_2 interface
  - increase in leakage current



[10.1109/LED.2020.2991351]



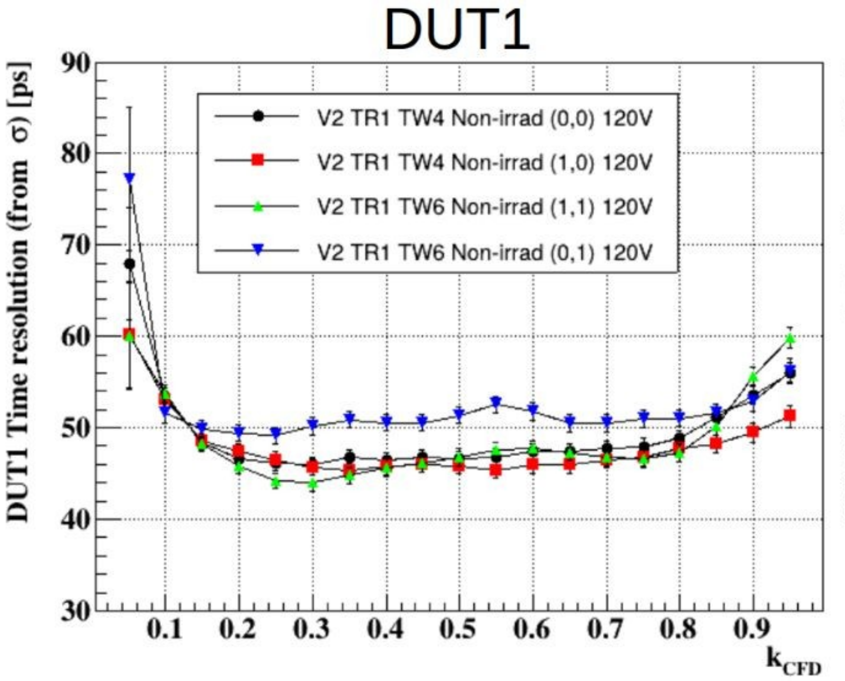


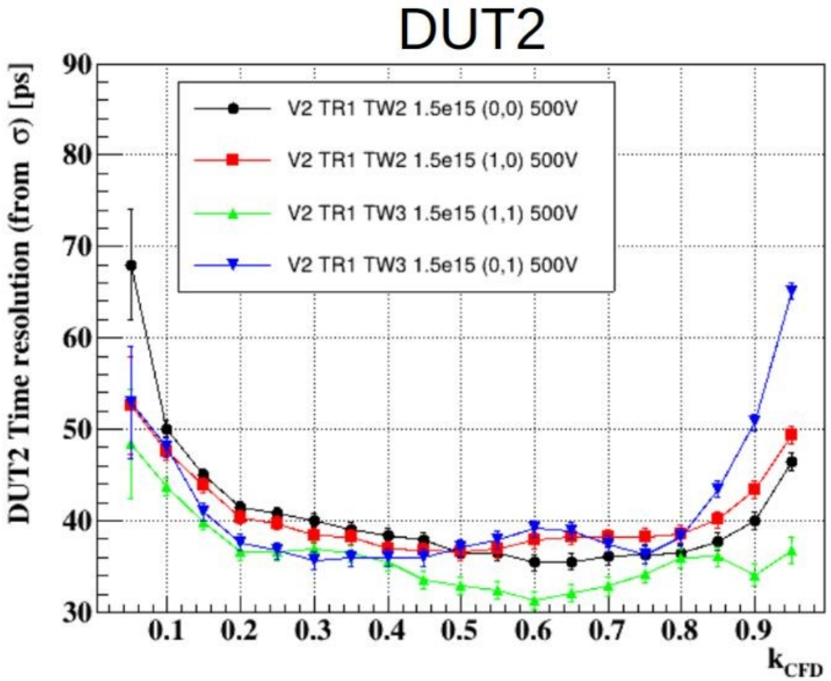
[10.3389/fphy.2024.1359179]

New LGAD technologies: trench-isolated LGADs

Recent results:

- pitches of 375 x 250 μm^2 and 45 µm depth (FBK) with different trenches' width, depth and process
- **σ_t ~30–45 ps** measured at SPS with 120 GeV pions
  - irradiation mitigates Landau fluctuations!
- *interpad distance* (no-gain region) of **zero**!
  - for 95% (non-irradiated) and 90% (1.5 x 10^{15} n_{eq} cm^{-2}) efficiency





M. Fernandez, TI-LGAD Meeting

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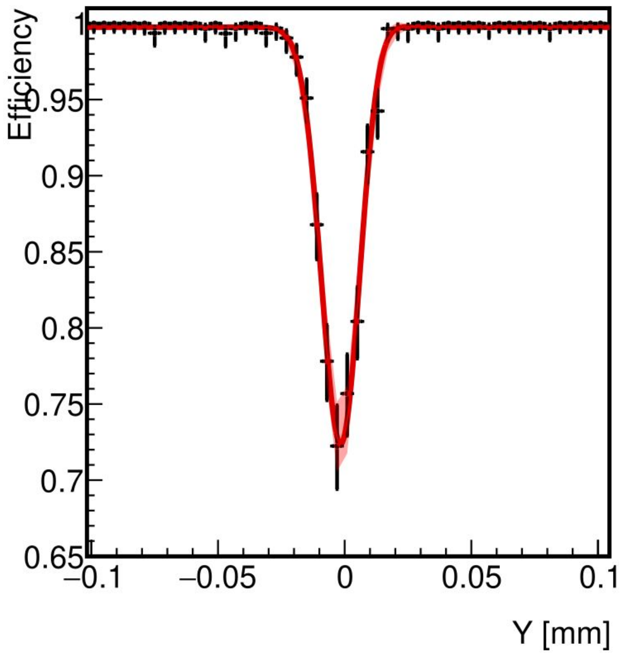
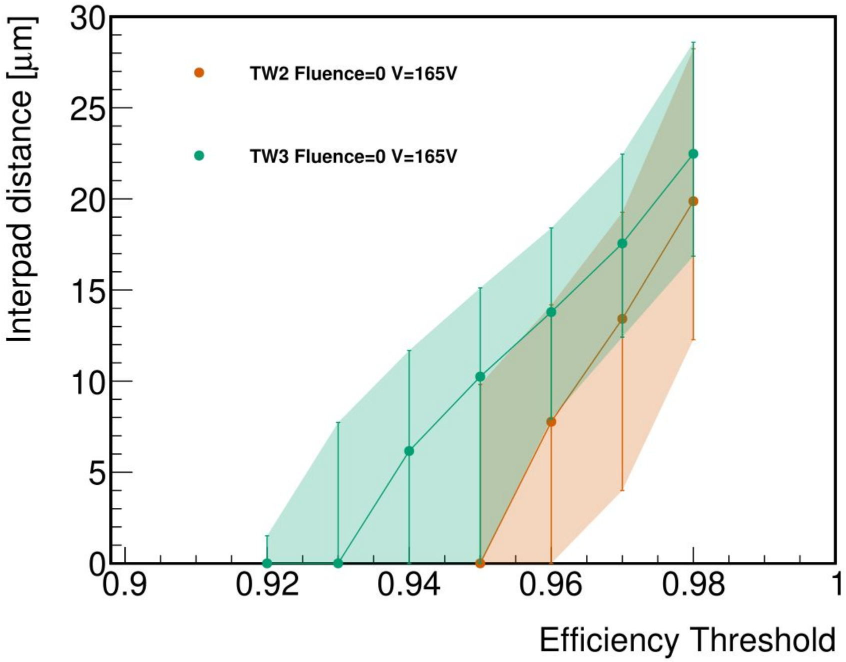




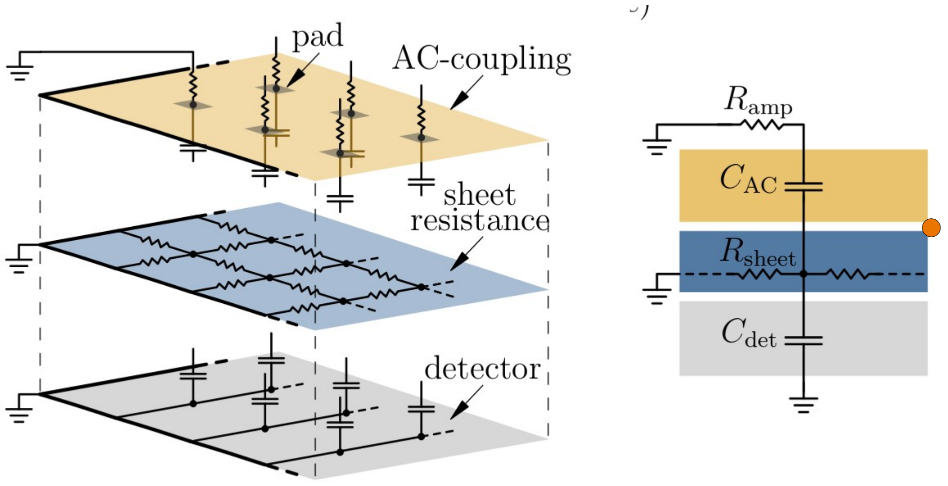
A. Carrera, TREDI21

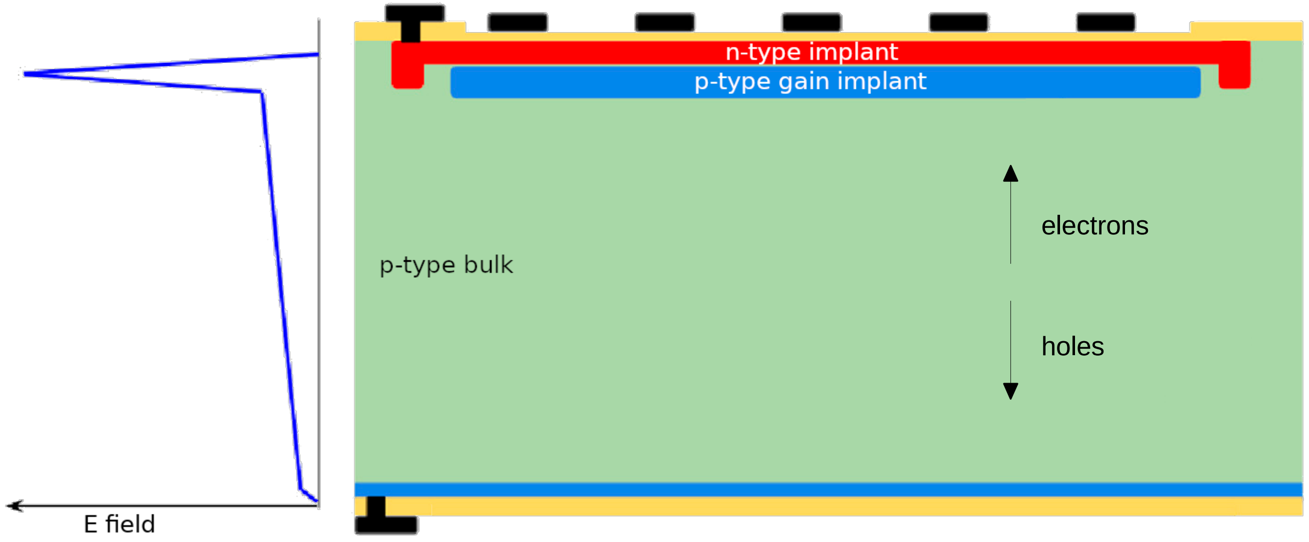
New LGAD technologies: AC-LGAD (RSD)

