Timing performance of small cell 3D silicon detectors

M. Carulla[+], V. Cindro[*], D. Flores[+], S. Hidalgo[+], B. Hiti[*], G. Kramberger[*], I. Mandić[*], A. Merlos[+], M. Mikuž[*], D. Quirion[+], G. Pellegrini[+], M. Zavrtanik[*]

[*] Jožef Stefan Institute, Ljubljana
[+] CNM Barcelona

Motivation

LGADs are the choice for timing detectors at HL-LHC and possibly 4D tracking in the future, but:

- radiation hardness is a problem – gain loss with fluence
- fill factor is a problem, especially when the cell size decreases
  - 1.3x1.3 mm^2 – 86% with 100 μm gap between the pads
  - 0.5x0.5 mm^2 – 69% with 100 μm gap between the pads

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

- They have fill factor 100%
- The radiation tolerance of small cell size devices is large (in signal) and allows operation at higher bias voltages (see 32nd RD50 talks of M. Manna and A. G. Alonso)

Well ..., this is not the end of the story:

- 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 ☹
- 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

We want to evaluate all these ...

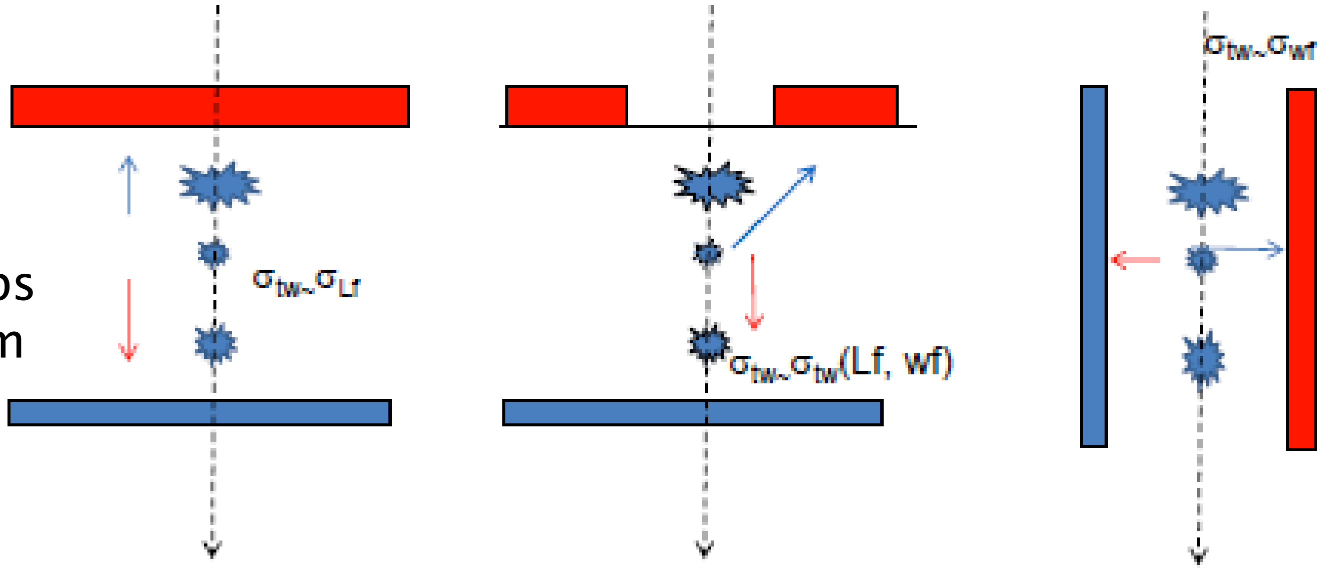
Time resolution

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

$$\sigma_j = N/(dV/dt) \sim t_p/(S/N) \quad , \quad \sigma_{TDC} = TDC_{bin}/\sqrt{12}$$

