Timing sensors in 3D technology

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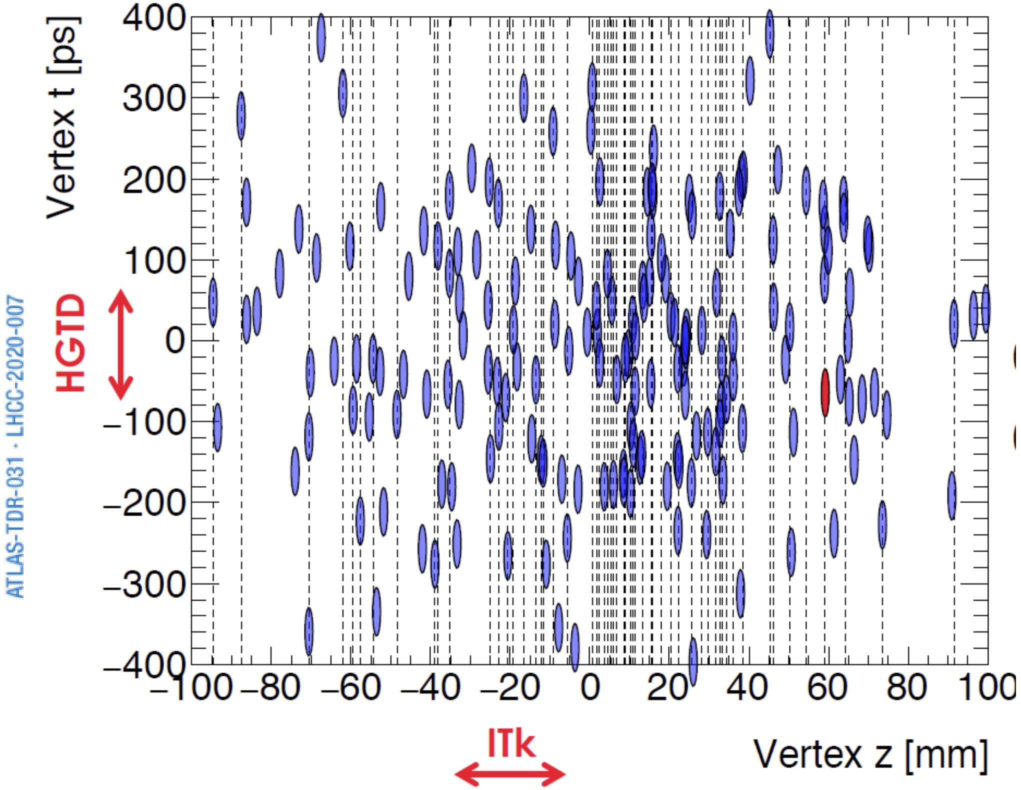
Outline

- Motivation
- Basics of Timing measurements
- Quick view of the LGADs – the choice for the HL-LHC
- 3D detectors for timing applications
  - 3D with conventional cylindrical/column electrodes
  - 3D with trench electrodes
- Conclusions

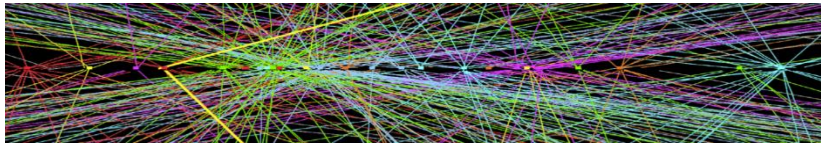
Motivation – Physics

HL-LHC upgrade Phase II (2027->)

- number of pileup collisions will increase to 140-200
- huge task to assign reconstructed particles to individual collisions and to extract interesting collisions
- Is there a way to separate vertices also not only in space but **also in time**



on average 1.6-2.35 vertices per mm



At LHC the vertices are distributed (Gaussian) with: σ_z=5 cm & σ_t=180 ps

Tracking detectors (pixel+strip) provide separation of primary vertices in forward region typically ~ 1 mm.

It is a task of the ATLAS-HGTD/CMS-MTD to provide timing resolution of around of ~35 ps for minimum ionizing particles (mip).

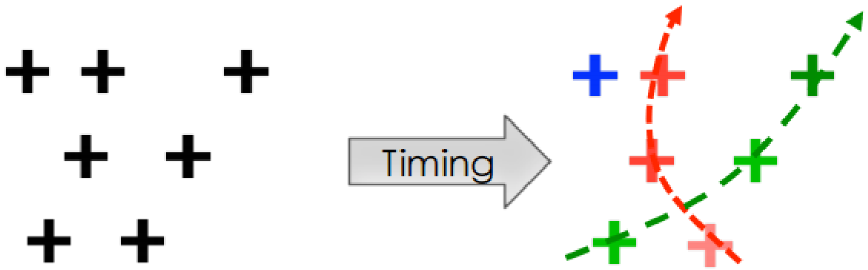
- ➢ 20-30% more effective luminosity
- ➢ improved reconstruction (b-tagging, isolation of photons leptons, rejection of pile-up jets …)

A goal for the future

Timing at each point along the track:

➔ Massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments

➔ Use only "time compatible points"



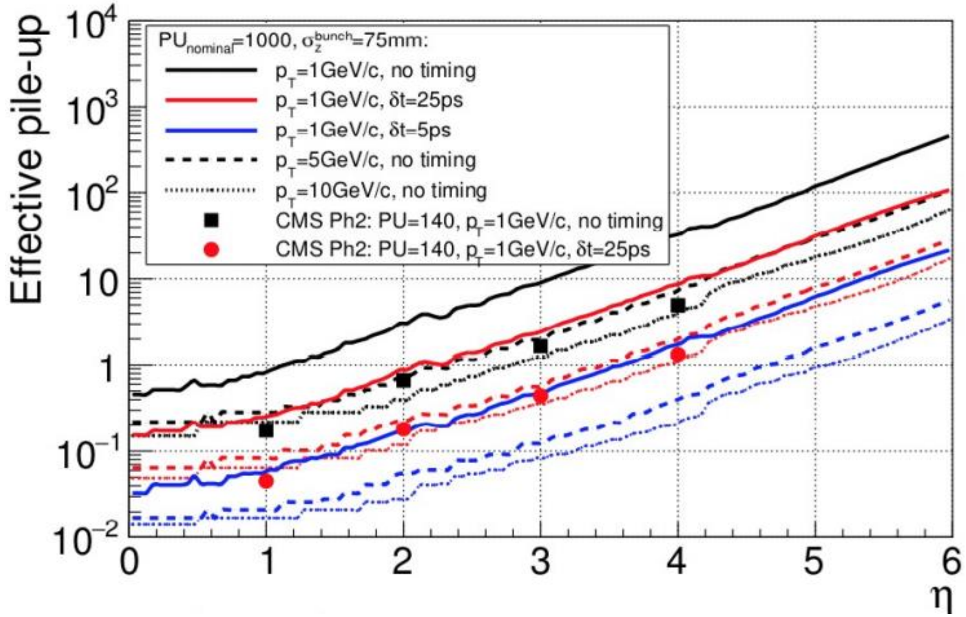
Timing of tracks - preferably on pixel level:

- no need for dedicated timing layers as e.g. at HL-LHC
- improved algorithms for track finding

FCC-hh – very challenging requirements by today's standards almost impossible for r<30 cm:

- radiation hardness up to 10^{18} cm^{-2}, 300 MGy
- timing of tracks ~10 ps
- cell sizes of 25x50 μm^2
- surface inner tracker 15 m^2

Effective pile up – number of vertices compatible with reconstructed tracks
Eff. pile-up = 1: Indication for unambiguous primary vertex identification

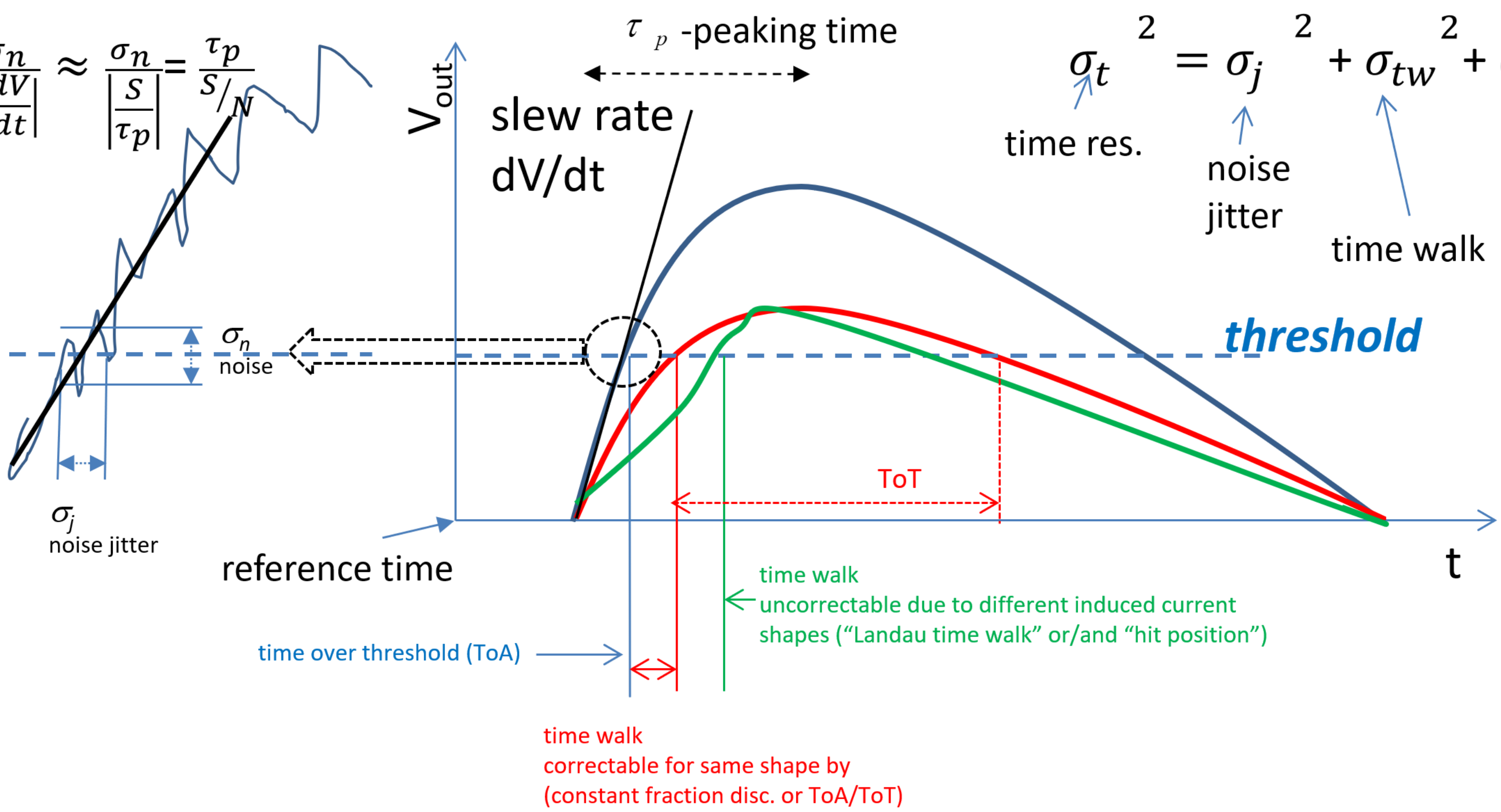


Timing measurements

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$

$$\sigma_t^2 = \sigma_j^2 + \sigma_{tw}^2 + \sigma_{TDC}^2$$

time res. noise jitter time walk TDC



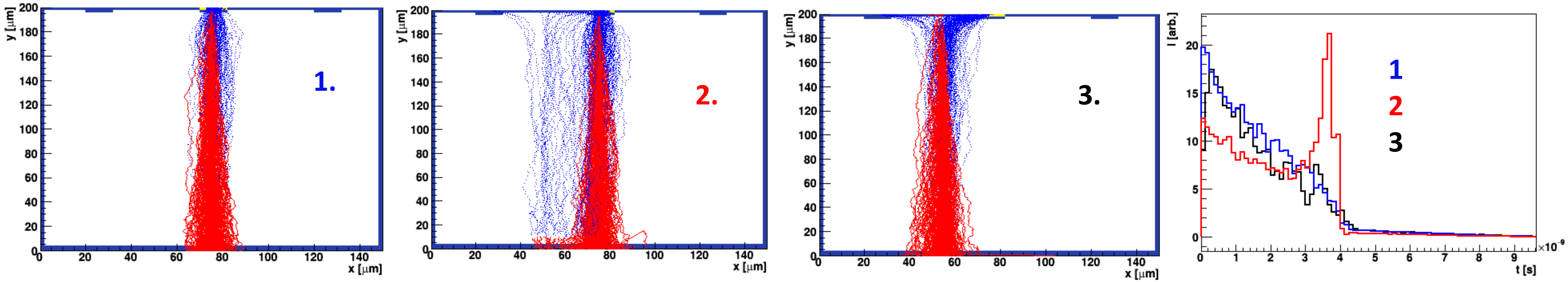
Time resolution

- σ_j -jitter – fast rise time and high signal/noise (related to ASIC)
- σ_{TDC} – vey good granularity a challenge for ASIC

σ_{tw}-time walk component includes (correlated – should not be simply summed in squares):

- weighting field/electric field contribution -> depends on hit position in segmented devices (sometimes called distortion component)
- Landau fluctuations in shape of the signal -> depends on hit position (segmented devices) and gain layer in LGADs
- Landau fluctuations in amount of deposited charge –> correctable with ToA-ToT or CFD

Example: 3 tracks hitting the same pixel/strips and depositing the same amount of charge, but with different induced currents!
(non-correctable time walk – will determine the limits of time resolution)