DRD3

Small electrodes *AC-coupled* to “one big LGAD” via thin dielectric layer:

- **continuous gain layer** → 100% fill factor by construction!
- e^- reach the n^+ layer and follow *shortest path to ground*
  - through **RC circuit** formed by n^+ layer and AC-coupled electrodes
  - the closer the electrode to hit-position, the lower the resistivity → e^- *split proportionally*
  - e^- *discharged* in the peripheral DC path to ground (with JTE)
- large **charge sharing** between readout electrodes
  - enhanced spatial resolution





[10.3389/fphy.2024.1359179]

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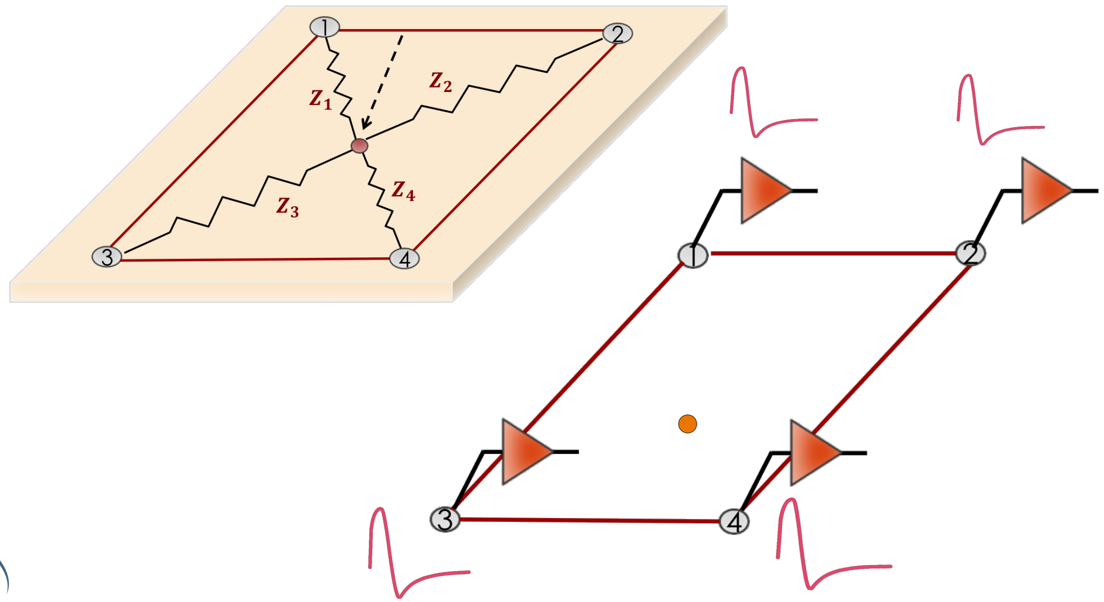
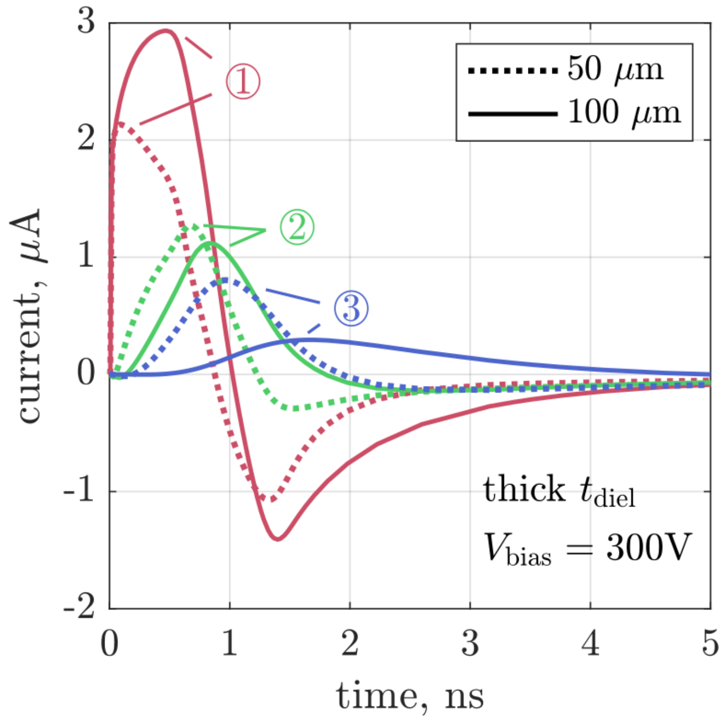


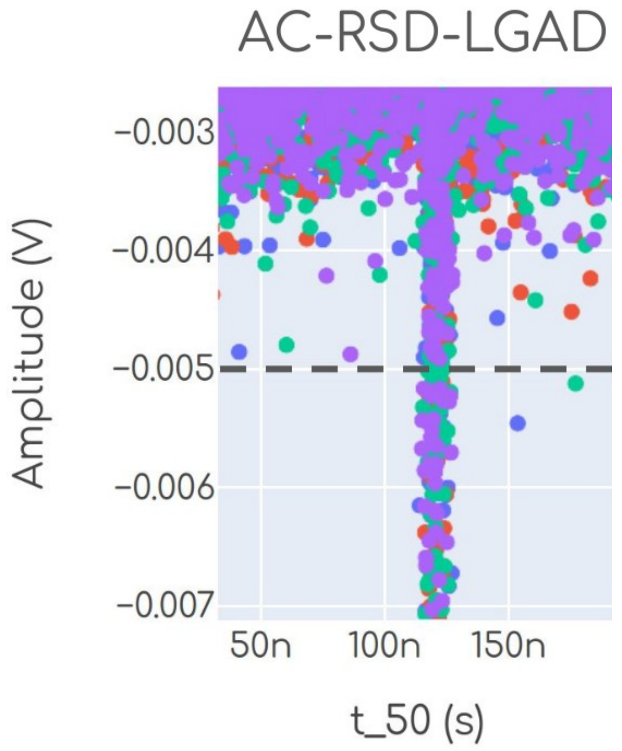


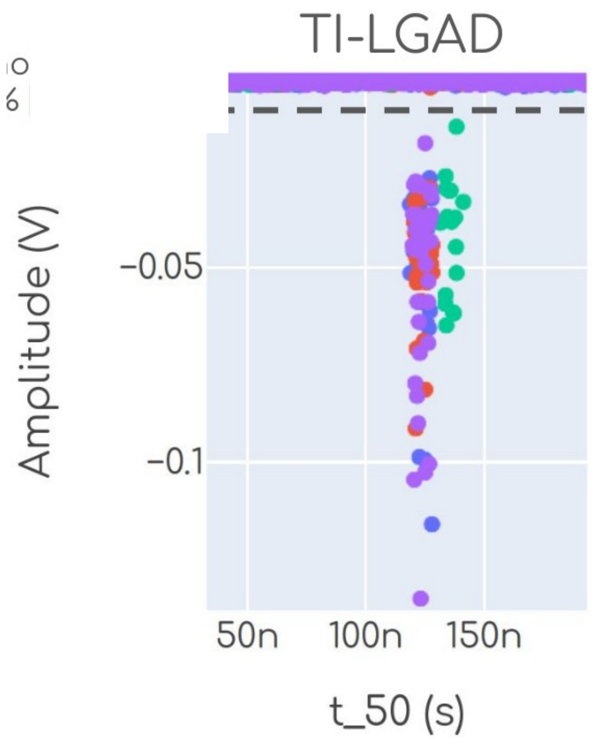
[10.1016/j.nima.2020.163479]

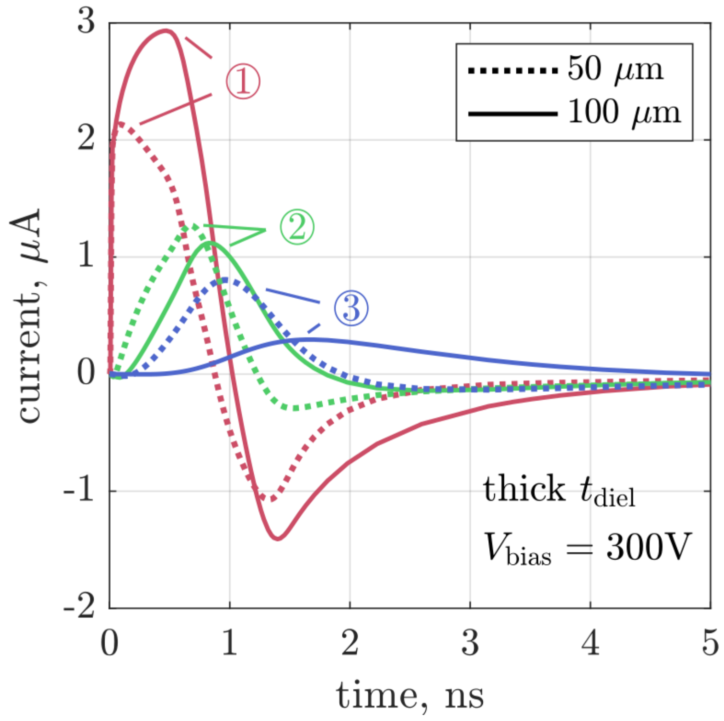
New LGAD technologies: AC-LGAD (RSD)

The **signal**:

- propagation of O(100 µm) before collection → signal spreading to a minimum of *four* electrodes
- baseline fluctuations (pile-up)
- bipolar signal → not compatible with charge-integrating electronics (photon science)