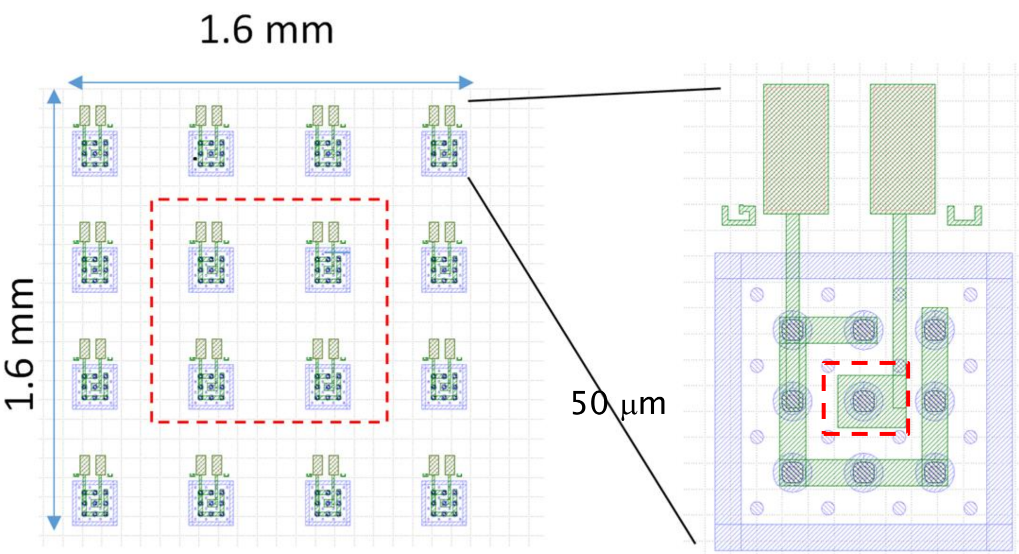
- σ_{tw}–time walk component includes (correlated – can not be summed in squares):
  - weighting field/eelectric field contribution -> depends on hit position in segmented devices (sometimes called distortion component)
  - Landau fluctuations in shape of the signal -> depends on hit position (segmented devices) and gain layer in LGADs
  - Landau fluctuations in amount of deposited charge -> correctable with ToA-ToT or CFD
- σ_j –jitter – fast rise time and high signal/noise

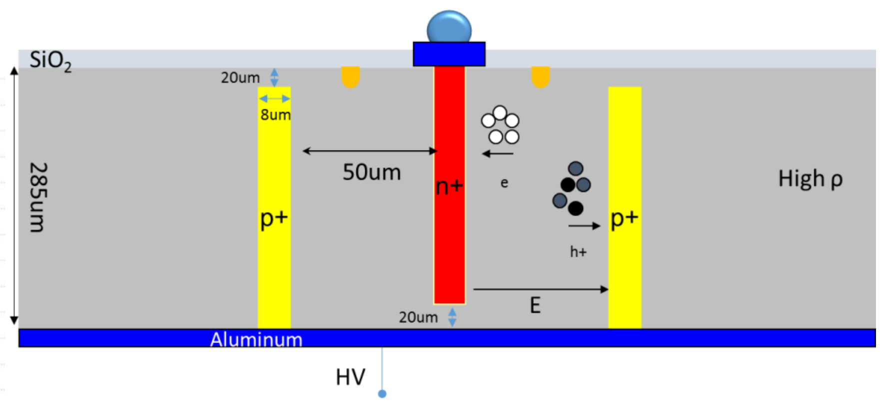
at high gain σ_{tw} ~25 ps for 50 μm LGAD



Devices under study

- CNM produced the devices almost ideal for such study – a 3x3 matrix with investigated cell in the middle and neighboring cells connected together
- cell size 50x50 μm^2 – RD53 chip design
- p-type bulk ($N_{eff}=-1.4\cdot10^{12}$ cm^{-3}), n-type collection
- 1E, holes 2R=8-10 μm and 300 μm thick
- max operational voltage before irradiation ~50 V