Landau fluctuations

Distortion due to E_w

Conventional planar silicon detectors

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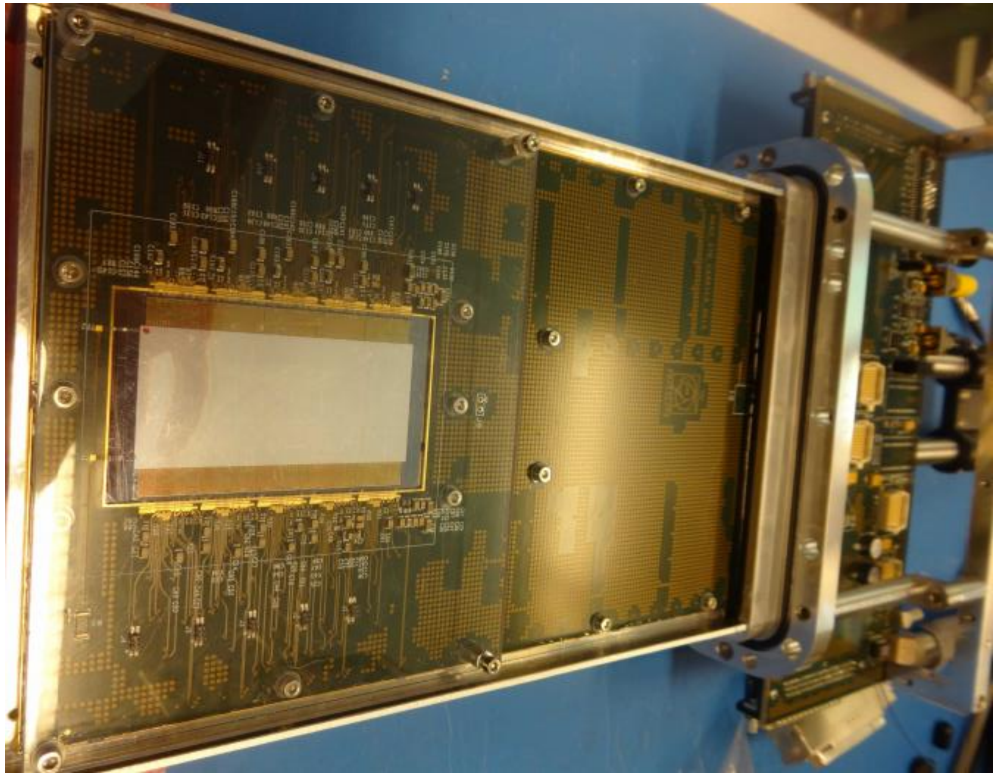
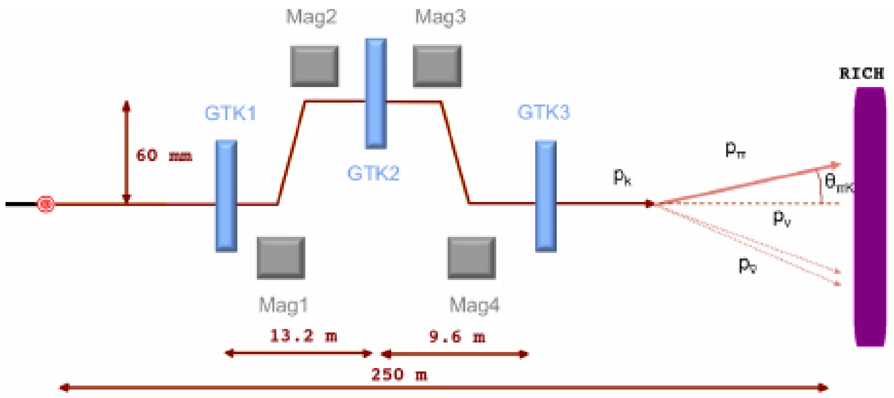
- NA62 Gigatracker combines good position resolution with timing good resolution (required for K, π separation).
  - Planar pixel sensors **p-on-n** of **200 μm (300x300 μm^2 , 0.5% X_o per station)**
  - The time resolution is around 150 ps, peaking time of 5 ns
  - Radiation tolerance to Φ_{eq}=2x10^{14} cm^{-2}
  - The key is the TDCPix ASIC
  - Time resolution – well studied:
    - Jitter – 80 ps
    - Time walk (hit position) - 85 ps
    - Energy straggling/Landau – 100 ps

TOTAL TIME RESOLUTION ~ 150 ps

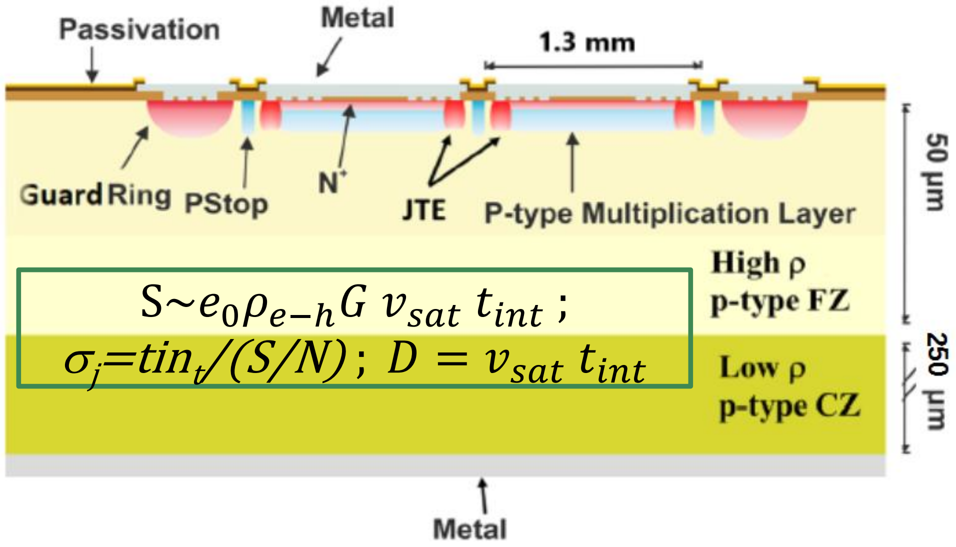


NA62, NIM A958 (2020) 162127



GigaTracker presents roughly the limit of achievable time resolution for conventional position sensitive planar detectors.

LGAD-s and their use at HL-LHC



$S \sim e_0 \rho_{e-h} G\, v_{sat}\, t_{int}$;

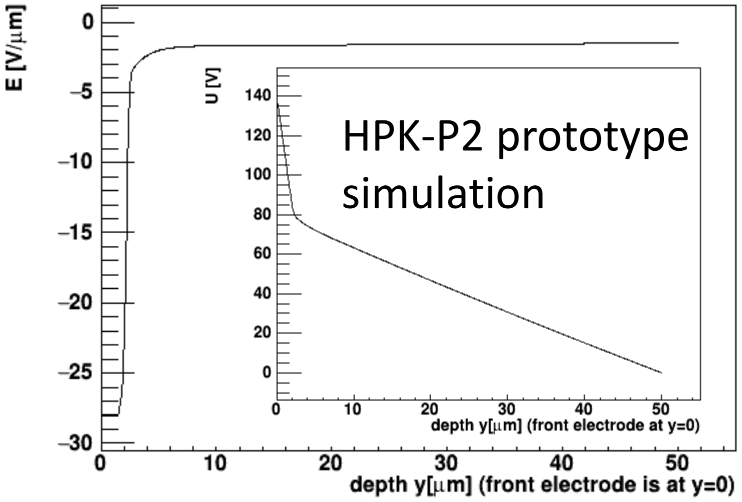
$\sigma_j = tin_t/(S/N)$; $D = v_{sat}\, t_{int}$

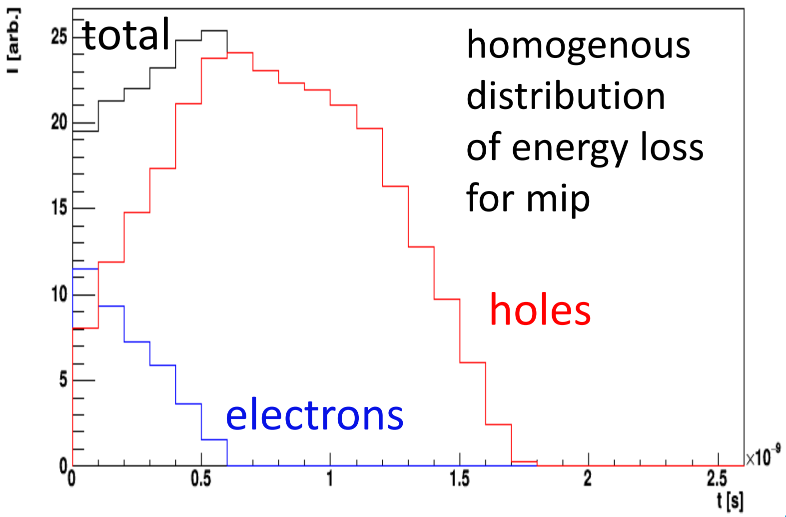
So ATLAS and CMS have used G~50 (excess noise prevents going higher), D=50 μm and t_{int}~1.2 ns:

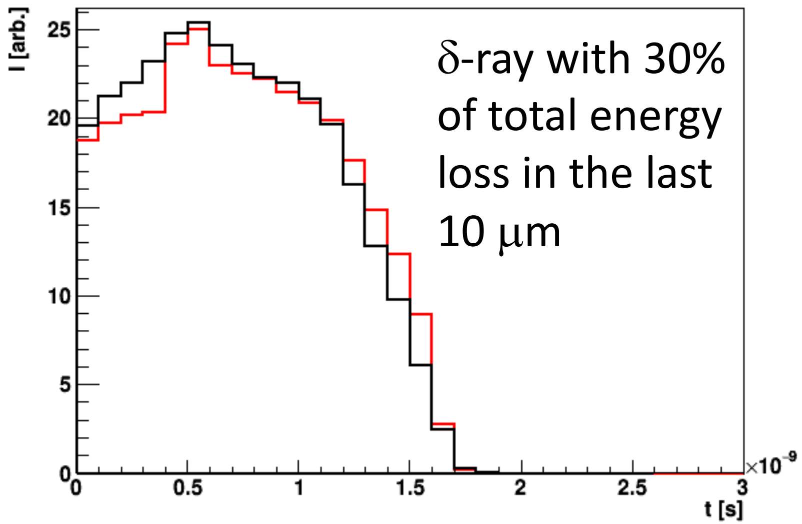
- σ_j=10 ps with discrete electronics G=30-60, S/N~60-120 -> 10 ps (agrees very well with measurements)
- Non-correctable time walk depends on Landau fluctuations only as the "distortion component" is negligible (1.3 mm >> 50 μm)
  - **σ_{tw}~25 ns for 50 μm**
  - **σ_{tw}~18 ns for 35 μm**

Sets the limit of resolution

Hartmut F-W Sadrozinski et al 2018 Rep. Prog. Phys. 81 026101







Timing measurements at HL-LHC

Both experiments use Low Gain Avalanche Sensor Technology and have very similar requirements:

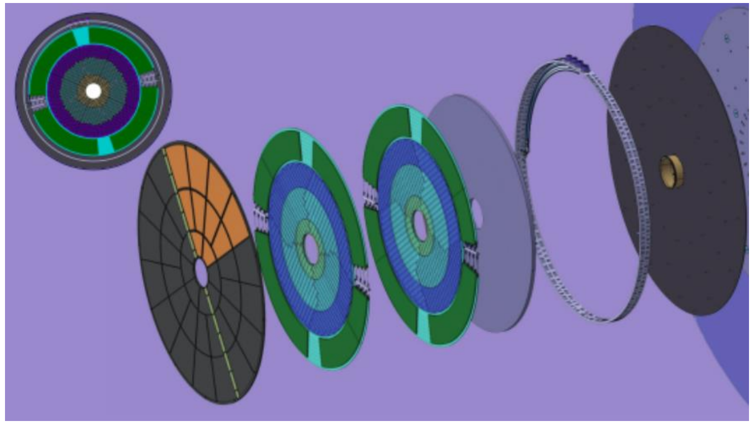
- sensor size 1.3x1.3 mm^2 (ATLAS 15x15, CMS 16x16 arrays)
- 50 μm thick active layer
- t_{int}=1.1ns , required charge MPV>4 fC (ATLAS), >6fC CMS
- σ_τ=50 ps /track (30-70 ps per layer) at the end of lifetime

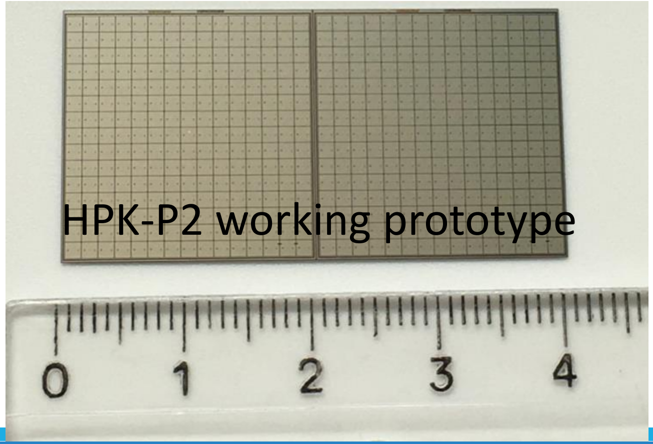
HGTD:

- η=2.4-4 coverage
- 2-2.7 points per track
- 8 m^2 of LGAD sensors (readout with ALTIROC)
- Radiation hardness: 2 MGy and Φ_{eq}=2.5e15 cm^{-2}
- Replacements of sensor (3x for the inner ring), 1x for the middle

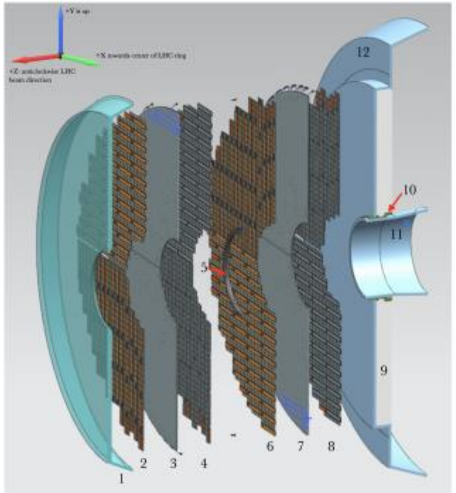
ETL:

- η=1.6-3 coverage
- 1-2 points/track (not full coverage)
- 14 m^2 of LGAD sensors (readout with ETLROC)
- Φ_{eq}=1.6x10^{15} cm^{-2} (no replacements)