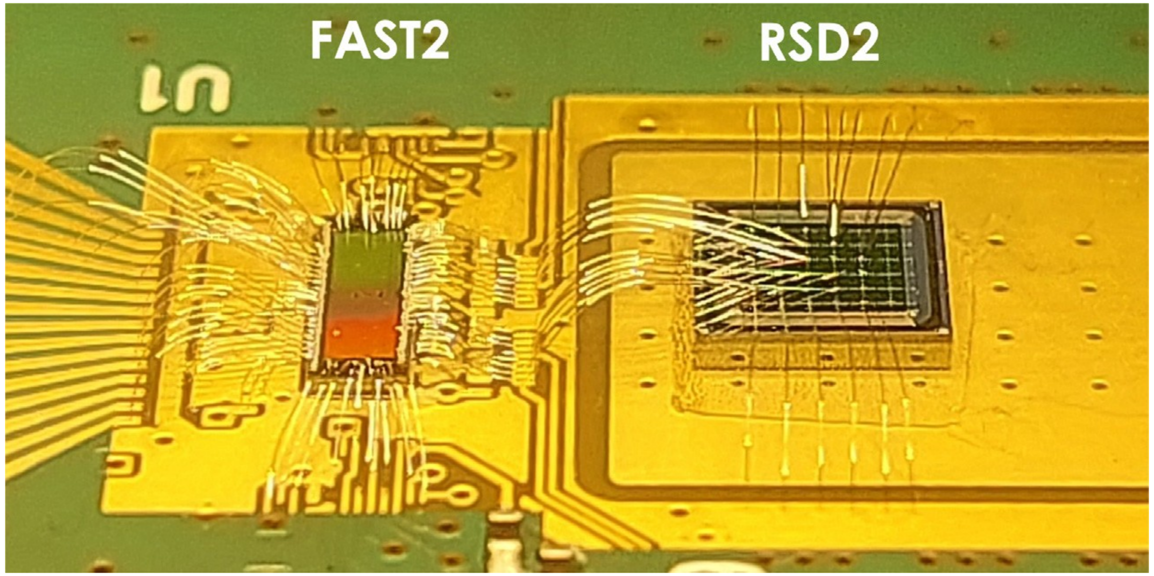


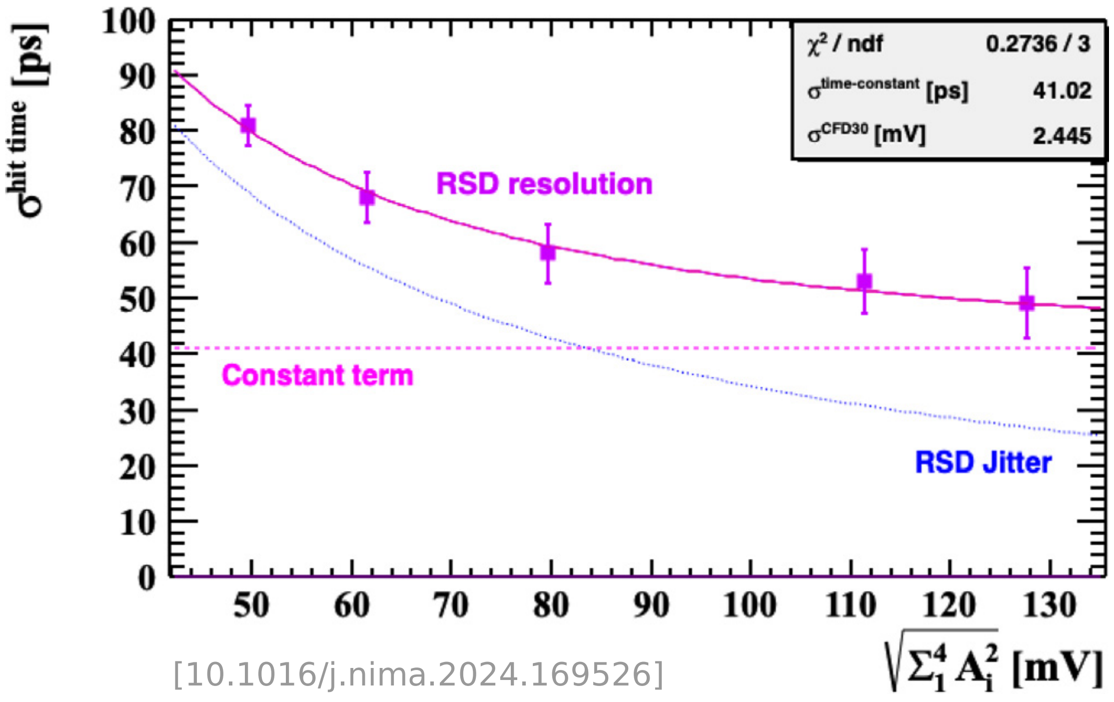
[10.1016/j.nima.2020.163479]

New LGAD technologies: AC-LGAD (RSD)

Recent results:

- pitch 450 µm and active volume of **55 µm** with cross-shaped electrodes (FBK)
  - readout with FAST2 ASIC tested at DESY with 5 GeV e^- beam
  - spatial resolution of **14 ± 1 µm** (3.4% pitch) and **σ_t ~49 ± 6 ps**



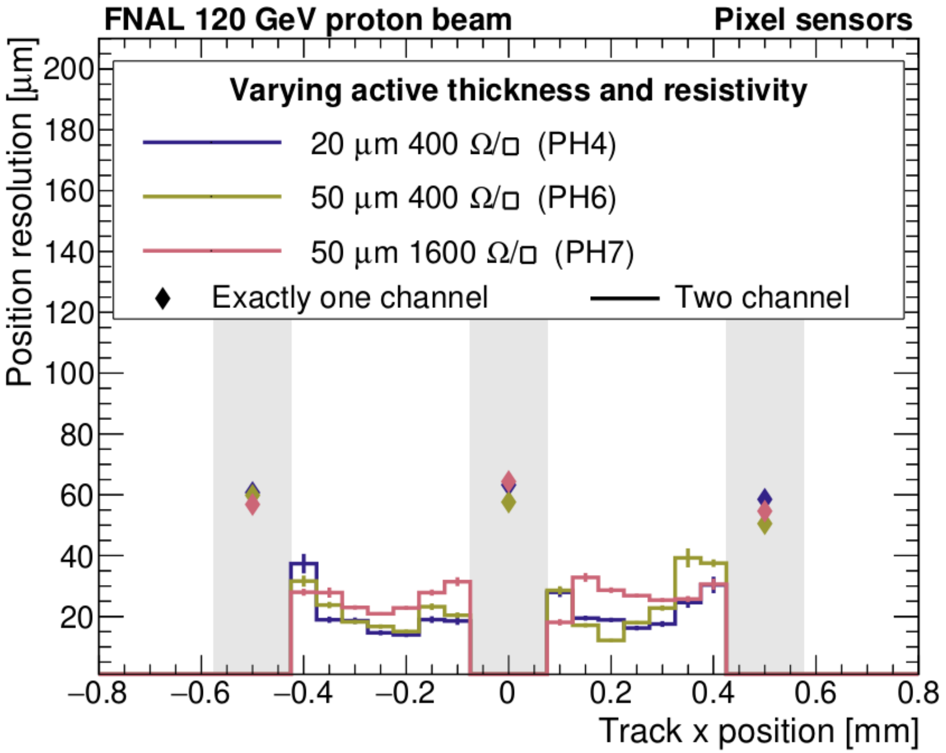


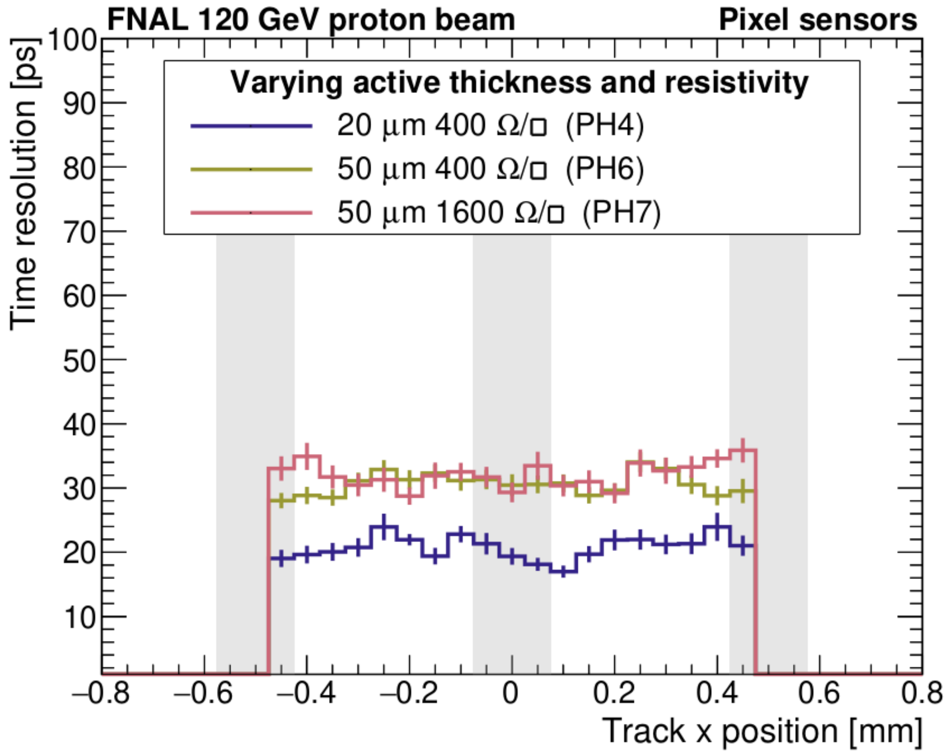
[10.1016/j.nima.2024.169526]

New LGAD technologies: AC-LGAD (RSD)

Recent results:

- pitch 500 µm, thinner active volumes (e.g. **20 µm**), square electrodes (HPK) and varying resistivity
- readout with FNAL/UCSC boards and tested at FNAL with 120 GeV proton beam
  - spatial resolution of **21 µm** and $\boldsymbol{\sigma_t}$ **~20 ps**





[10.48550/arXiv.2407.09928]

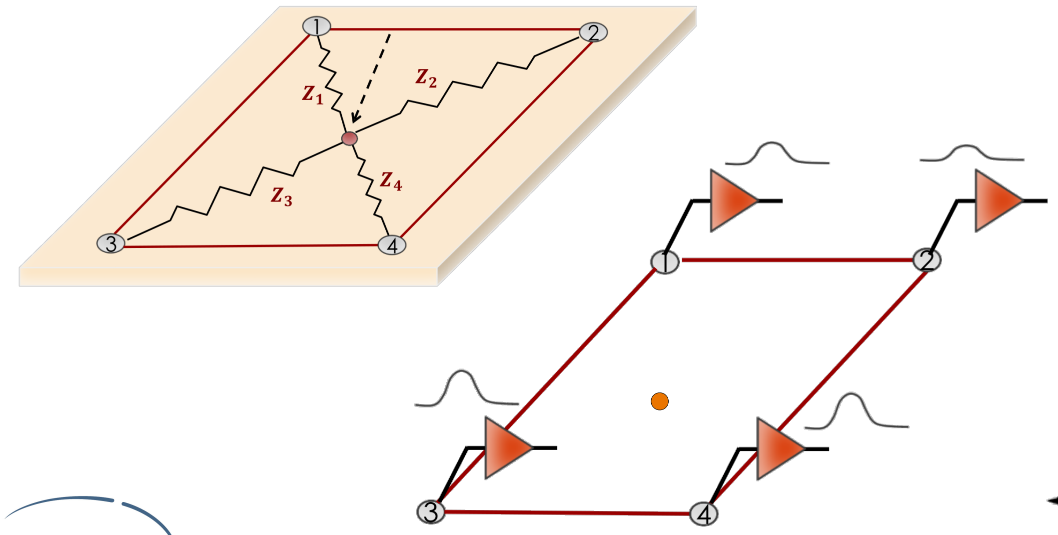
New LGAD technologies: DC-LGAD (RSD)

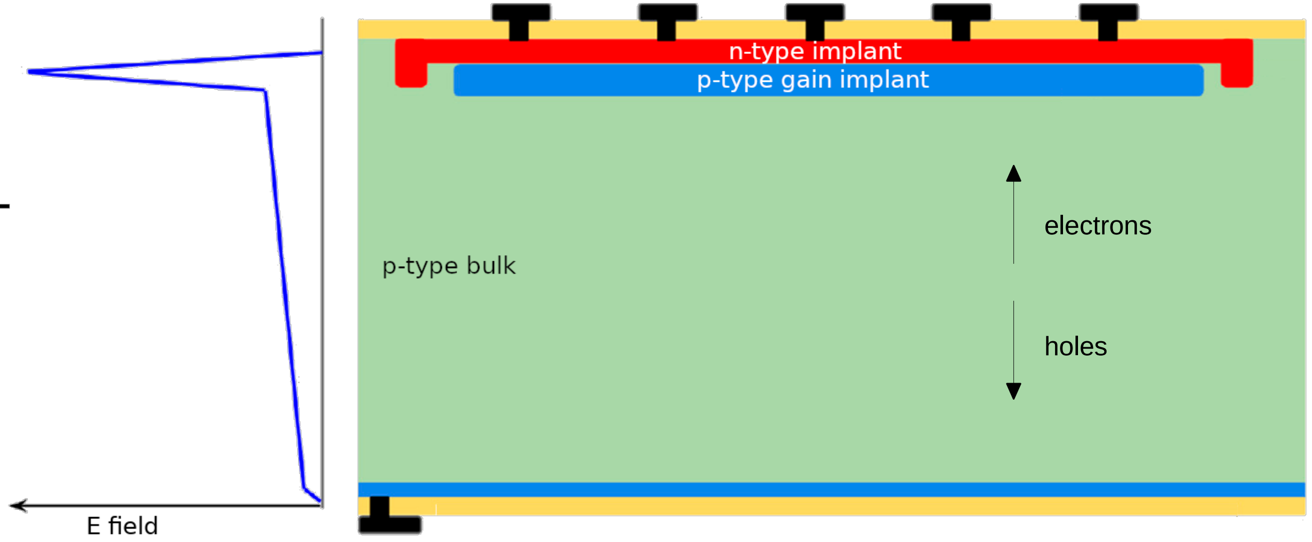
To avoid the **signal spreading** of AC-LGADs → DC-LGADs:

- *removed dielectric* between electrodes and n^+ layer → **ohmic contact**
- **electric isolation** of pixels via *high sheet resistance* of n^+ layer and optimization of *inter-pads distance*

The **signal**:

- is fully contained (well controlled charge sharing) → scalable to larger devices
- unipolar and absence of baseline fluctuations
- non-uniform resolution across sensor area





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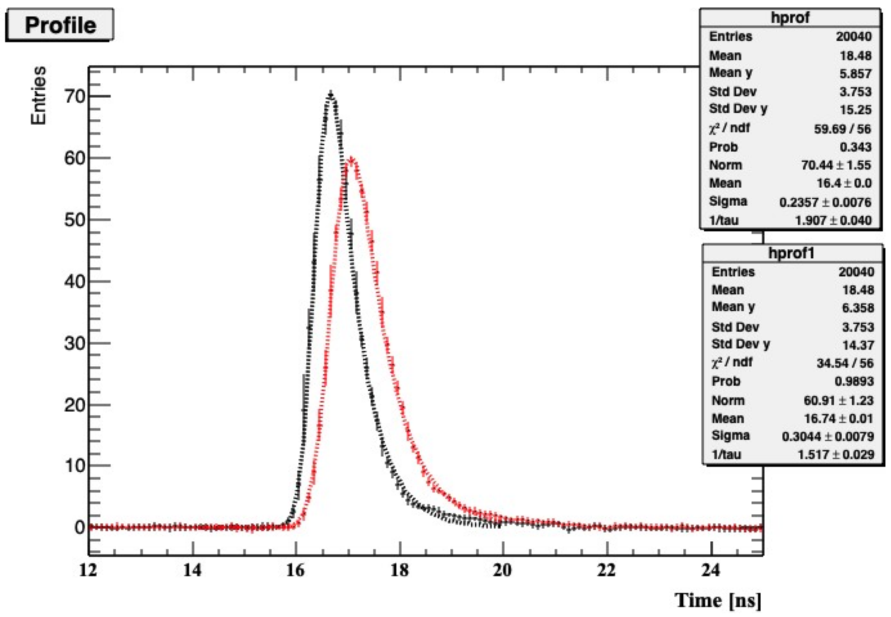
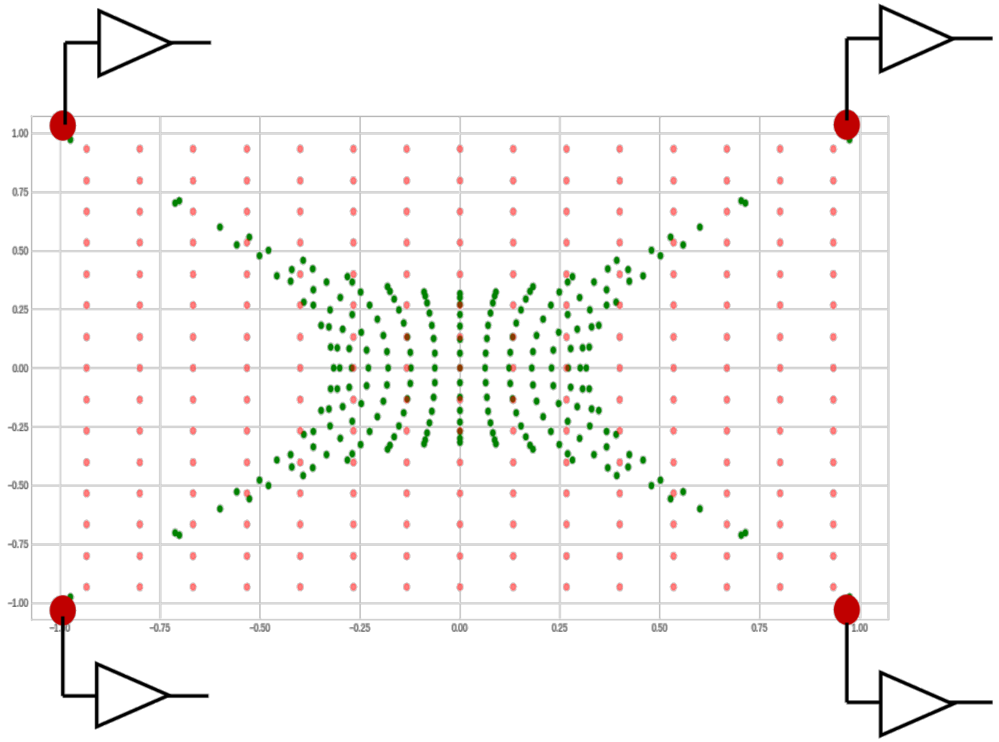
[10.1016/j.nima.2022.167815]





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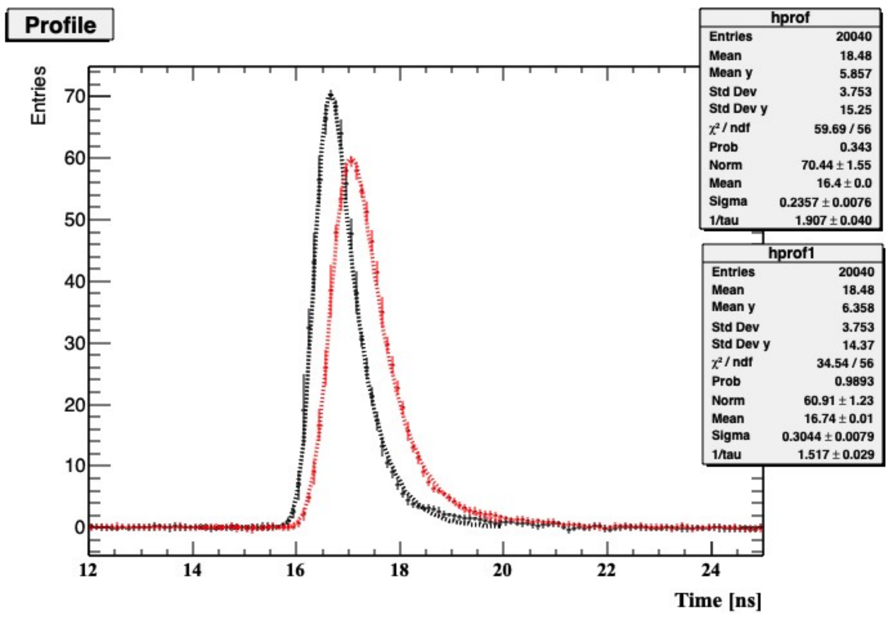