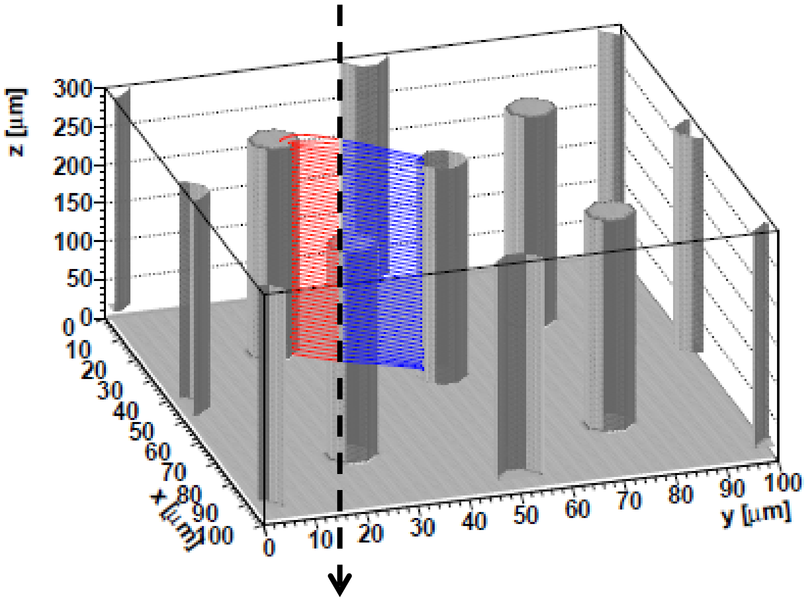


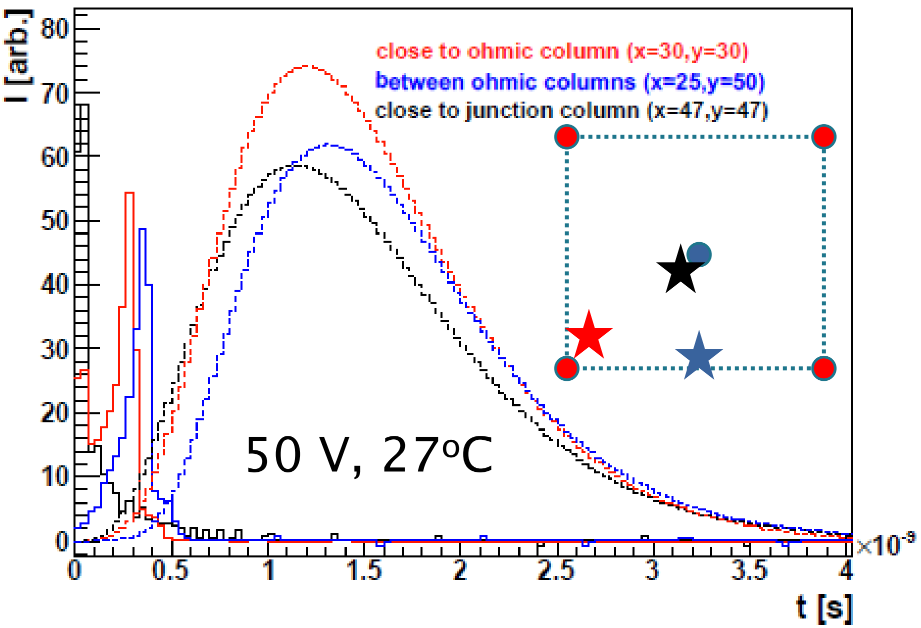
Such device was measured and simulated
(also Edge-TCT, Top-TCT scans were done, but won't be shown)