HPK-P2 working prototype

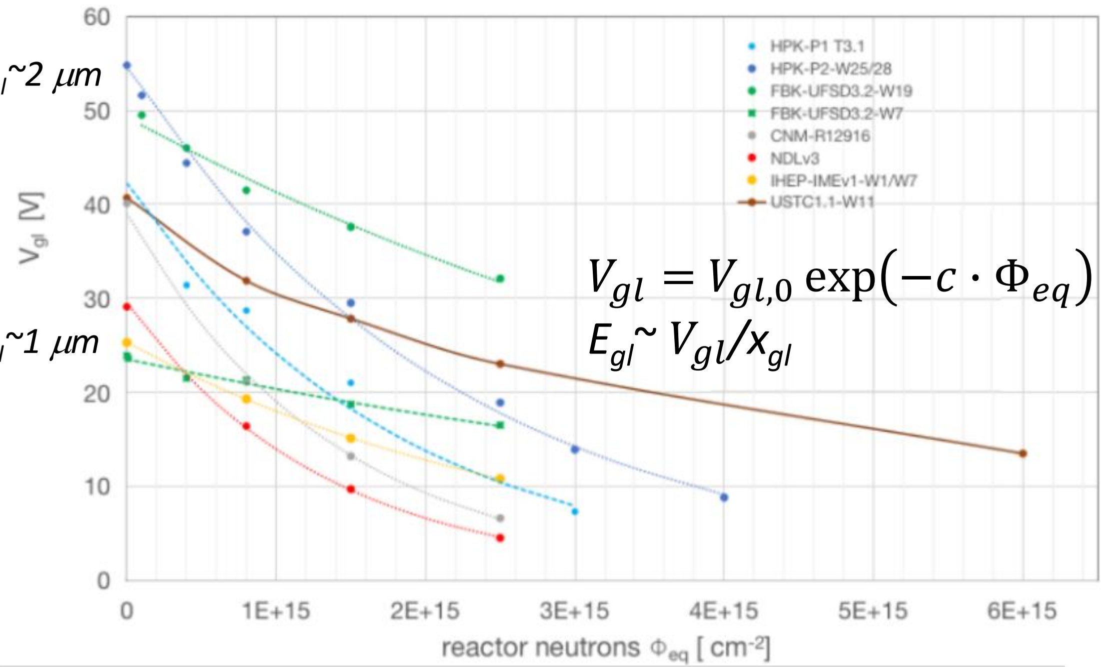


Radiation hardness (1^{st} problem of LGADs)

The main problem is radiation hardness (see M. Moll's presentation)

x_{gl}~2 μm

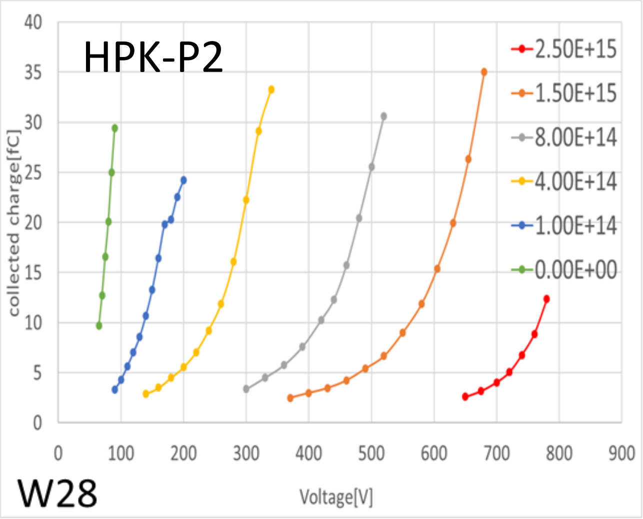
x_{gl}~1 μm

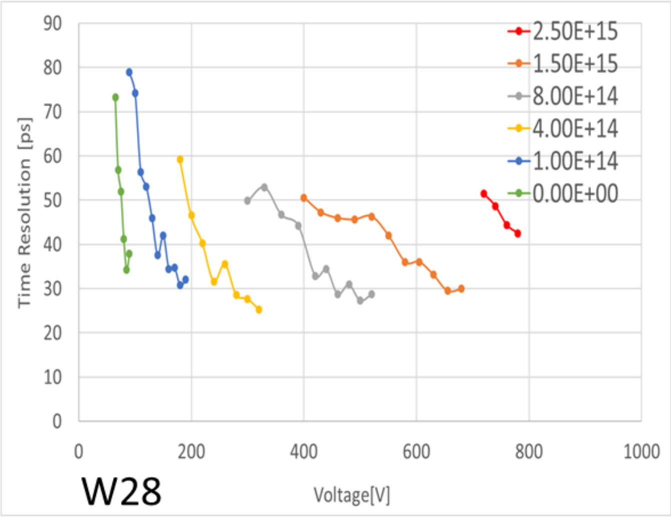


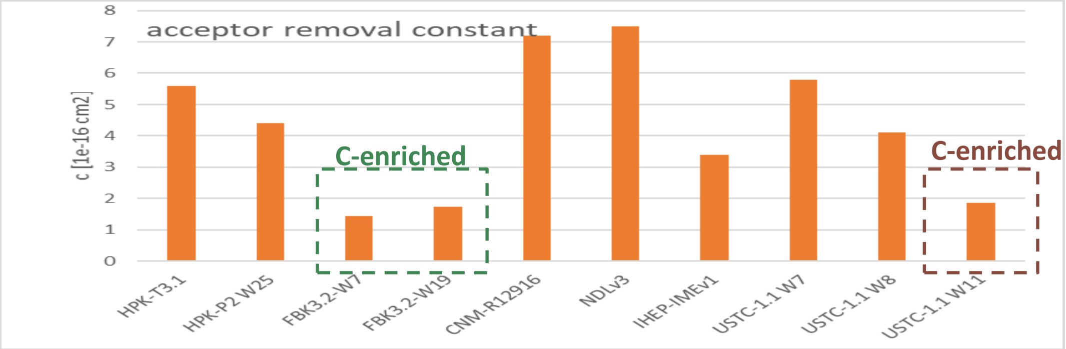
$$V_{gl} = V_{gl,0} \exp(-c \cdot \Phi_{eq})$$

E_{gl}~ V_{gl}/x_{gl}

Loss of gain layer doping has to be compensated by larger bias







Radiation reduces the gain layer doping and by that the gain

- In thin sensors the loss can be compensated by the bias
- Many attempts to design a more radiation hard gain layer design

The LGADs are limited to fluences $\Phi_{eq}<3\times10^{15}$ - even with C enrichment.

Fill – factor (2nd problem of LGADs)

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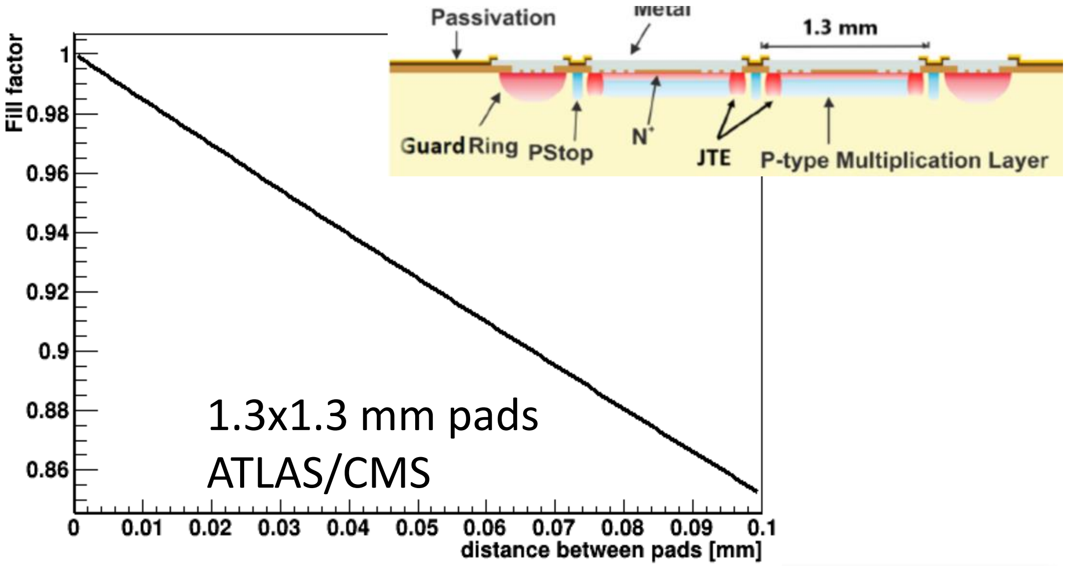
LGADs to be used at HL-LHC don't have a good fill factor:

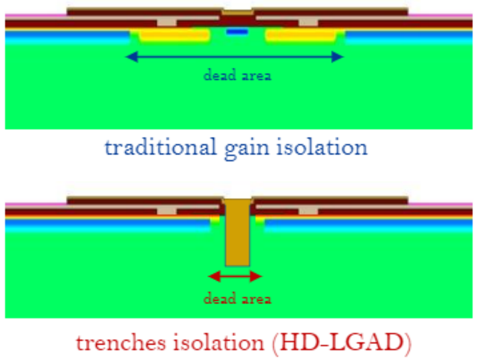
- Isolation between the pads (IP) requires space and this is the region without gain, where it is not possible to achieve desired CC and time resolution
- The reduction of IP is possible, but there is a danger of breakdown if pads get disconnected – HGTD/ETL > 40 μm



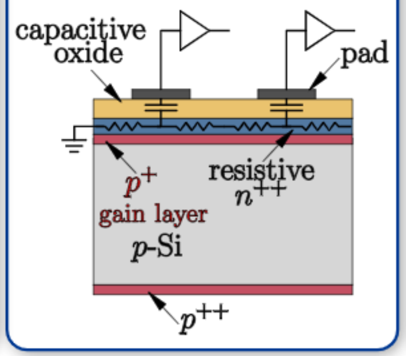
There are several ways of mitigating that but they all have limitations at:

- High particle rates (AC,DJ-LGAD)
- "Large" fluence (AC)
- Very small pixel sizes (TI-LGAD)
- DS processing (iLGAD)

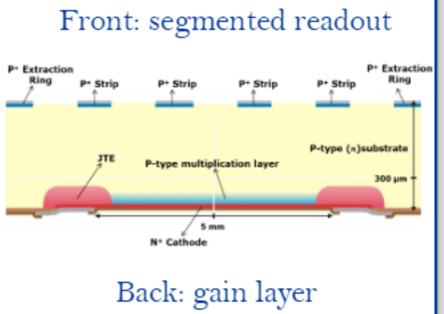
Trench Isolation LGAD



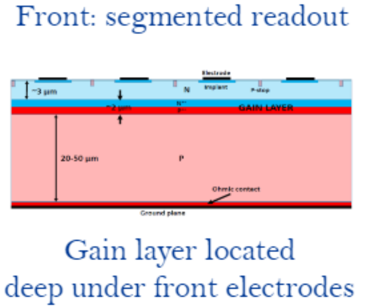
AC-LGAD



Invers LGAD



Deep Junction LGAD



see M.Moll's presentation

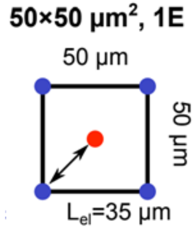
3D detectors for timing applications

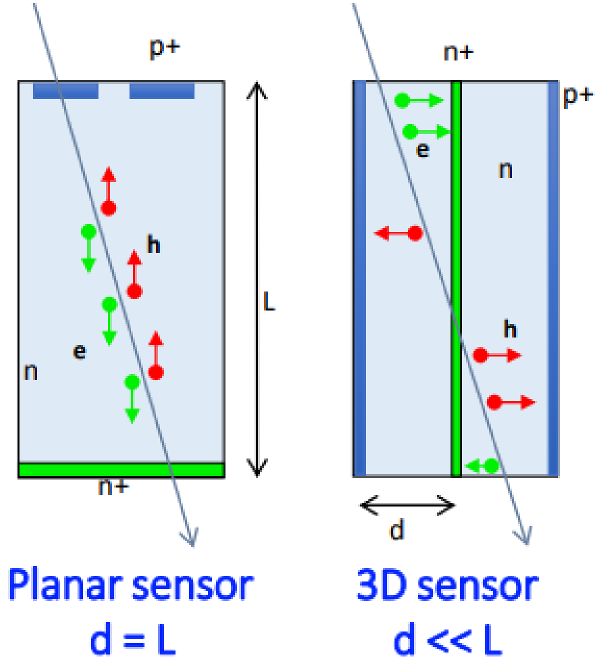
How about 3D (of all types) as timing detectors?

- They have fill factor ~100% (inclined tracks)
- The radiation tolerance of small cell size devices is large (in signal) and allows operation at higher bias voltages (next slide)

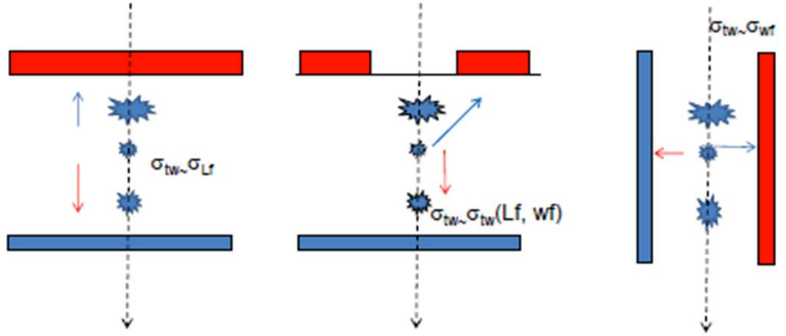
But/However:

- 3D can be fast – ☺ short drift distance, but ☹saddle regions in the field
- There is no multiplication ☹, but they can be thicker as Landau fluctuations don't matter much, so the signal can be partially compensated ☺
- The weighting field – hit position - will impact the signal ☹ (replacement of the Landau fluctuation problem with the impact position problem).
- for small size sensors and large thickness the capacitance will be much larger, hence noise and the jitter
- Lower operation voltages than for LGADs and possibly lower current ($I_{LGAD}=G \cdot I_{gen}$) result in smaller power dissipation