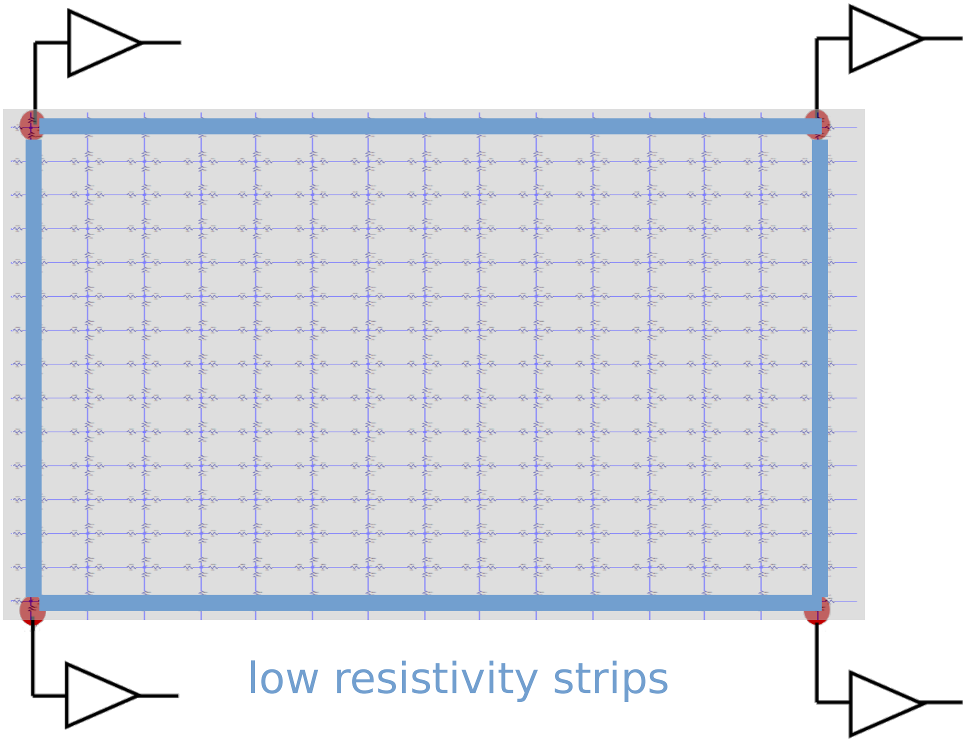

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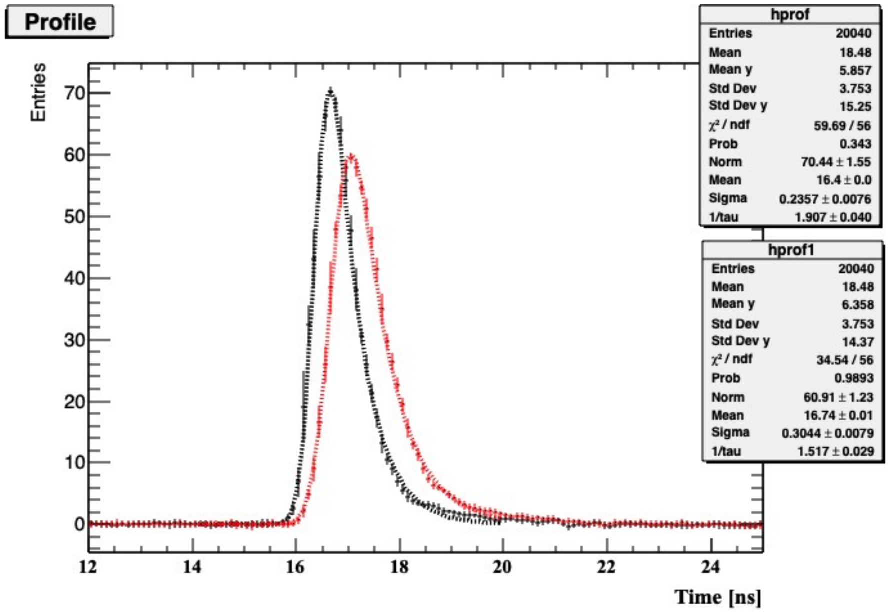
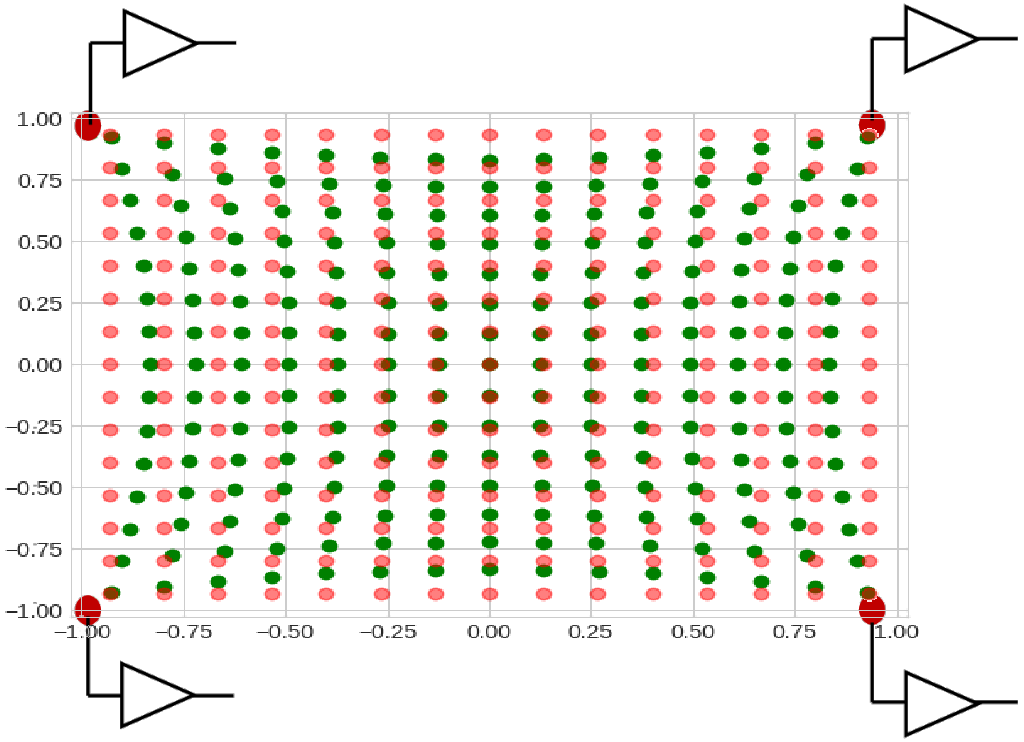


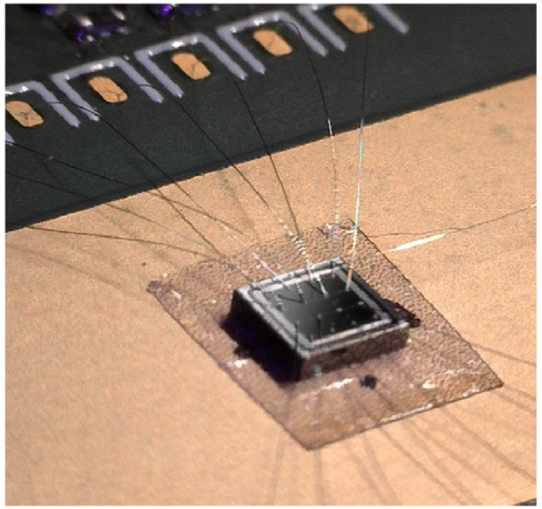


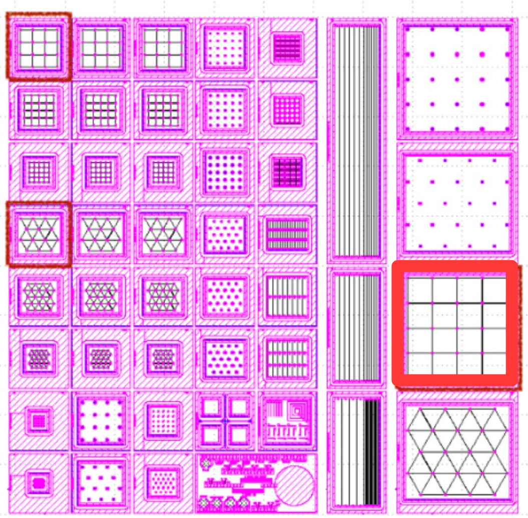
New LGAD technologies: DC-LGAD (RSD)

<u>Recent results:</u>

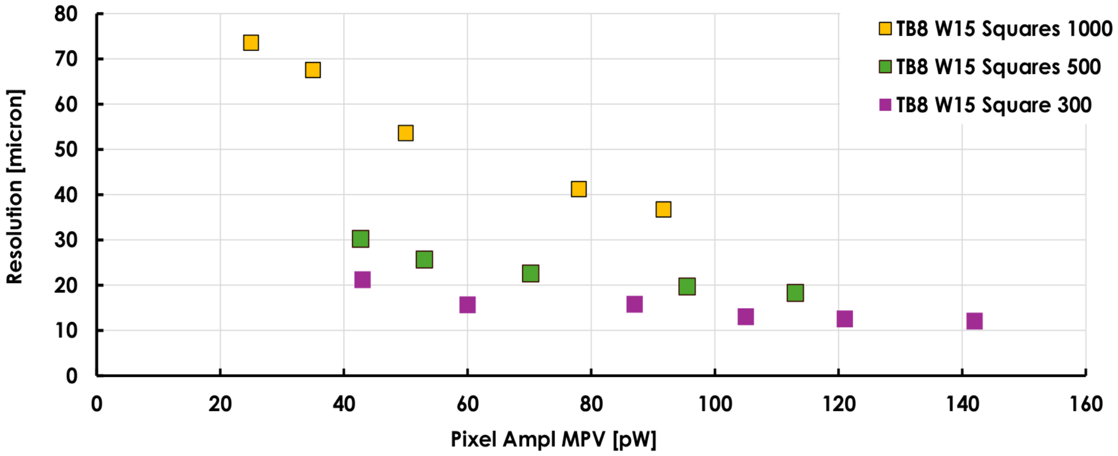
- test beam in DESY with 5.2 GeV e^-
  - thickness of **55 µm** and pitches of 300, 500 and 1000 µm
  - low resistivity and square electrodes
  - read out by FNAL board
- **σ_t ~40 ps** doesn't depend on pitch!
- spatial resolution does, reaching **10 µm**

[10.1016/j.nima.2025.170796]

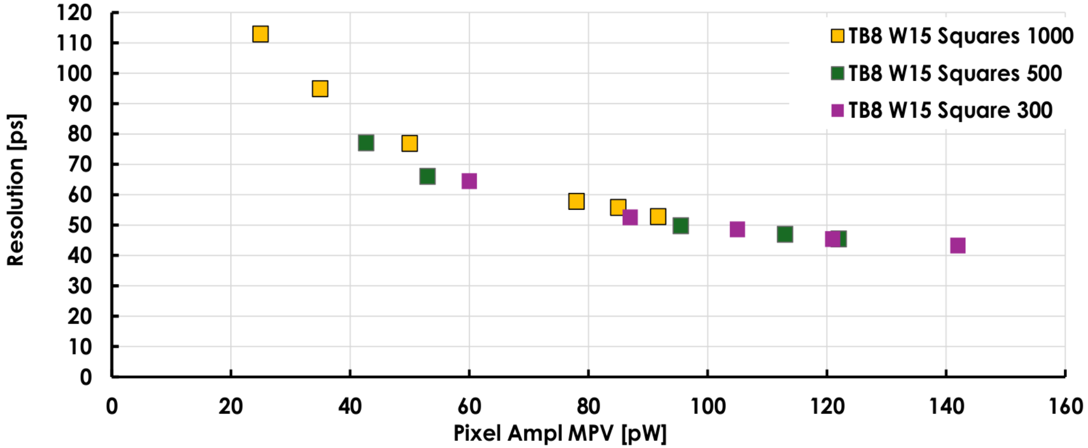




Spatial Resolution



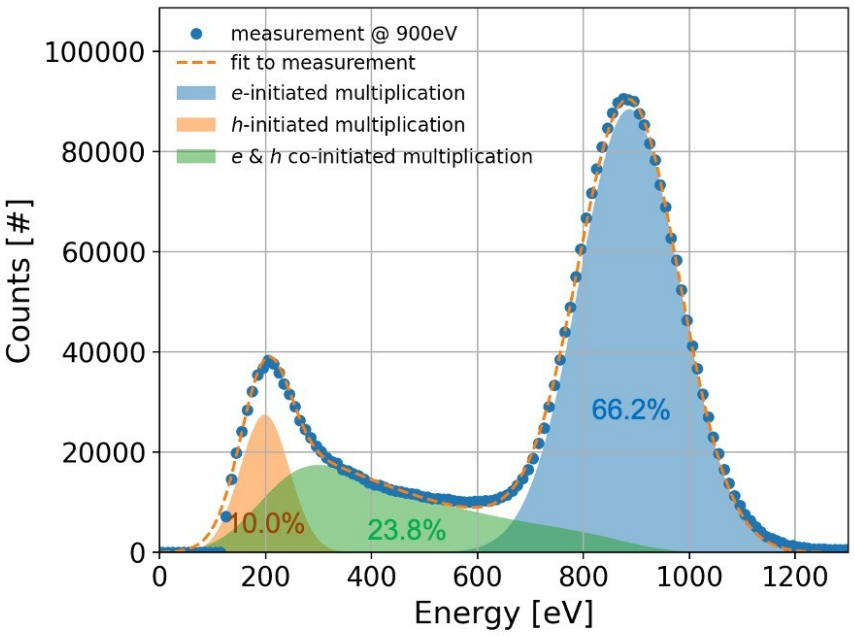
Temporal Resolution

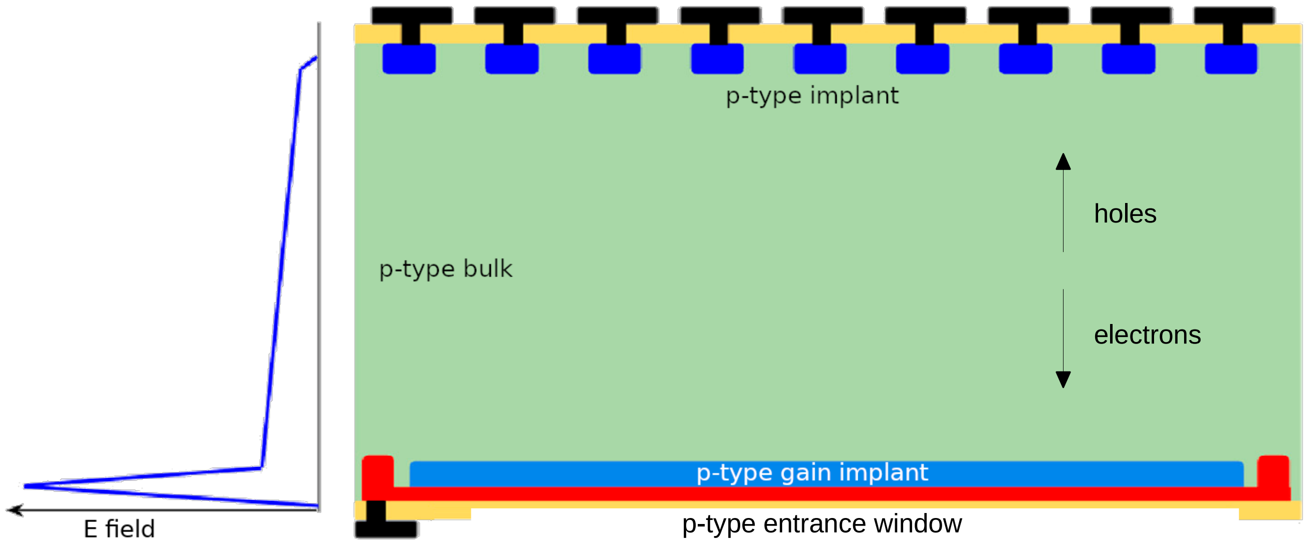


New LGAD technologies: inverted LGAD (i-LGAD)