SIMULATION

Simulation of detectors

kdetsim.org

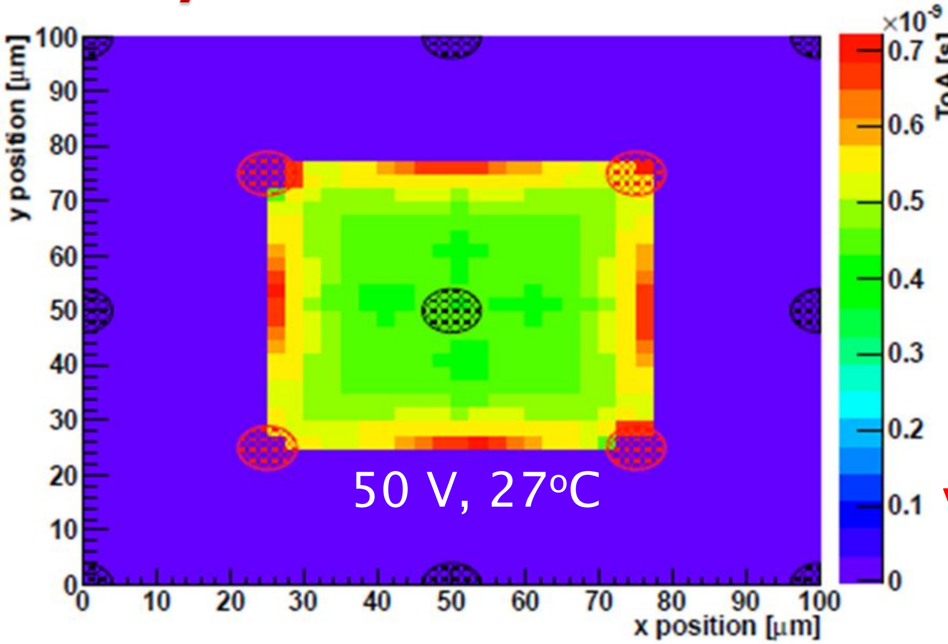


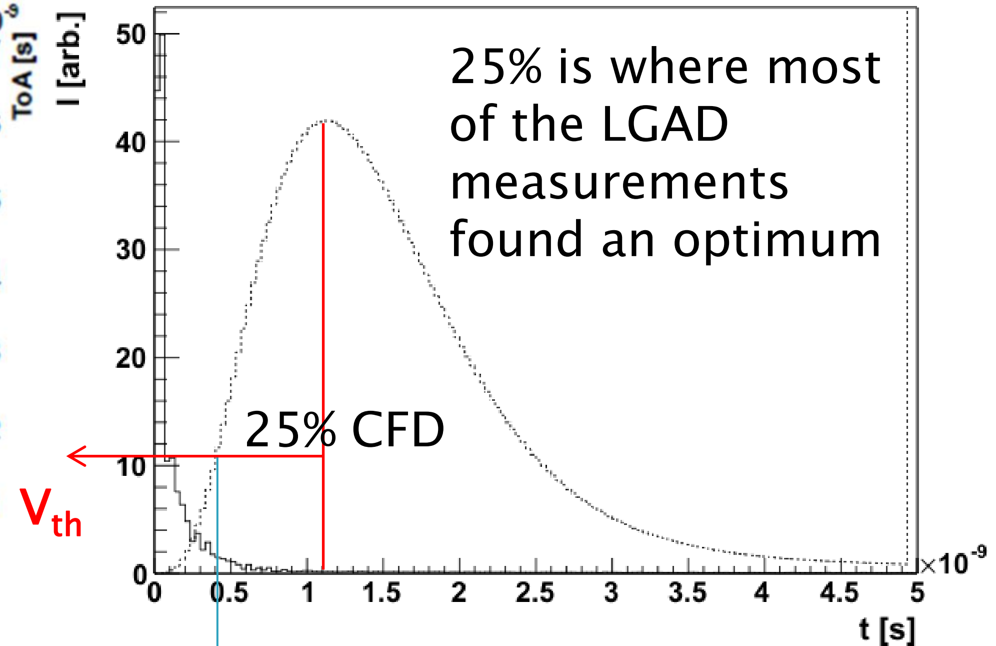


- KDetSim was used in three dimension to simulate detectors (see indico.cern.ch/event/456679/contributions/1126324/).
- solves Laplace (Uw) and Poisson (U) equations for given N_{eff} to get E,E_w and then performs drift in steps solving equation of motion
- Unirradiated sensors -> no trapping, no multiplication
- CR-RC^3 shaping with 1 ns peaking time – shaping type is not crucial