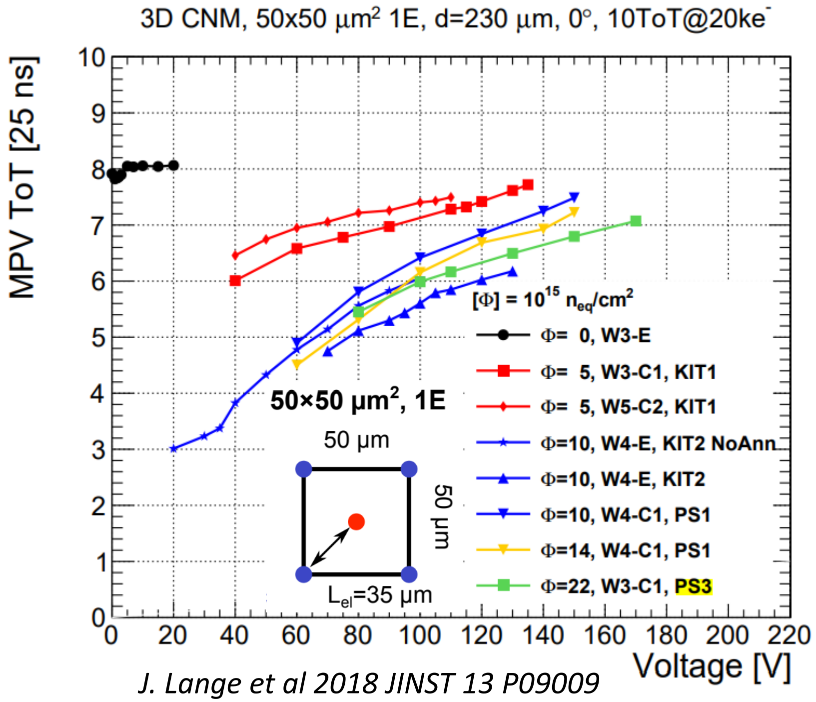




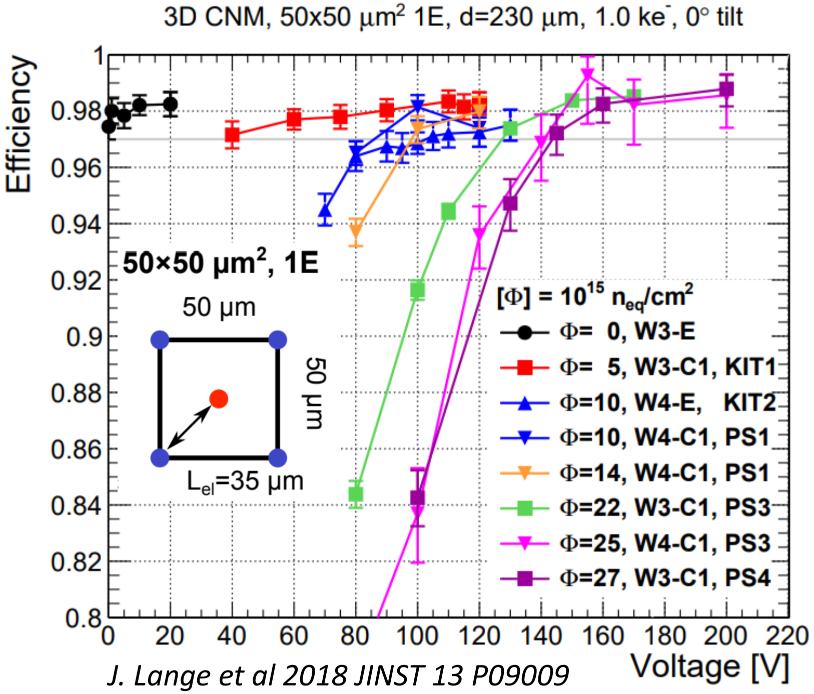
S. Parker, 1997



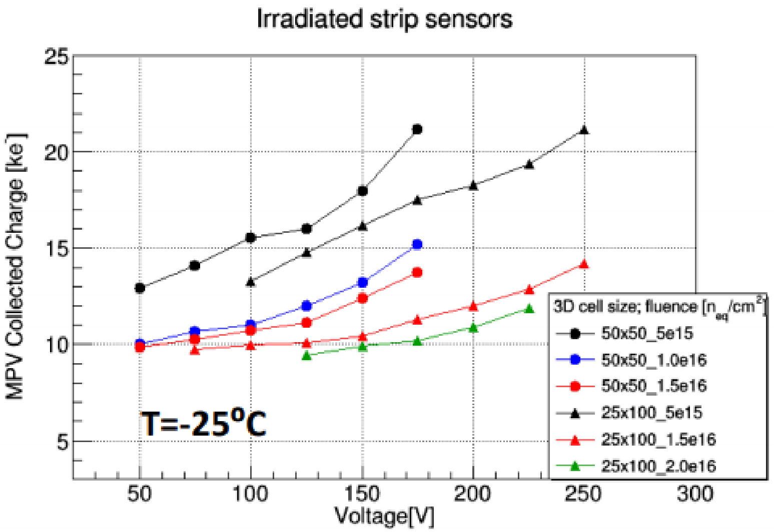
Radiation hardness of 3D design



J. Lange et al 2018 JINST 13 P09009



J. Lange et al 2018 JINST 13 P09009

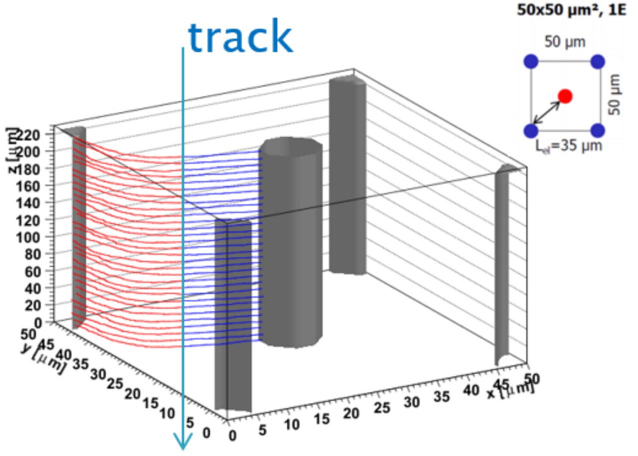


Good charge collection after large fluences (detection efficiency equal to the non-irradiated one after Φ_{eq}~3x10^{16} cm^{-2} :

- short drift distance and depletion depth
- ability to bias to >200 V
- Saturation of effective trapping times, effective doping concentration and possibly leakage generations current allow them to be operated to $\Phi_{eq}>10^{17}$ cm^{-2}

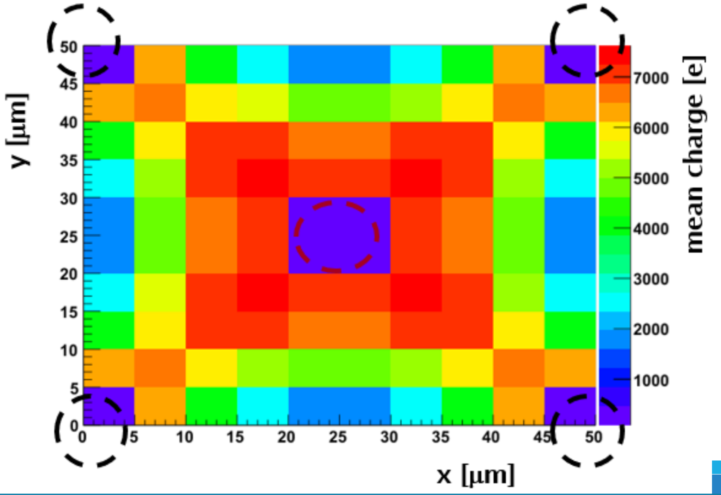
Operation of 3D sensors at >1e17 cm^{-2}

Simulation with known damage parameters



mean charge

$1\cdot10^{17}$ cm^{-2},200 V, 0^{o}, ,−20^{o}C

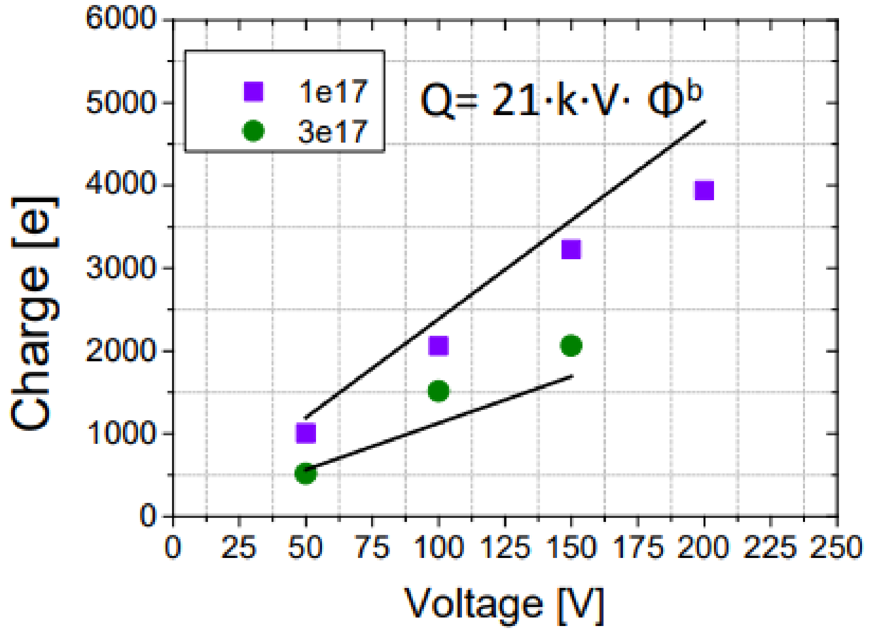


G. Kramberger, 11th HSTD, 2017

Measurements of 3D - Strip sensors irradiated to FCC-hh fluences using TCT/Alibava setups

M. Manna et al., NIMA 979 (2020) 164458.

M. Manna et al., 35th RD50 workshop,2019



- Simulation and measurements are roughly compatible
- It seems that 3D sensors can offer enough signal for detection even at extreme fluences

What are the limits of 3D as a timing detector?

Timing measurements – devices used

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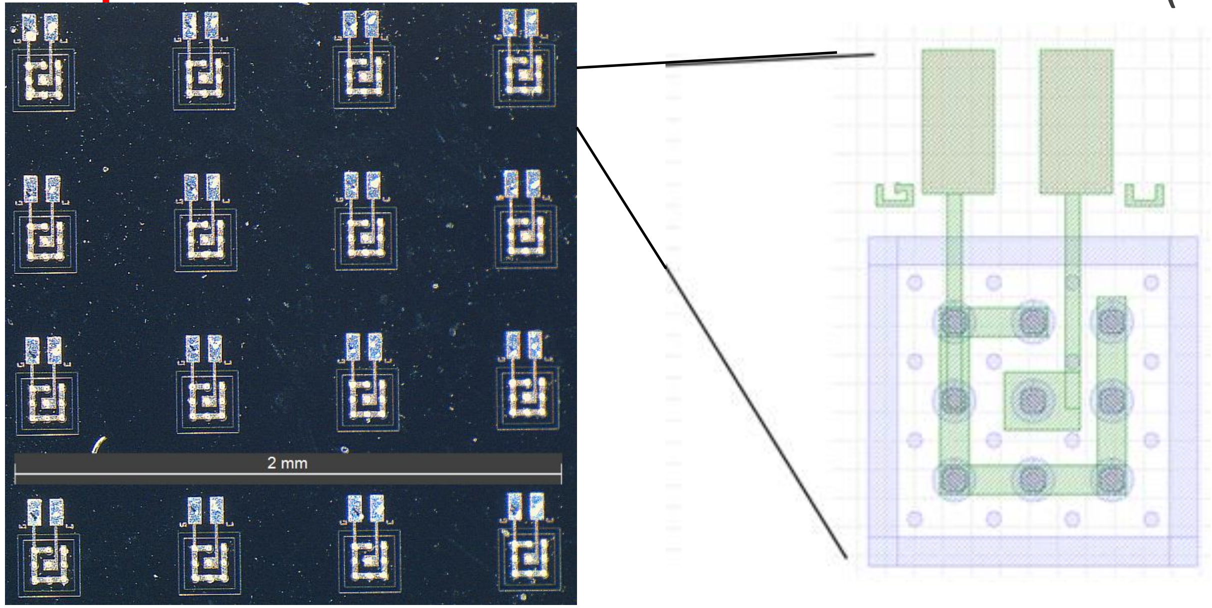
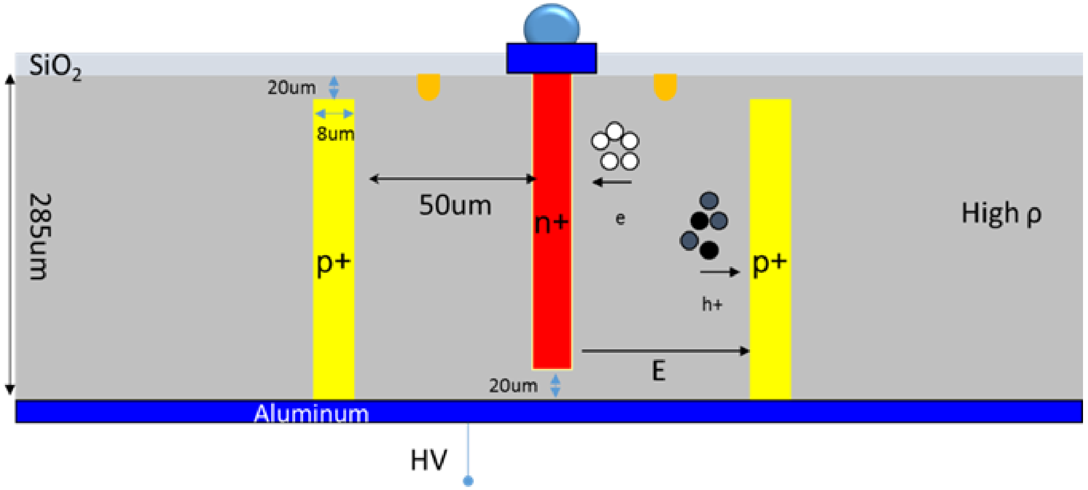
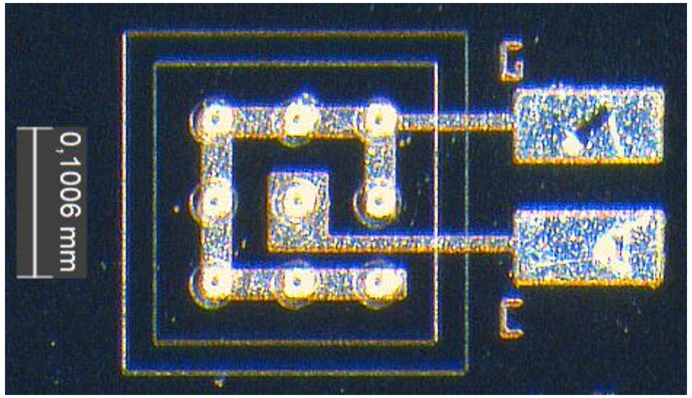
The problem is lack of a suitable readout for studies (50x50 μm^2 << 1.3x1.3 mm^2)





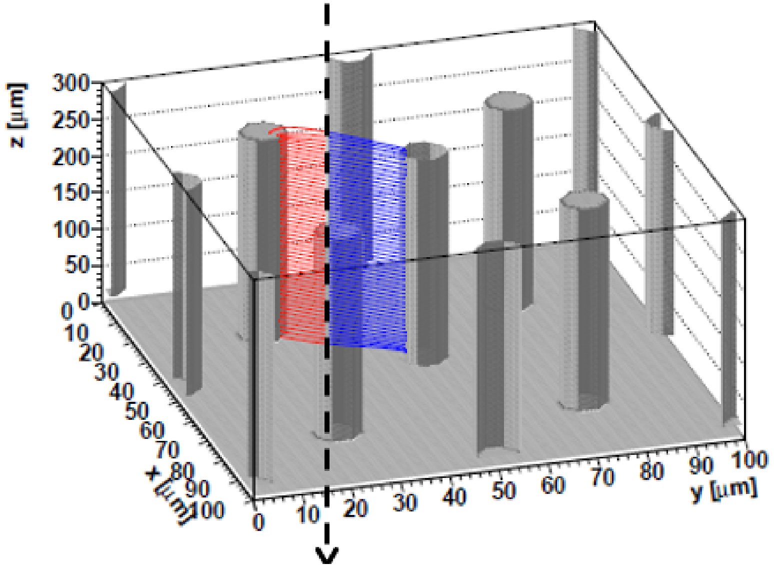
CNM produced the devices almost ideal for such study – a 3x3 matrix with investigated cell in the middle and neighbouring cells connected together