Continuous gain layer at **backside** and **split p^{++}** electrodes:

- 100% fill factor by construction!
- gain layer at backside → soft x-rays (few μm penetration)
- signals with opposite polarity (positive)
  - p^{++} on p technology collects holes
- complicated production for backside processing → thicker sensors = worse timing





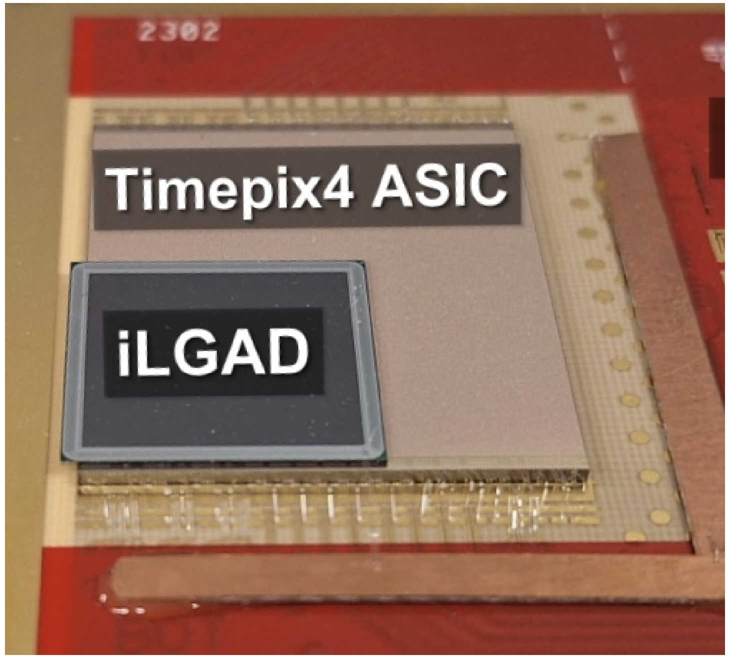
[10.3389/fphy.2024.1359179]

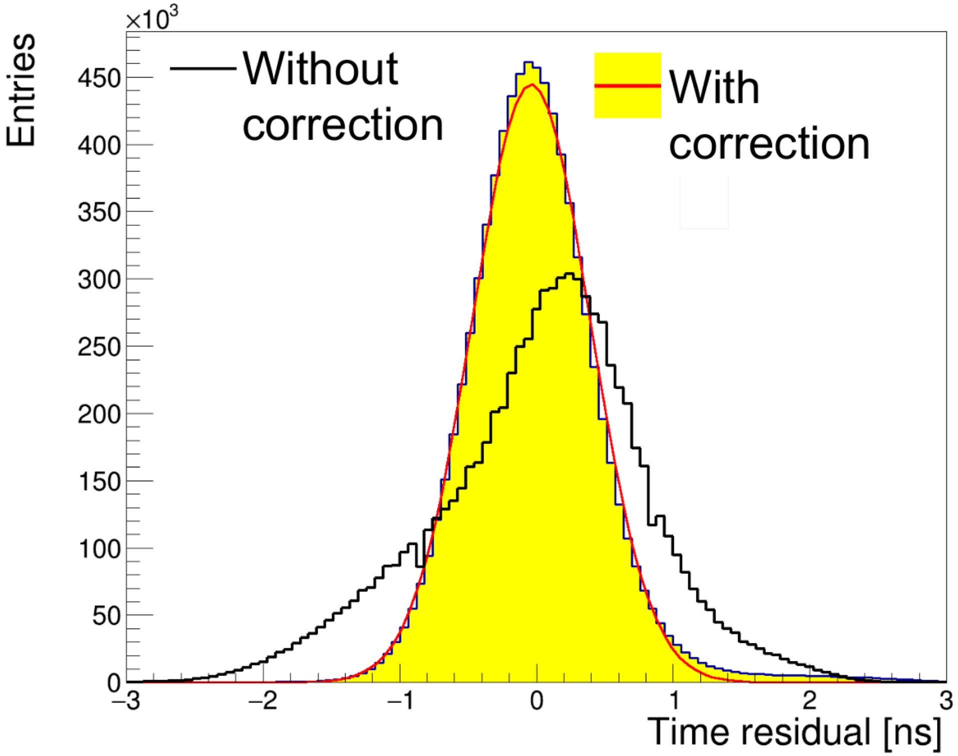
New LGAD technologies: inverted LGAD (i-LGAD)

Recent results:

- thickness of **250 µm** with pitches of 55 µm (Micron Semiconductors)
  - paired to Timepix4 readout board and tested with 180 GeV/c hadron beam
- approach aimed at achieving high spatial resolution **~4.3 µm**
- **σ_t ~358 ps** (with time-walk corrections)

[arXiv:2509.09308]





New LGAD technologies: nLGAD

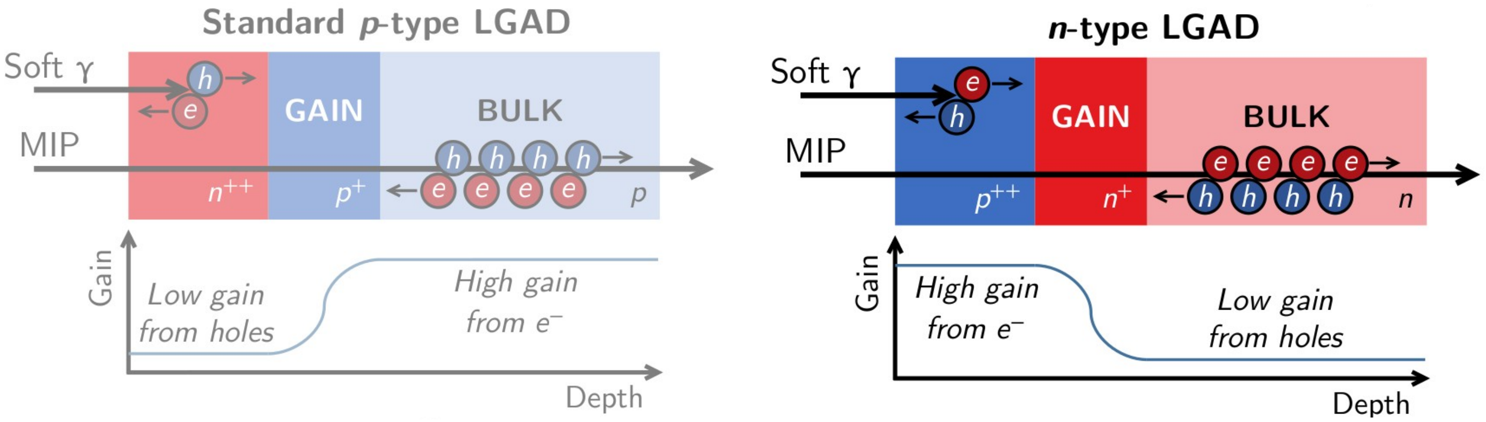
DRD3

New technology for **soft x-ray** detection (< 1 keV):

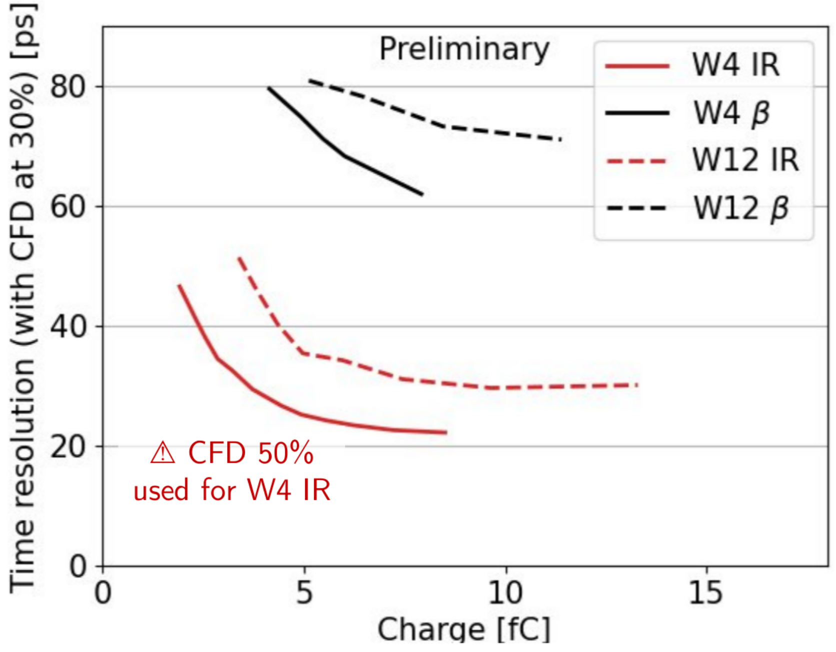
- gain depends on *species triggering avalanche* and is **higher for e$^-$**
- *inverted doping* with respect to standard LGADs (also for i-LGADs)

Recent results:

- thickness of **55 µm** with 1.3 mm pitch (FBK)
  - readout with 4 GHz oscilloscope
- time resolution with β particles of **62 ps**



[L. Massaccesi, TREDI21]



LPNHE PARIS

New LGAD technologies: deep-junction LGAD

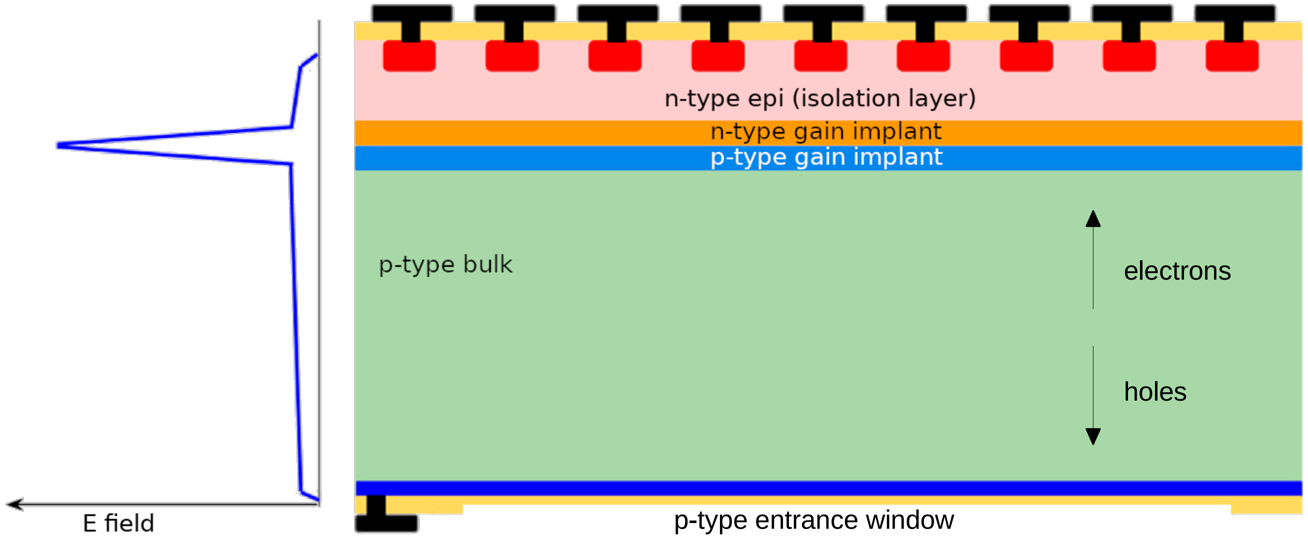
Very new technology, only recently fabricated:

- larger window for photo-detection
- p-n junction buried **5 µm** into bulk → 100% fill factor, but non standard process
    1) implantation of gain layers on different wafers, then w-w bonding and thinning
    2) p-type substrate with gain implants close to surface plus epitaxial growth of n-type layer

- small pixels segmentation by creation of n^+ *contacts* separated by p-stop rings

<u>Recent results:</u>

- not tested yet!