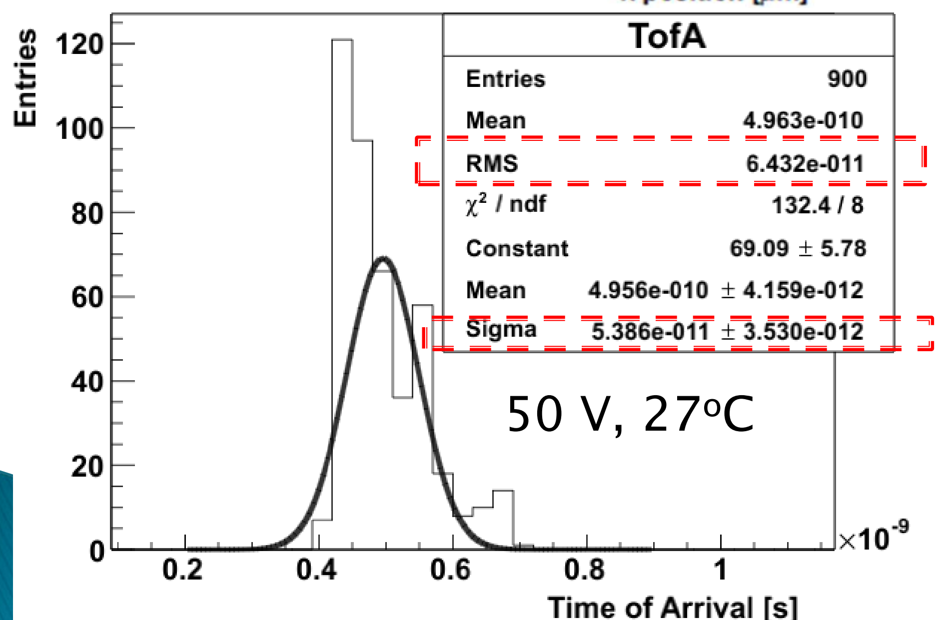
Noise parameters that depend on electronics were not considered -> only time walk was studied!