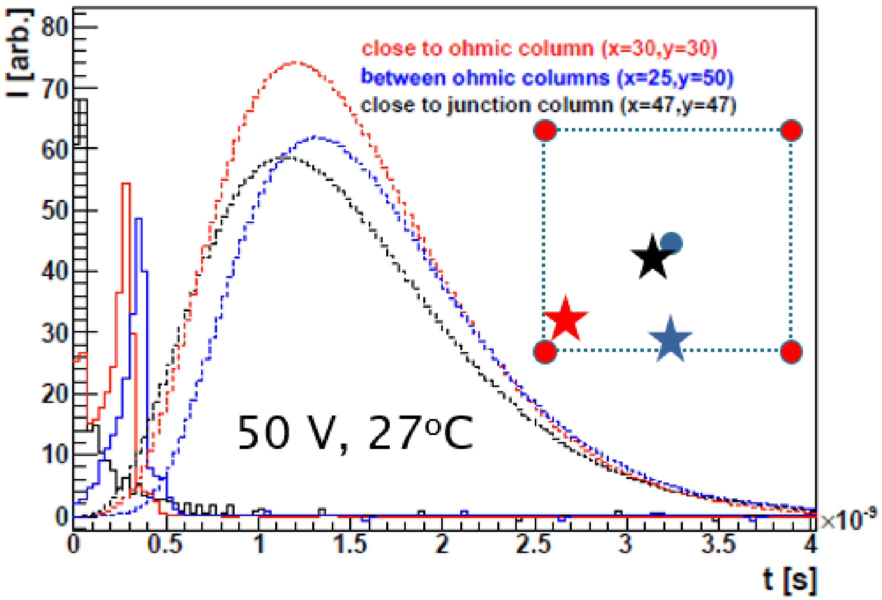
- cell size 50x50 μm^2 – RD53 chip design
- p-type bulk (N_{eff}=-1.4·10^{12} cm^{-3}), n-type collection electrode
- 1E, holes $2R$=8-10 μm and 235 μm and 285 μm thick
- max operational voltage before irradiation ~50-150 V

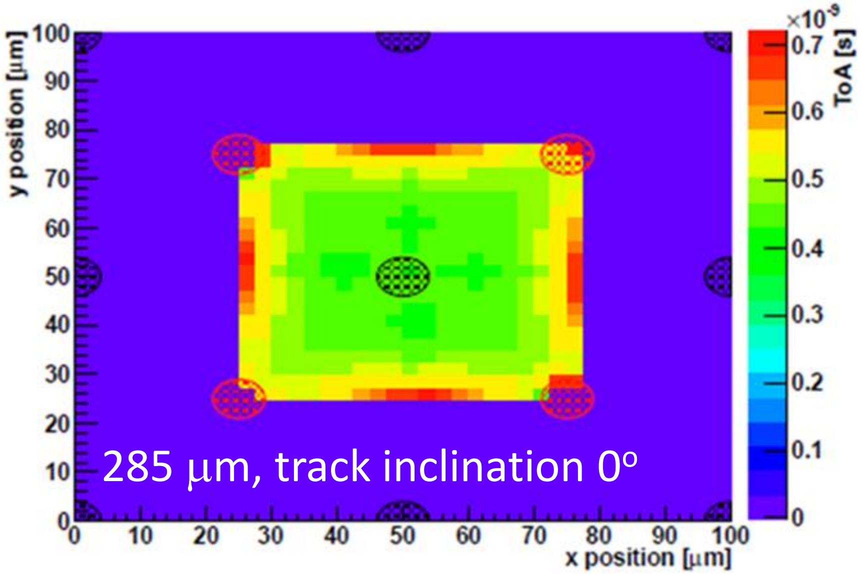


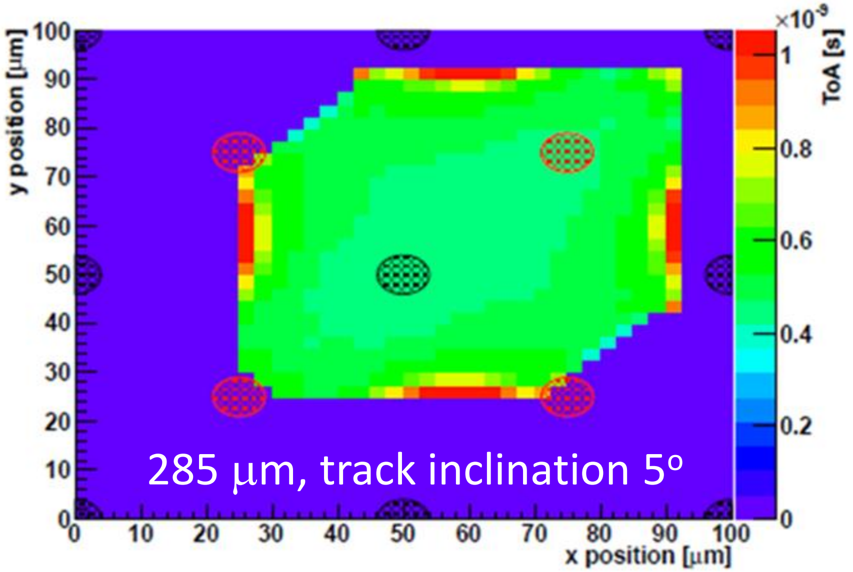
Simulation of the device (single cell)

kdetsim.org









G. Kramberger et al., NIMA 934 (2019) p. 26.

Simulated at room temperature and 50 V

- Signals are faster than in LGADs – approximately the same drift distance, but no gain
- Low field regions (saddle potential) between ohmic columns worsen the timing resolution (spread in ToA

Simulation (cell size, V_{bias}, T)

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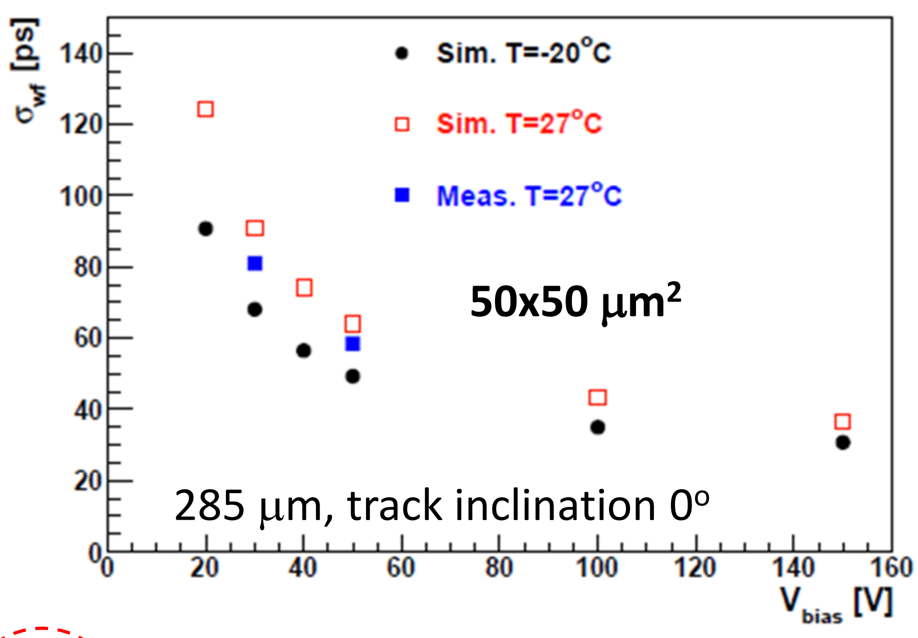
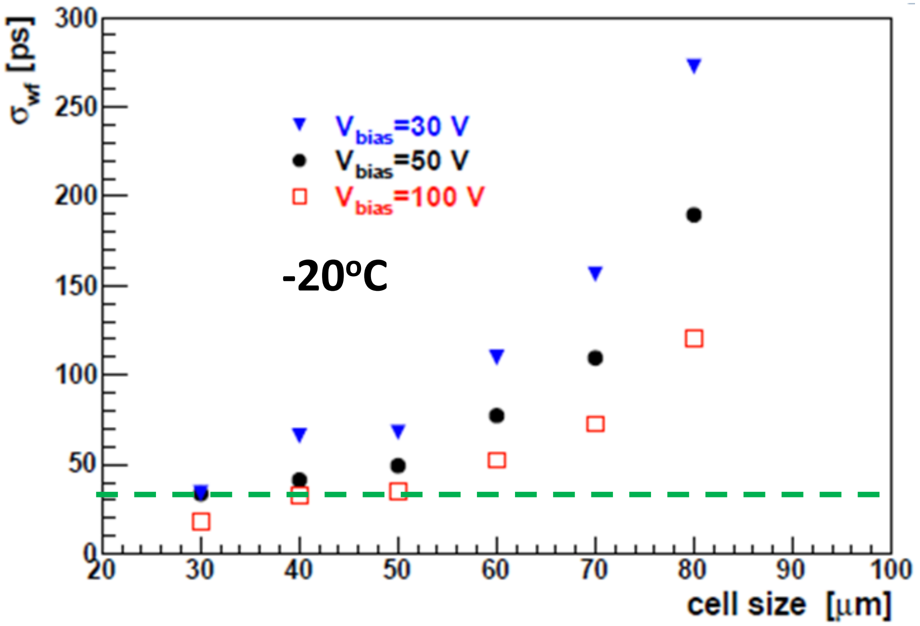
G. Kramberger et al., NIMA 934 (2019) p. 26.





$\sigma_t^2 = \boldsymbol{\sigma_{wf}^2} + \sigma_j^2$ → E_w/distortion dominates time walk

$\cancel{\sigma_{lf}\text{=small negligible}}$

A good agreement of the first measurements with simulations!

For single square cell readout σ_{wf}

- for bias voltages of >50 V
- cell sizes <=50 μm
- low temperatures <-20°C

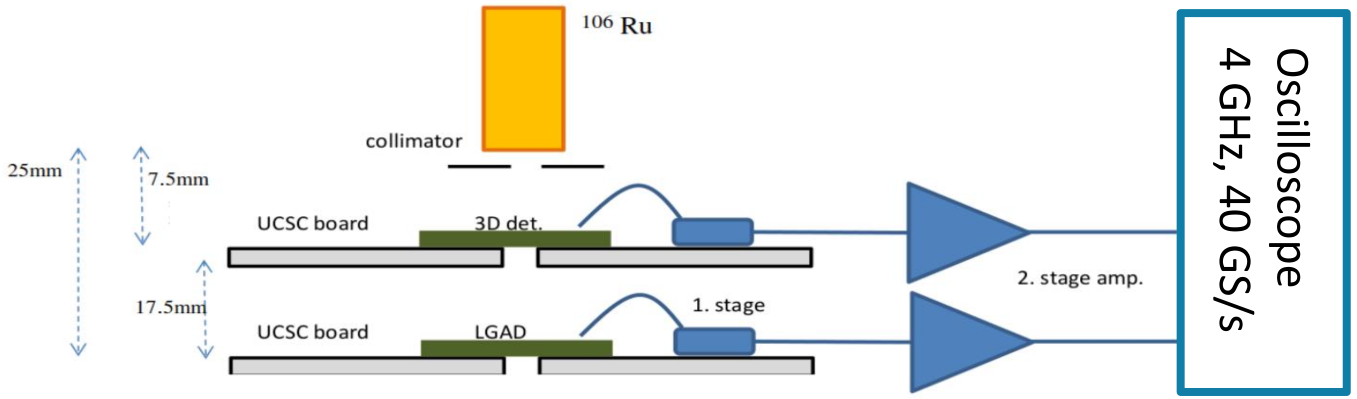
time walk of ~30 ps is achievable for 50x50 μm² cells

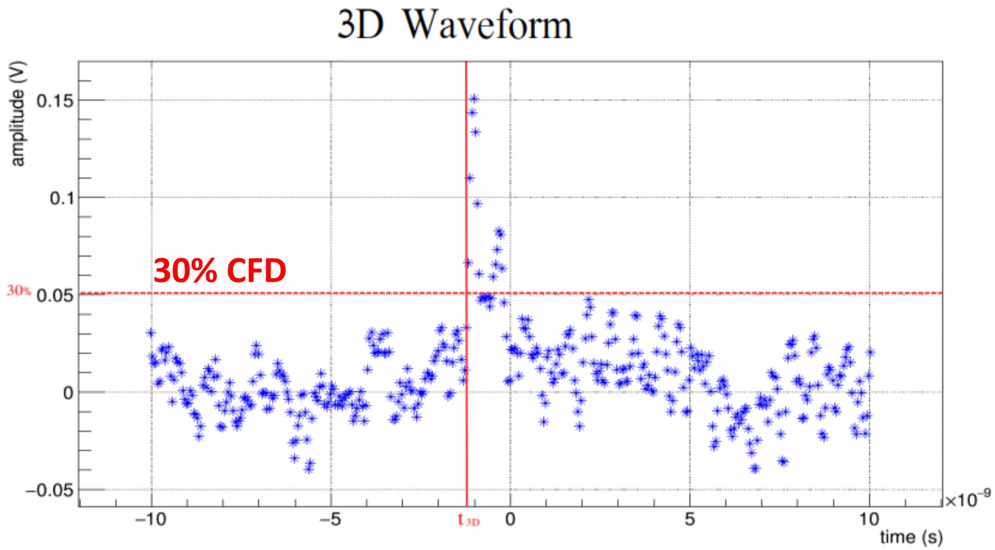
For multiple cell connected together and inclined tracks even better time resolution can be achieved