[10.3389/fphy.2024.1359179]

Conclusions

That's **a LOT** of LGAD designs.

- you made it to the end of this presentation (*excellent*)
- you probably won't remember everything...
- ...so you can look at this table!

LGAD design	**thickness** [μm]	σ_t [ps]	σ_{hit} [μm]	**link**
standard	50	25	-	arXiv:2512.01855
trench-isolated	45	30	-	M. Fernandez, TI-LGAD Meeting
AC-LGAD	20	20	21	10.48550/arXiv.2407.09928
DC-LGAD	55	40	10	10.1016/j.nima.2025.170796
I-LGAD	250	358	4.3	arXiv:2509.09308
N-LGAD	55	62	-	L. Massaccesi, TREDI21
DJ-LGAD	-	-	-	F. Capocasa, TREDI21

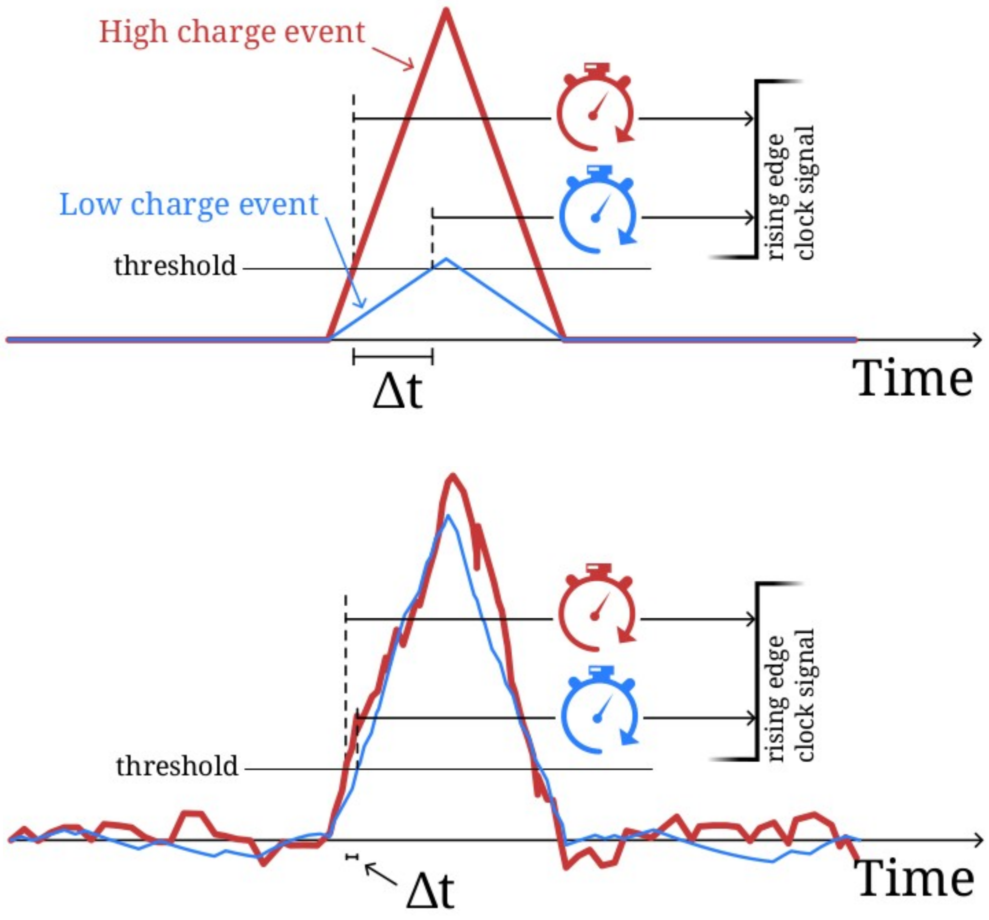
Thank you for your attention!

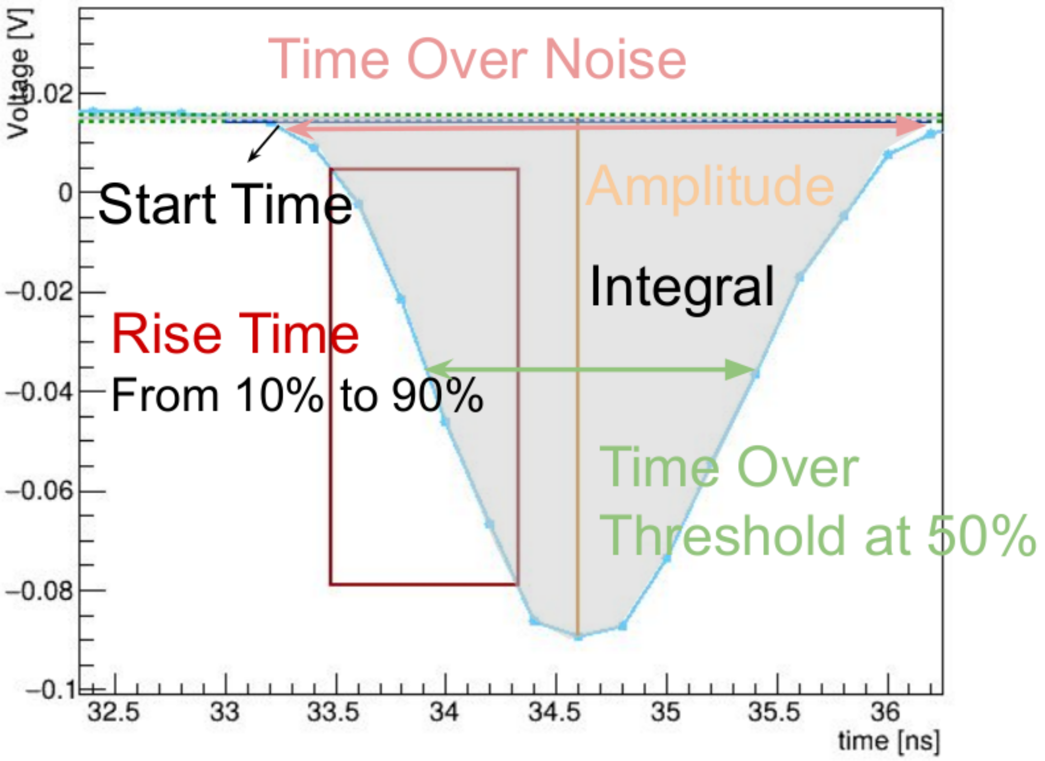
Backup

kCFD: constant fraction discrimination

Technique used to map big and large signals to a common reference shape:

- reduce impact of Landau noise





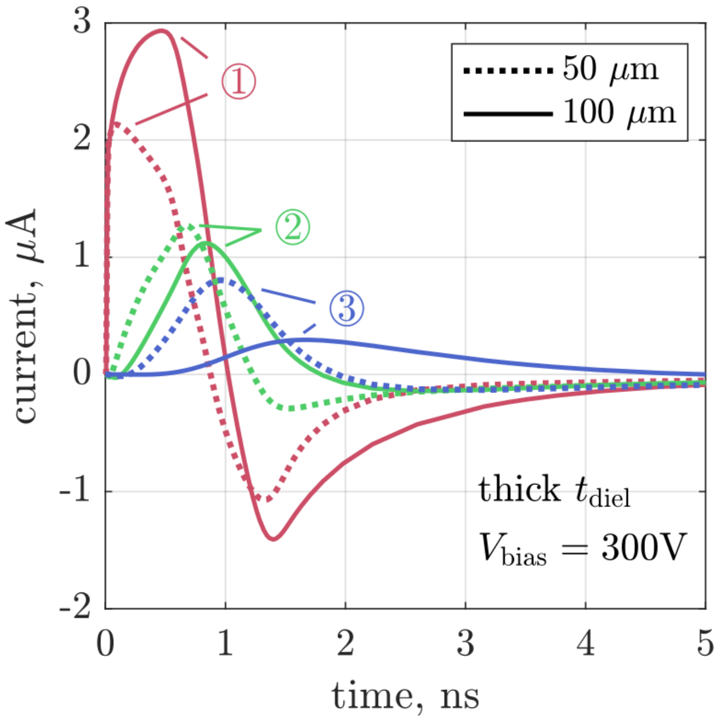
New LGAD technologies: AC-LGAD (RSD)

The **signal**:

- propagation of O(100 μm) before collection → signal spreading to a minimum of *four* electrodes
- baseline fluctuations (pile-up)
- bipolar signal → not compatible with charge-integrating electronics (photon science)

Signal **shape**:

- *positive* lobe: current lateral spread
  - lossy transmission line (n^+ layer/bulk/AC-pads)
- *negative* lobe: AC-pad *RC* discharge
  - *R* → read-out input resistance, the n+ sheet resistance
  - *C* → capacitance towards sensor backside and metal pad
  - large RC = larger signal (good) and discharge time (bad)

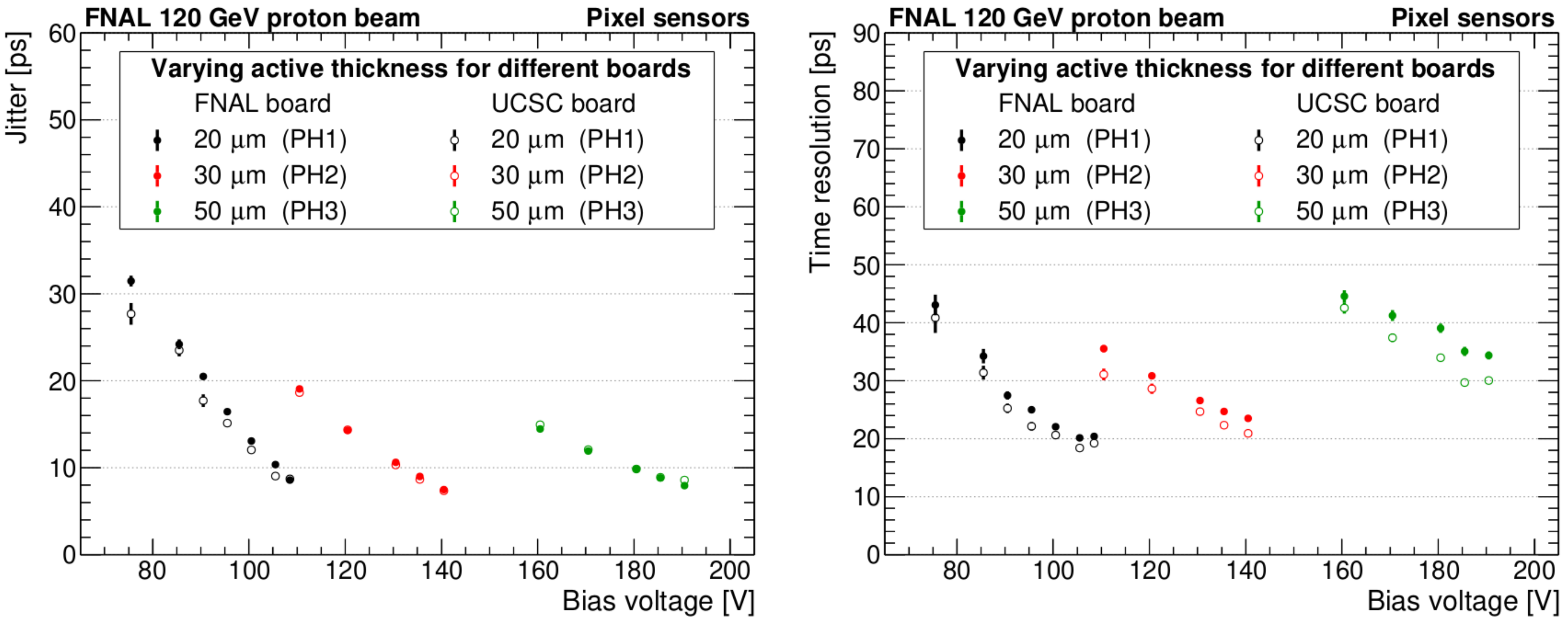


[10.1016/j.nima.2020.163479]