Perpendicular tracks



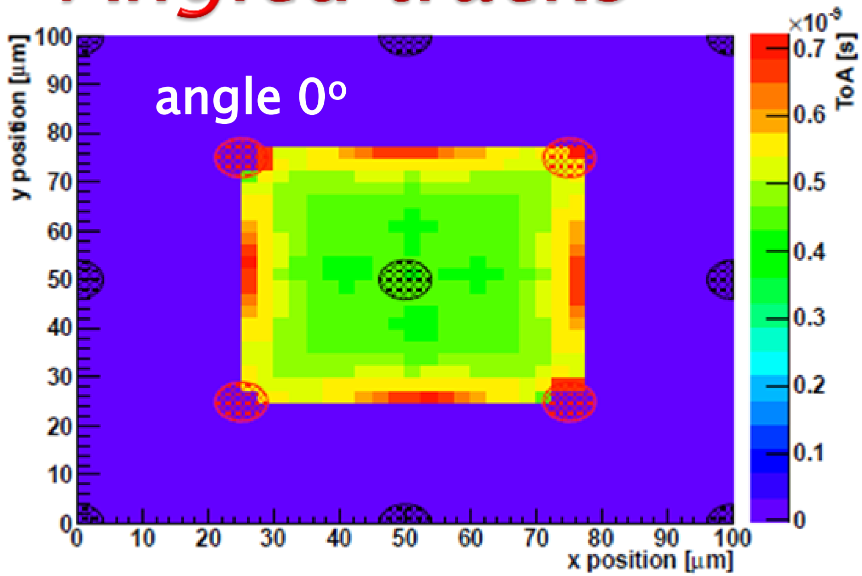


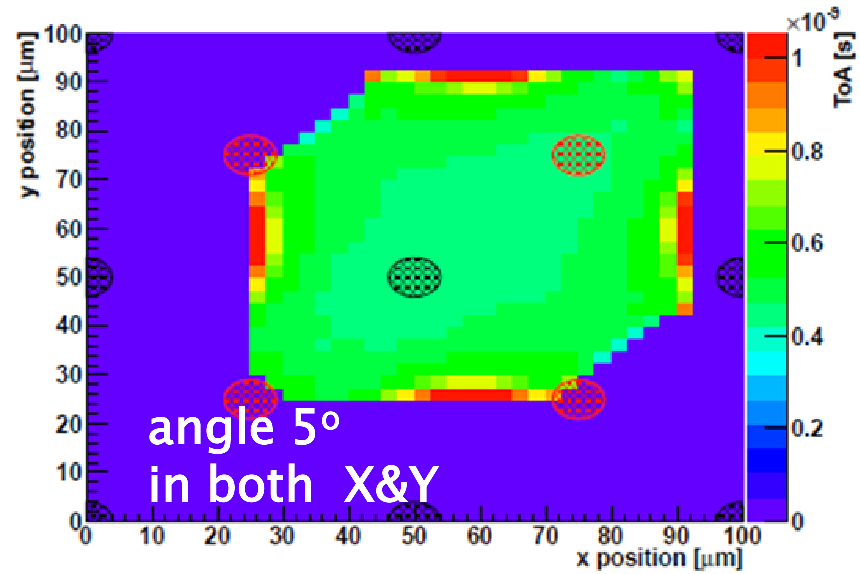
ToA (time over amplitude/of arrival)

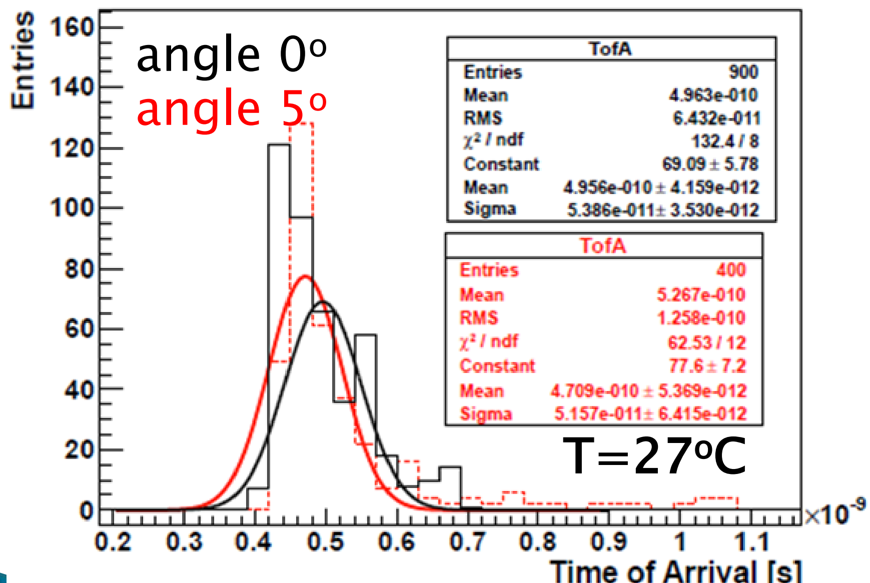


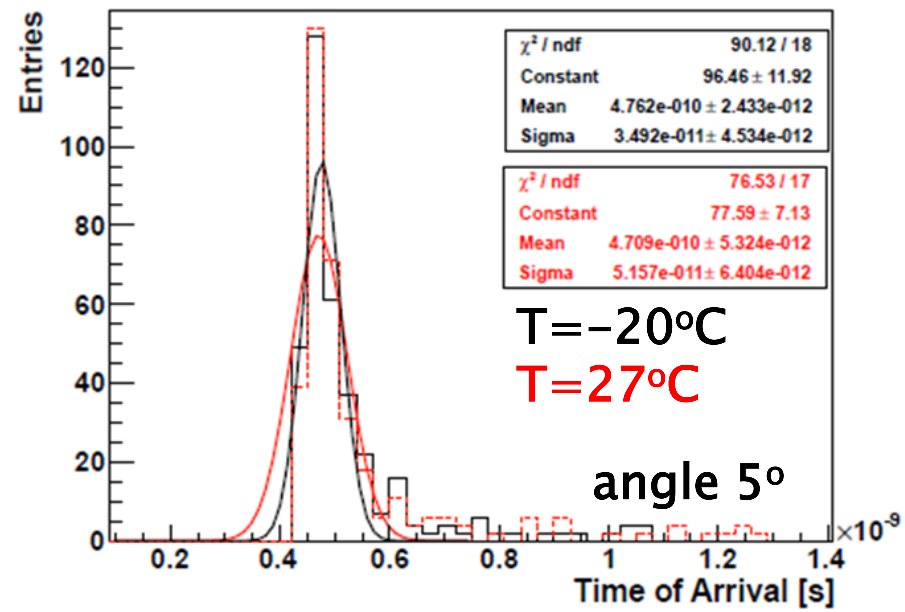
- at least 1000e is required to consider hit for analysis
- a uniform "simulation scan" over the surface shows areas of slower/faster signal
- Outer junction columns (black) are separate electrodes – individual cells