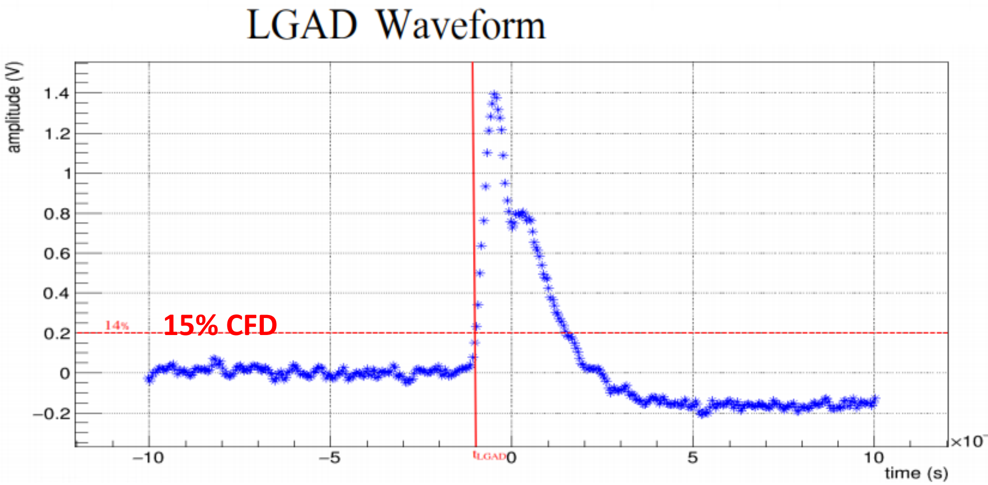
- around 20-25 ps for 50x50 μm² cell

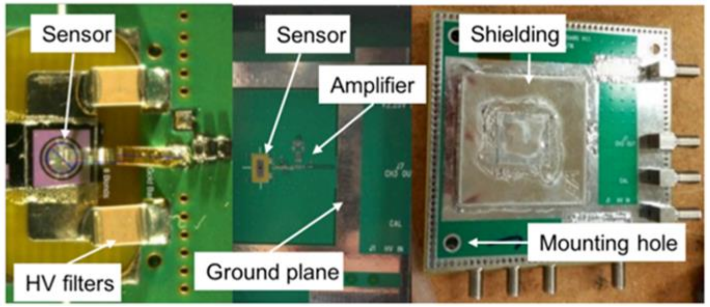
Single cell timing measurements

D. De Simone et al, 37th RD50 workshop,2020



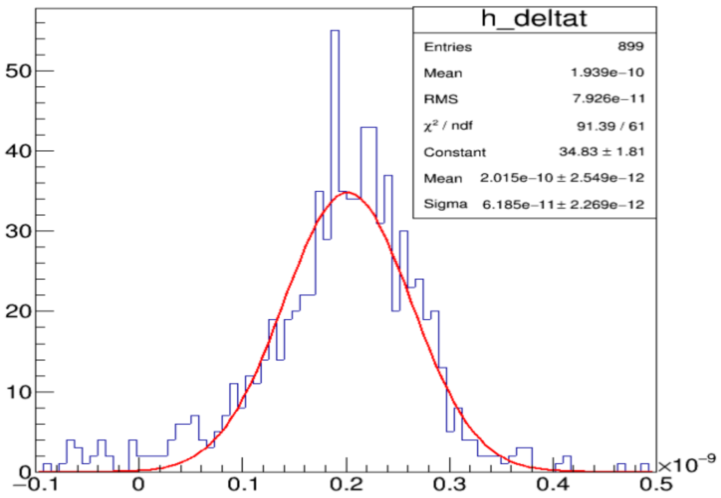






"UCSC timing boards" used – the same used in most LGAD studies for HL-LHC (470Ω TZ amplifiers, >3 GHz)

$\Delta t = t^*_{LGAD} - t^*_{3D}$

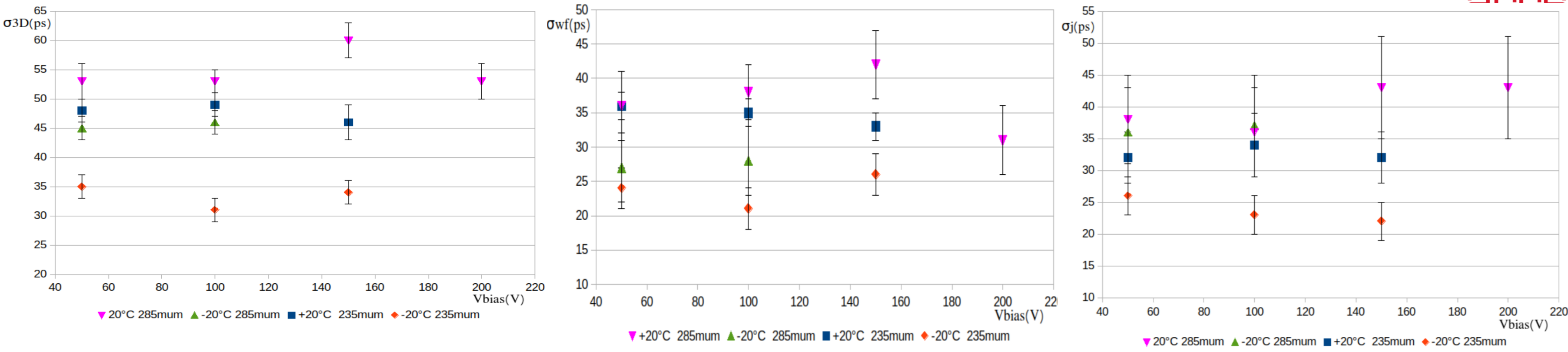


Fit on Δt to obtain: $\sigma_t = (\sigma^2_{LGAD} + \sigma^2_{3D})^{1/2}$

$\sigma^2_{wf} \approx \sigma^2_{3D} - \sigma^2_{j,3D}$

σ_t, σ_{wf} and σ_j

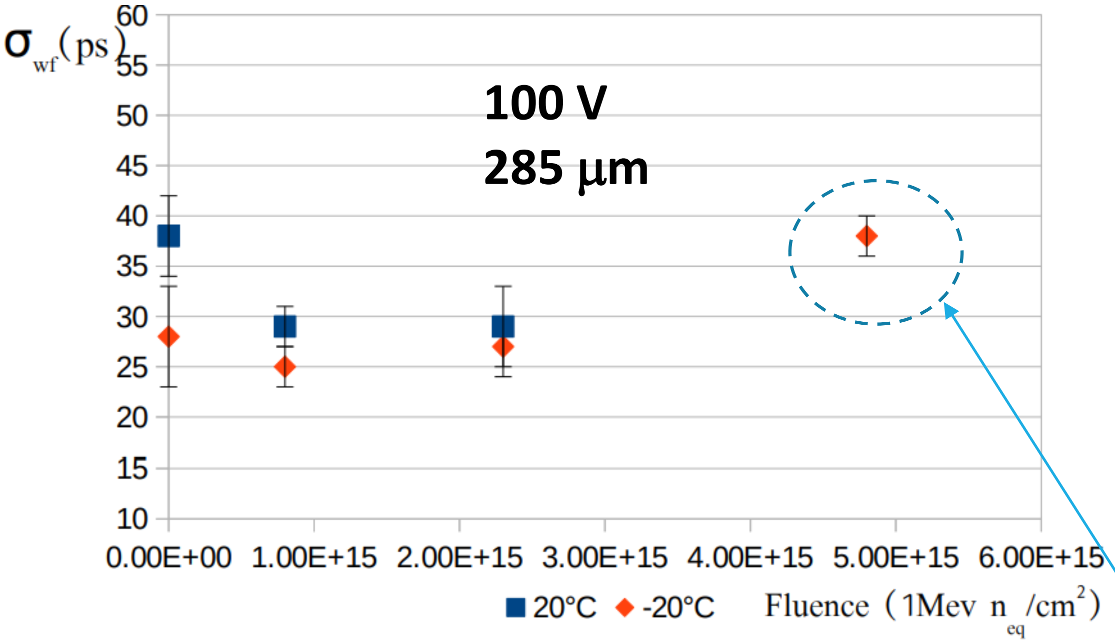
D. De Simone et al, 37th RD50 workshop,2020
D. De Simone et al, 16th TRENTO workshop,2021

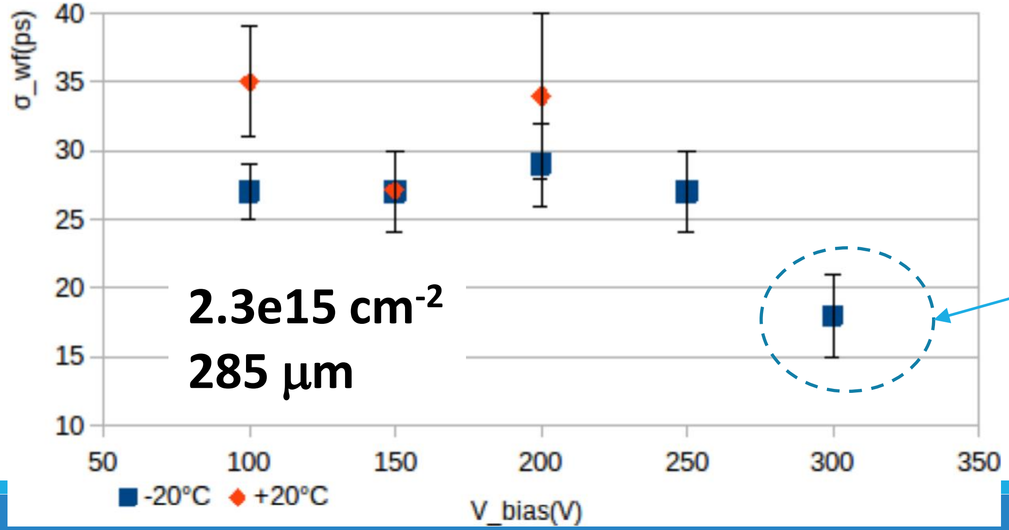


- Time resolution of around
  - 45 (55) ps at -20°C (20°C) for 285 μm thick sensors
  - 35 (45) ps at -20°C (20°C) for 235 μm thick sensors
- Time walk contribution independent on thickness
  - ~35 ps at 20°C and ~25 ps at -20°C
- Slightly lower jitter for 235 μm thick detector – yet to be understood

Measurements are even slightly better than predicted by simulations!

Performance after irradiations



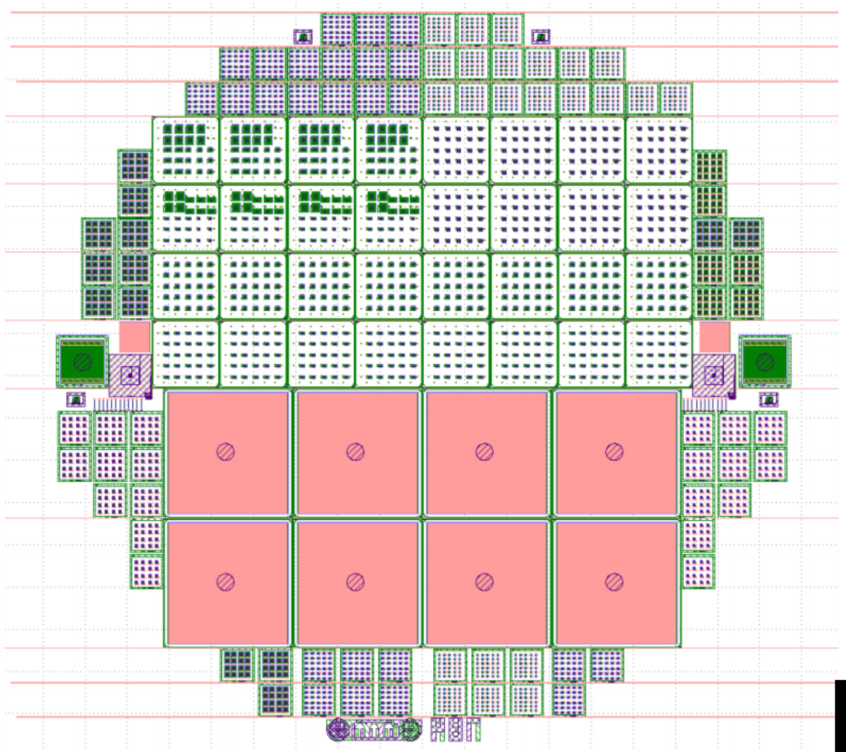


$+20°$	σ_{3D} (ps)	σ_j (ps)	σ_{wf} (ps)
not irradiated	53±2	36±7	38±4
8e14 MeV n_{eq}/cm^2	37±2	23±3	29±2
2.3e15 MeV n_{eq}/cm^2	44±2	26±5	29±3
-20°	σ_{3D} (ps)	σ_j (ps)	σ_{wf} (ps)
not irradiated	37±2	23±3	28±5
8e14 MeV n_{eq}/cm^2	34±2	23±3	34±2
2.3e15 MeV n_{eq}/cm^2	35±2	23±4	27±3

- No impact or slightly better performance after irradiations.
- At 5×10^{15} cm^{-2} the σ_{wf} increases by 10 ps – not yet understood why (rebonding ?)
- At high bias voltages the σ_{wf} can improve due to charge multiplication?