New LGAD technologies: AC-LGAD (RSD)

Recent results:

- pitch 500 µm, thinner active volumes (e.g. **20 µm**), square electrodes (HPK) and varying resistivity
- readout with FNAL/UCSC boards and tested at FNAL with 120 GeV proton beam
  - spatial resolution of **21 µm** and **σ_t ~20 ps**

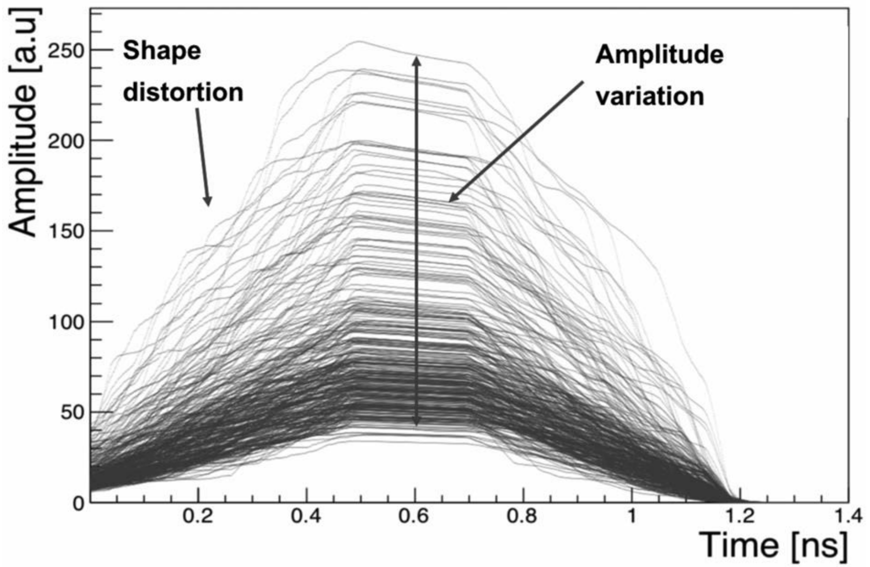


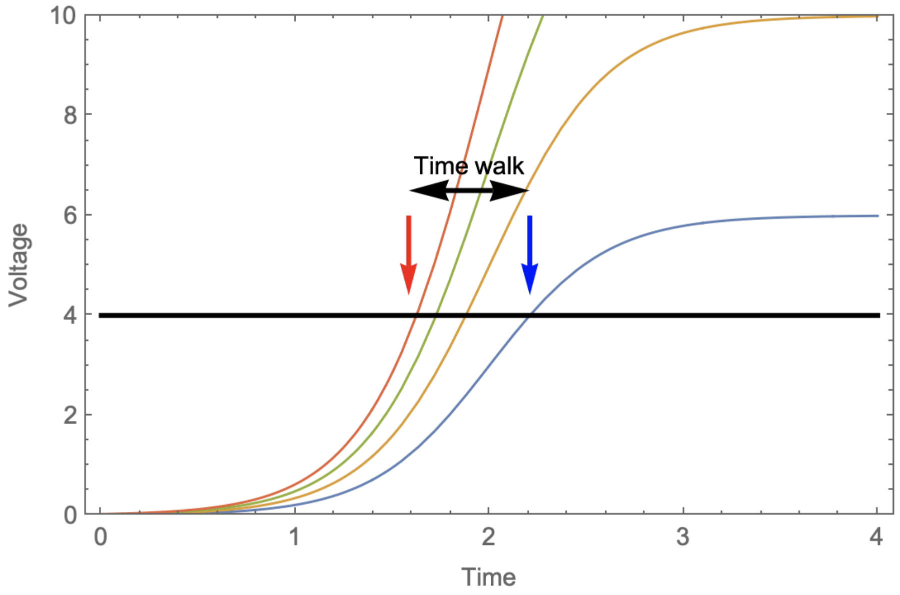
[10.48550/arXiv.2407.09928]

Another problem: noise sources

Most important factors contributing to temporal resolution σ_t:

- $\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{Landau}^2 + \sigma_{time\text{-}walk}^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2$
  - σ_{Landau} and $\sigma_{time\text{-}walk}$: non-uniform energy deposition by impinging particles
  - σ_{jitter}: electronic noise
  - $\sigma_{distortion}$: non-saturated drift velocity (non-uniform weighting field) → negligible
  - σ_{TDC}: finite size of TDC bins





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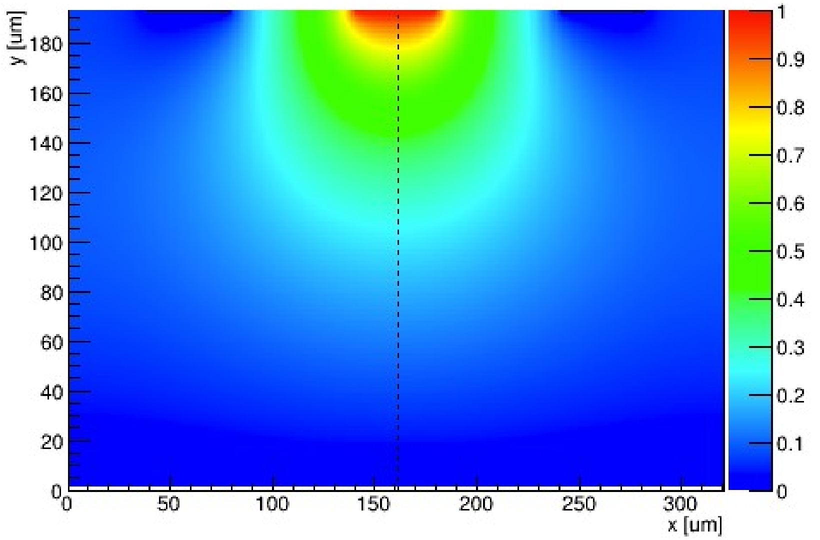
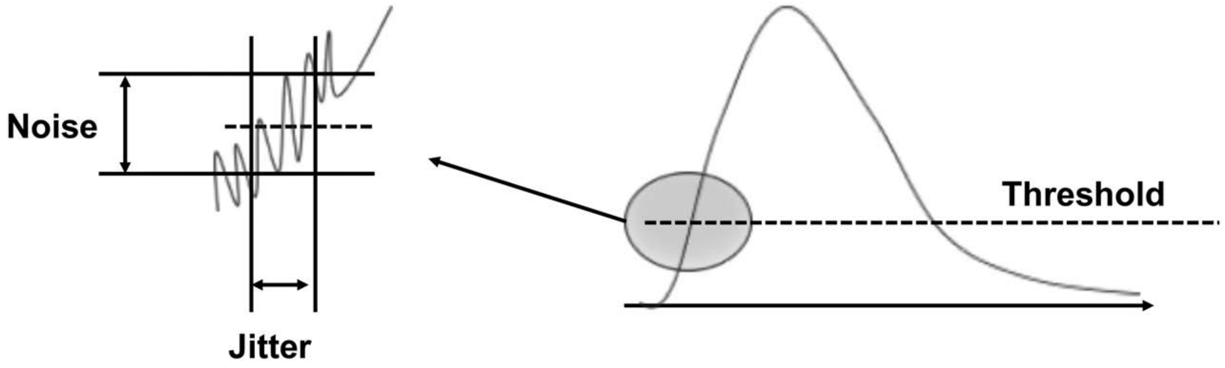




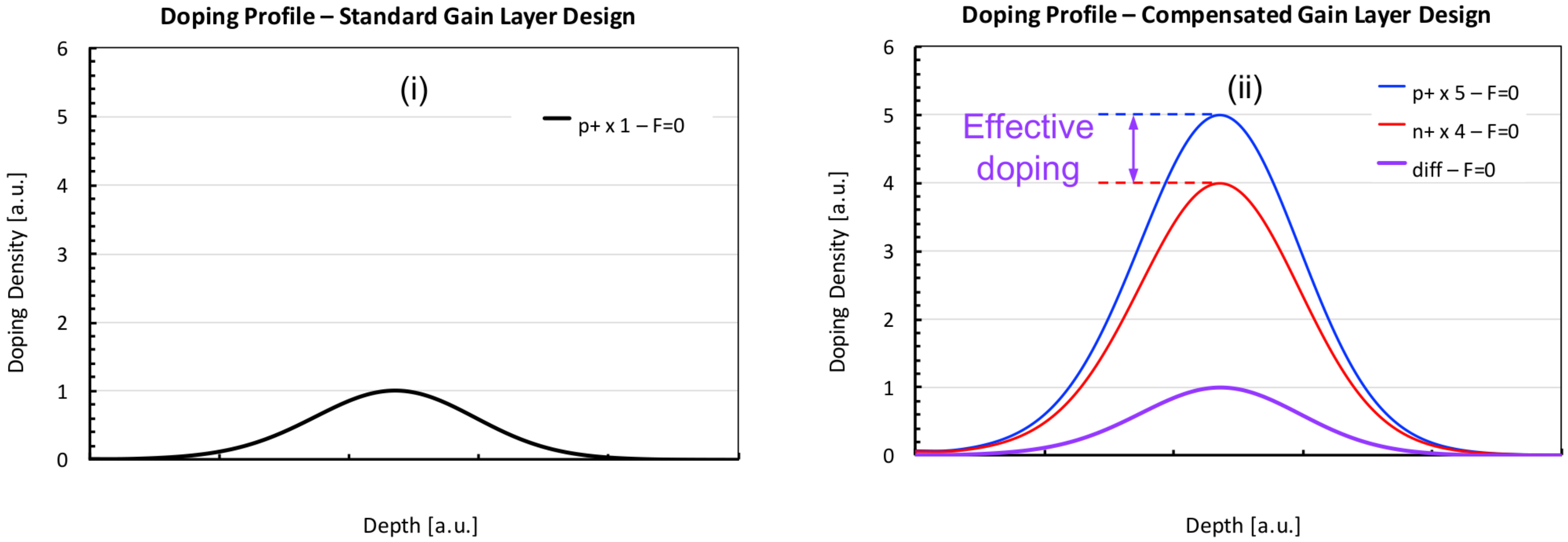
Yet another problem: radiation hardness

Irradiation causes three main defects:

- decreased charge collection efficiency, increased leakage current and change of doping profiles

The p^+ gain implant is doped with acceptors → deactivated by boron deactivation:

- no gain at a fluence of circa $10^{16}\ n_{eq}\ cm^{-2}$ circa
- defect engineering: acceptors (boron, indium, gallium) co-implanted with carbon
- compensation of p^+ and n^+ dopants



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