Angled tracks



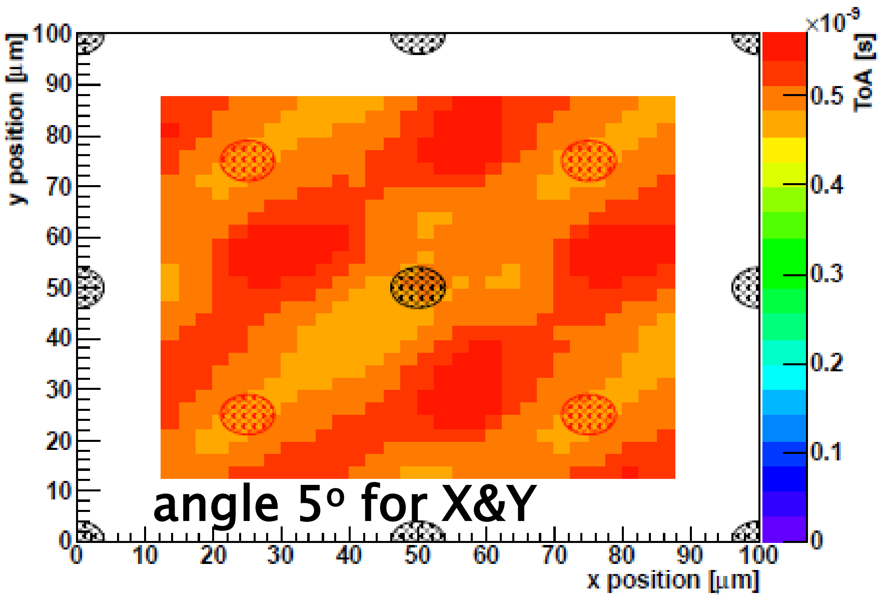


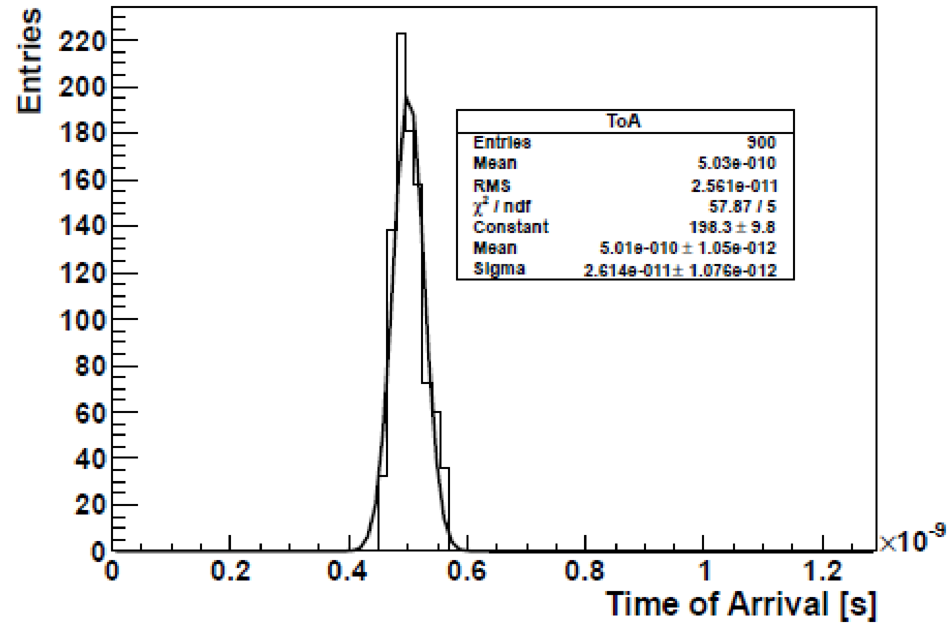




At lower temperature the decrease of ToA distribution is significant.
At larger angle the width gets smaller although there are out layers.