D. De Simone et al, 37th RD50 workshop,2020
D. De Simone et al, 16th TRENTO workshop,2021

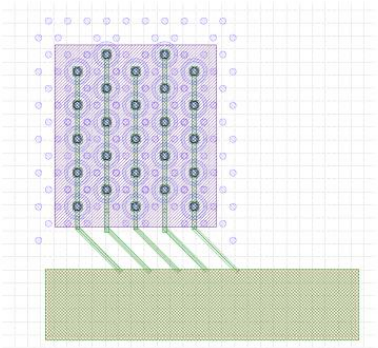
Future – RD50 3D timing project



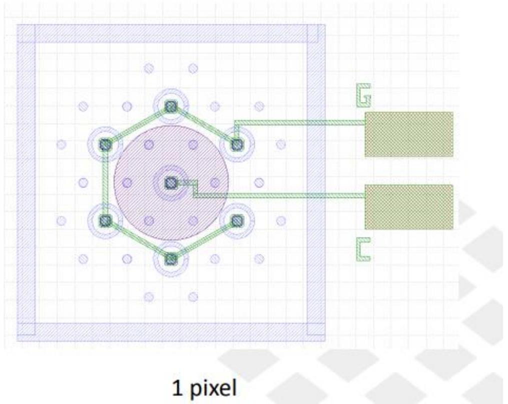
Altiroc 1
Medipix 3
Simple pad

Diodes

- 50x50um (100x100 pixels) **3**- orthogonal
- 50x50um (10x10 pixels), **6**- orthogonal , **7**- hexagon
- 50x50um (5x5 pixels) **4**- hexagonal + **5**- orthogonal
- 50x50um (1 pixel) **1**- orthogonal + **2**- hexagonal

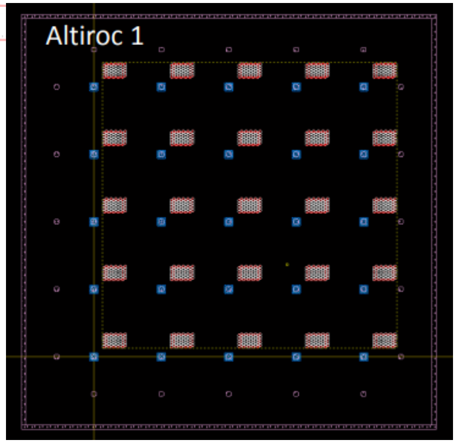


5x5 pixels



1 pixel

8 wafers of different thickness with different test structures will be produced by CNM – processing has started

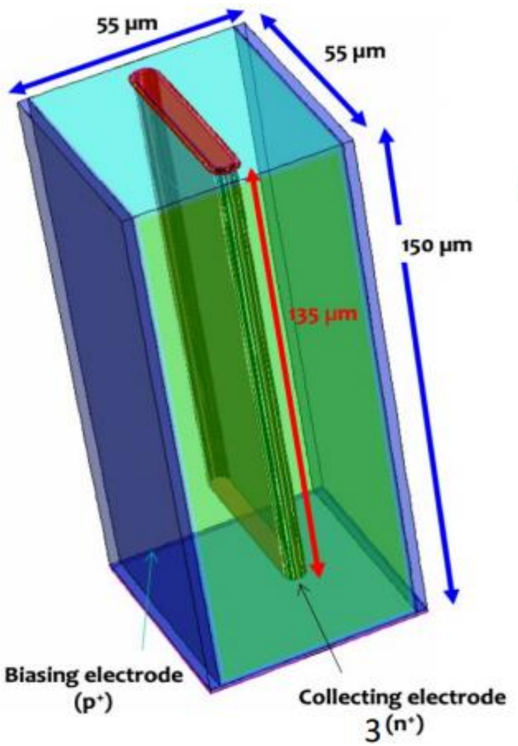


Activity	Institute	Lead
Wafer processing	CNM Barcelona	G. Pellegrini
Process/Detector simulations	CNM Barcelona	G. Pellegrini
Signal/timing performance simulations	JSI, Uni. Freiburg	G. Kramberger
TCT measurements	Uni. Freiburg, JSI, IFAE	U. Parzefall
Electrical characterization	Uni Freiburg, JSI, UZH, IFAE	C. Betancourt
Neutron irradiations	JSI	G. Kramberger
Timing measurements (with discrete electronics, ALTIROC)	JSI, UZH, Uni. Freiburg, IFAE	S. Grinstein

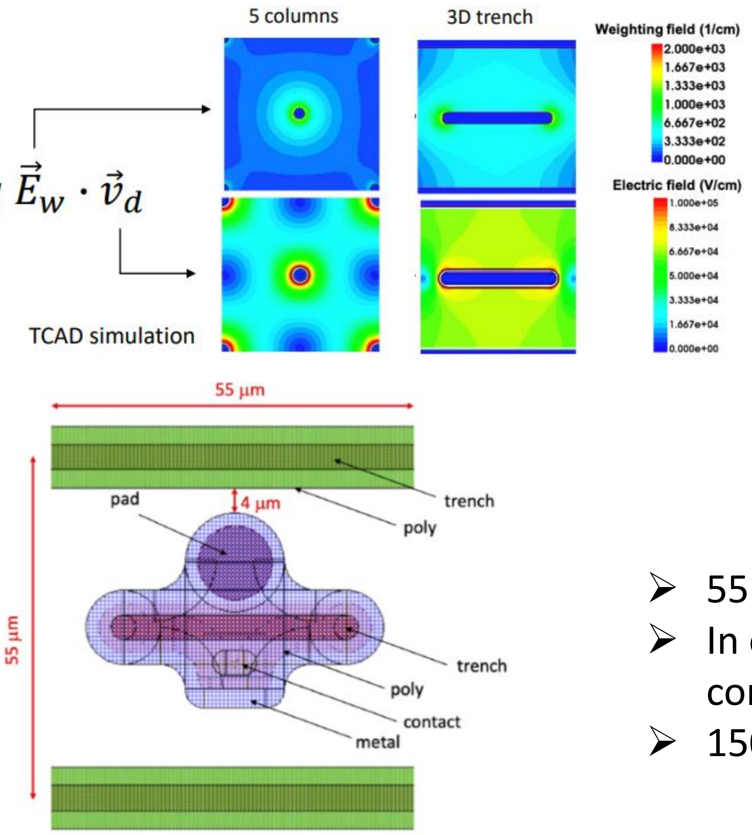
Trench 3D timing detectors

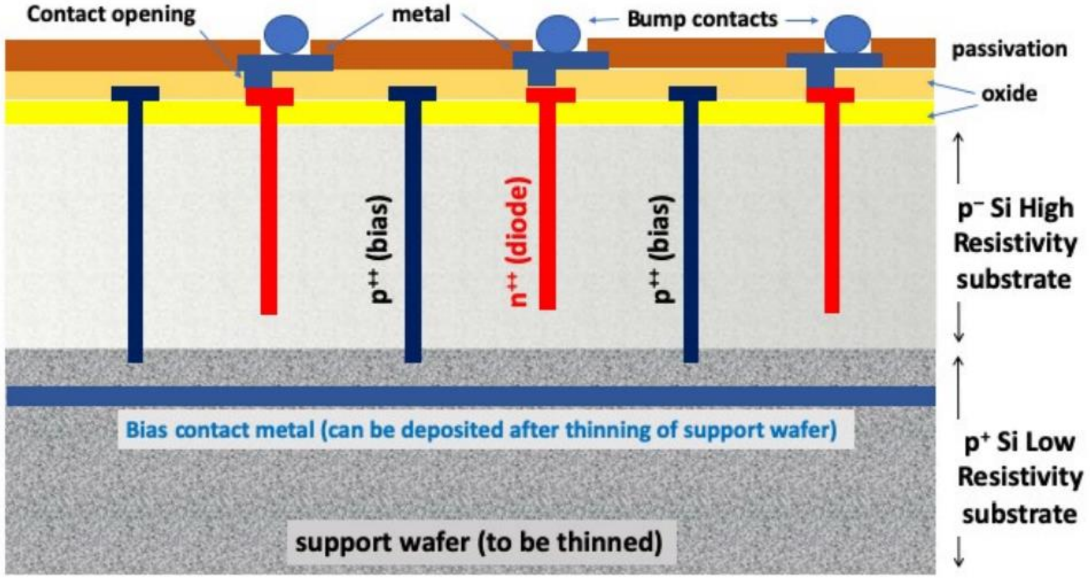
A. Lampis, 16th TRENTO workshop, 2021
M. Garau, 16th TRENTO workshop, 2021

How to improve σ_{wf} ? Optimize the design for E_w , and minimize the "price to pay" for that.



$$i = q\,\vec{E}_w \cdot \vec{v}_d$$





- 55µm x 55µm pixels (for TimePix/Medipix ASIC family)
- In each pixel a 40 µm long n^{++} trench is placed between continuous p++ trenches used for the bias
- 150µm-thick active thickness, on a 350 µm-thick support wafer

Test beam measurements

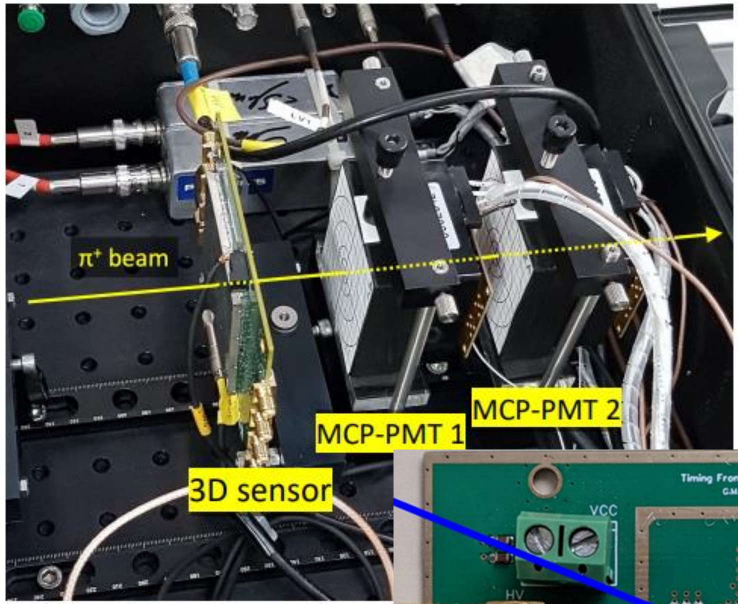
JSI Ljubljana Slovenia

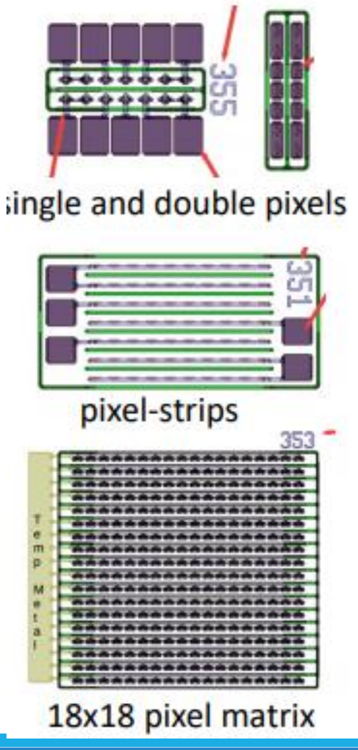
Slovenian Research Agency

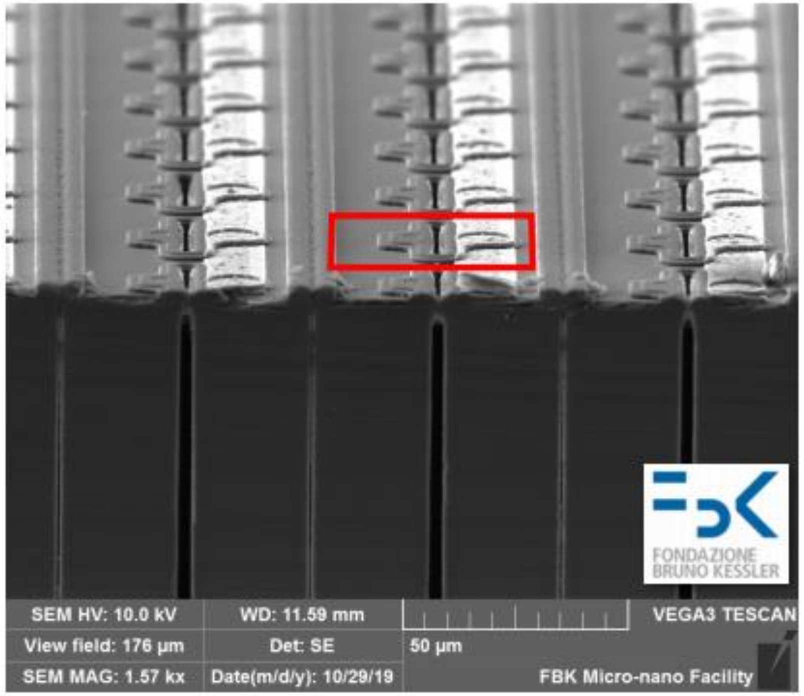
Paul Scherrer Institut (PSI): π beam, 280 MeV/c
Structure tested: double pixel
The discrete electronics board developed within TimeSpot was used.

- **55x55 μm²** pixels
- **150 μm** active thickness
- Collection electrode **135 μm** deep

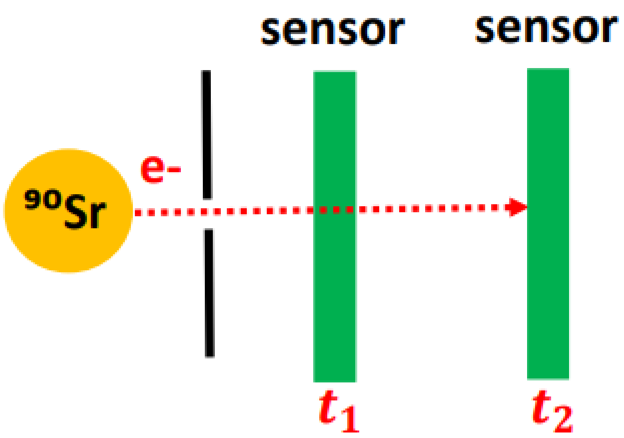
A. Lampis, 16th TRENTO workshop, 2021
M. Garau, 16th TRENTO workshop, 2021

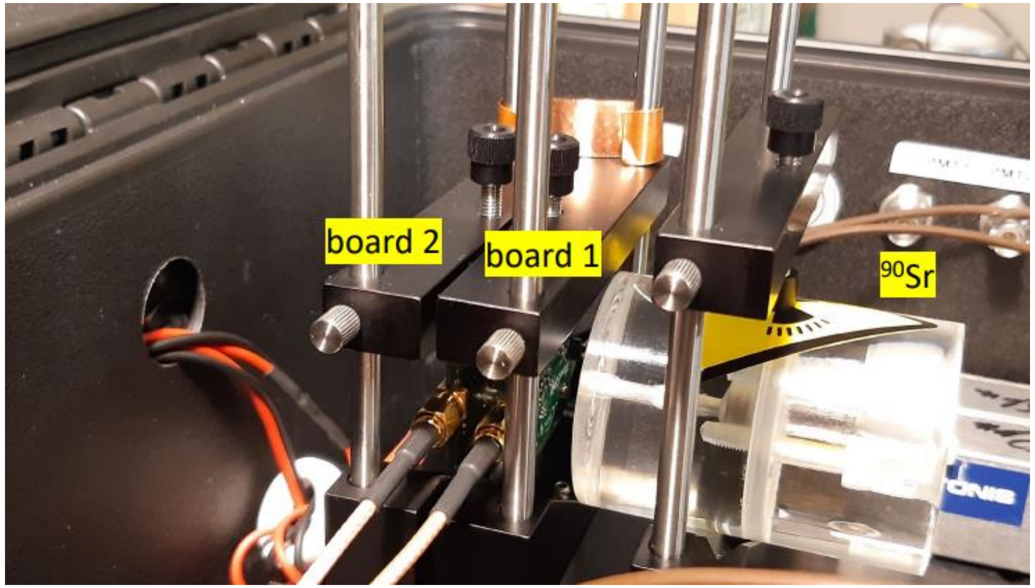


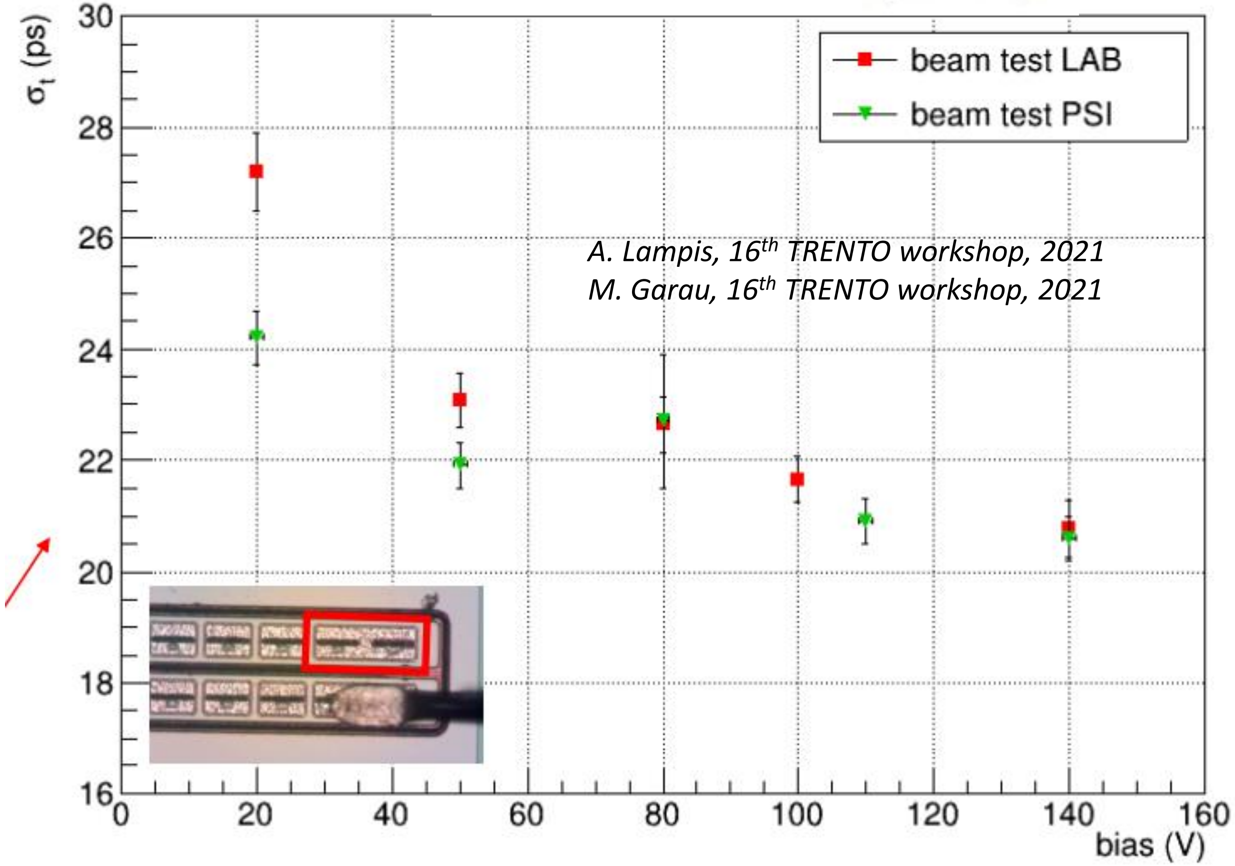




Measured time resolution

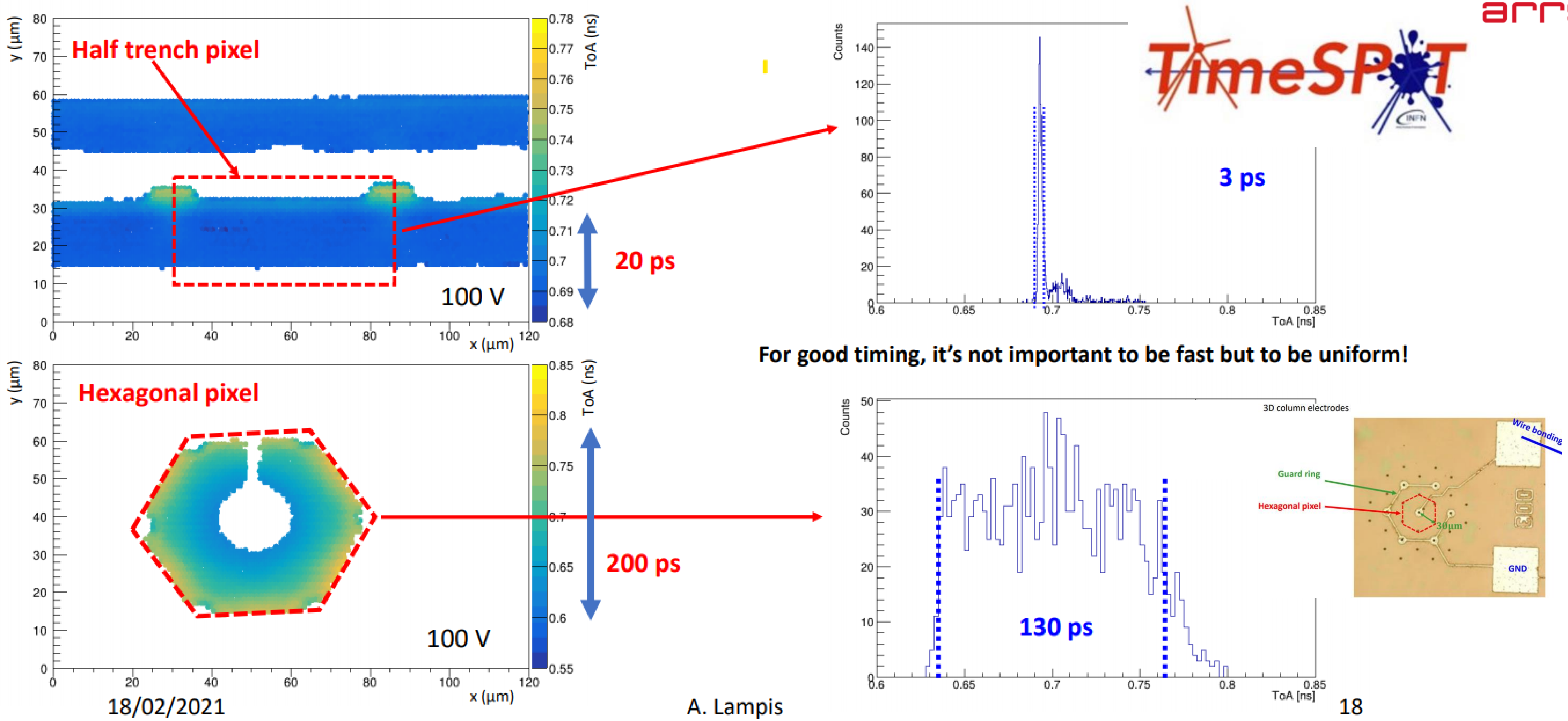






Time resolution around ~15 ps better than for column 3D.

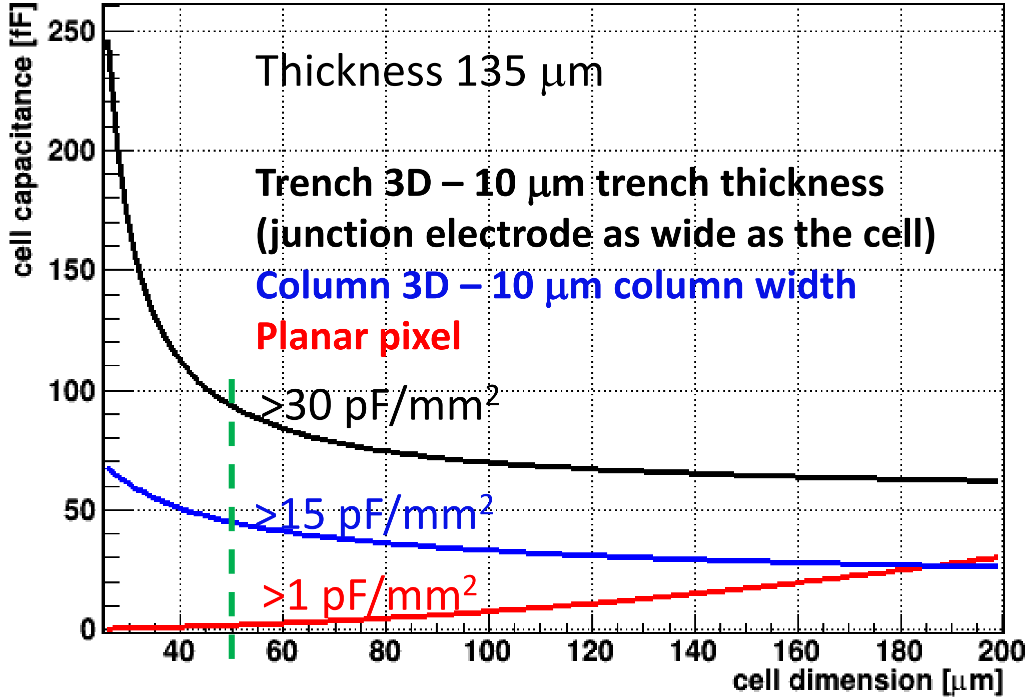
ToA distribution for different designs

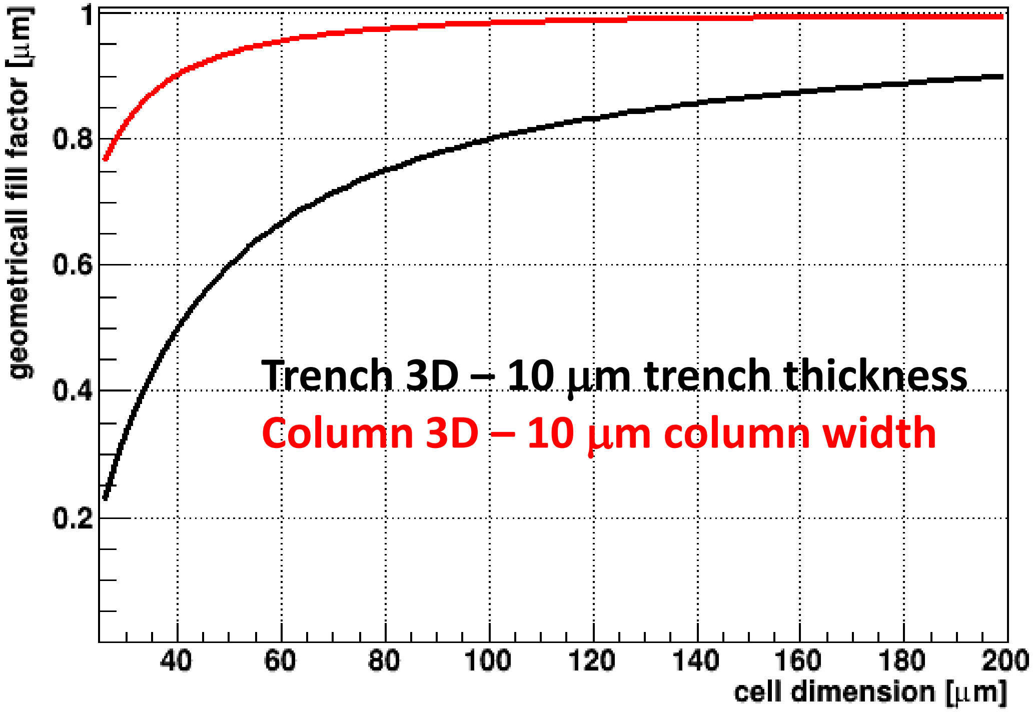


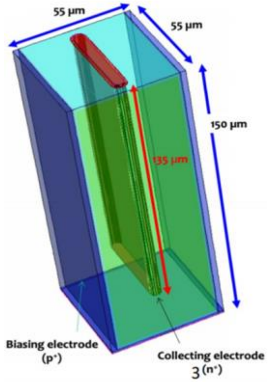
For good timing, it's not important to be fast but to be uniform!

TCT measurements (ToA wrt to laser trigger) of the response of the sensor to ps laser pulses focused to 5 µm.

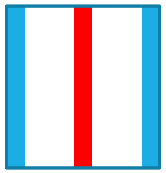
Drawback of 3D design (C and fill factor)



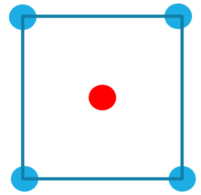




- Much larger capacitance of the trench design wrt. to column and planar (ASIC is crucial)
- At small cell sizes needed for superior timing resolution the fill factor is small
  - For column like the direction of the inclined tracks is not very important
  - For trench detectors the direction of tracks is crucial (detector design tailored to application)



not fully efficient for all φ at $\theta \neq 0$



fully efficient at $\theta \neq 0$

Outlook for the future – σ_t=10 ps goal

- The cell size should be even more reduced – that makes sense only if the column widths are reduced from ~10 μm to <5 μm. For FCC-hh the cell size of ~25x25 μm^2 is required for position resolution anyway.
- Narrower columns will reduce also the capacitance -> improvement of S/N and reduction of the jitter.
- Extreme radiation hardness requires thicker active layer to improve the signal (and hit efficiency)
  - improved aspect ratio of Deep Reactive Ion Etching (DRIE) is crucial.
  - larger thickness will lead to large cluster sizes …?!
- If large fill factor is required trench design could be less appropriate
  - reducing the cell size the jitter will become the main contribution to the time resolution (fast integration and good signal/noise needed) and there will be little difference between column and trench design.
  - the fragility of the wafer may become an issue at small cell sizes.

The 3D design with several important modifications is very likely the solution for 4D tracking where high radiation tolerance is required!

Appropriate ASIC development is equally challenging in terms of radiation hardness, power consumption and required functionality per pixel.

Conclusions

- Track timing is valuable for HL-LHC, while for any future hadron collider correct assignment of the tracks to different vertices and better track finding will become crucial (4D tracking).
- LGADs are viable solution for HL-LHC where 30 ps track resolution is possible, but they have two main drawbacks: radiation hardness and fill factor for which 3D silicon detectors can be a solution
- TimeSpot/INFN and RD50 3D timing projects are ongoing to explore performance of the detectors
- 3D technology with small cell design (50x50 μm^2) have been shown to achieve:
  - time resolution of around 35-40 ps with "standard" columns before and after irradiation to 5e15 cm^{-2} (with time walk contribution of around 25 ps)
  - time resolution of around 20-25 ps with trenches (almost entirely jitter)
- Trench design offers superb time-walk contribution (of few ps), but suffers from larger capacitance and worse fill factor
- Improving aspect ratio of DRIE should allow for even smaller cells (column 3D cells) where time walk contribution to timing resolution can approach to ~10 ps
- There are a lot of problems ahead, but at the moment there is no other technology outperforming 3D when superb radiation hardness and timing resolution are required.