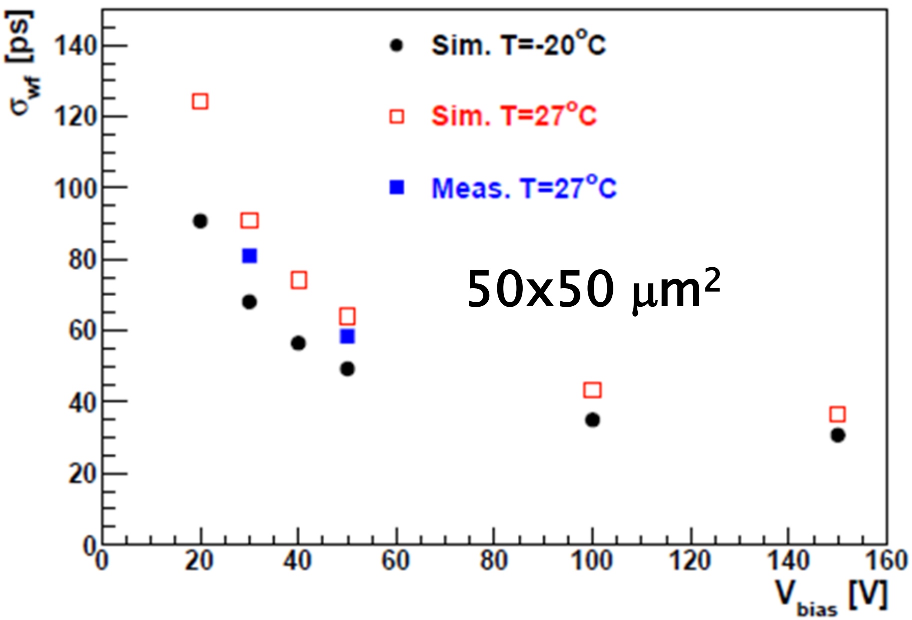
Merging cells into single electrode

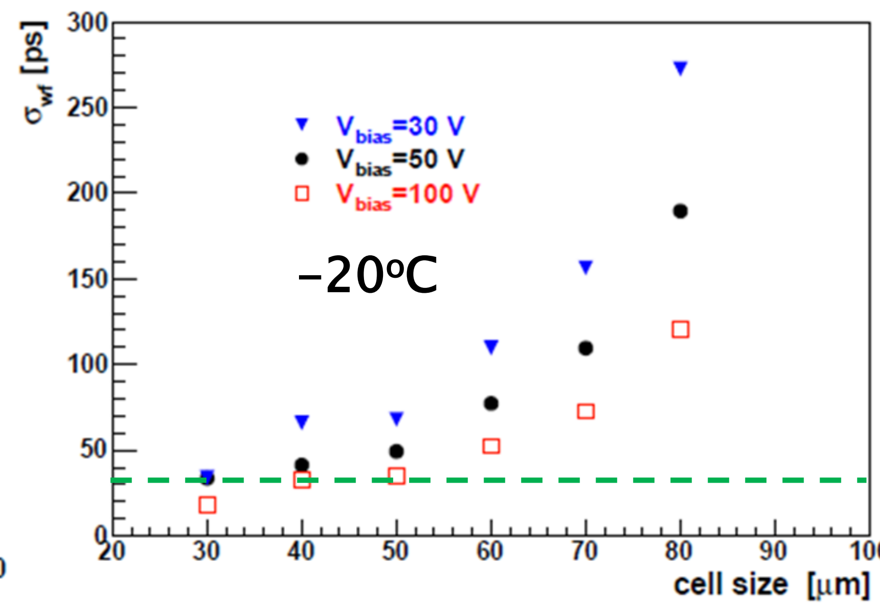


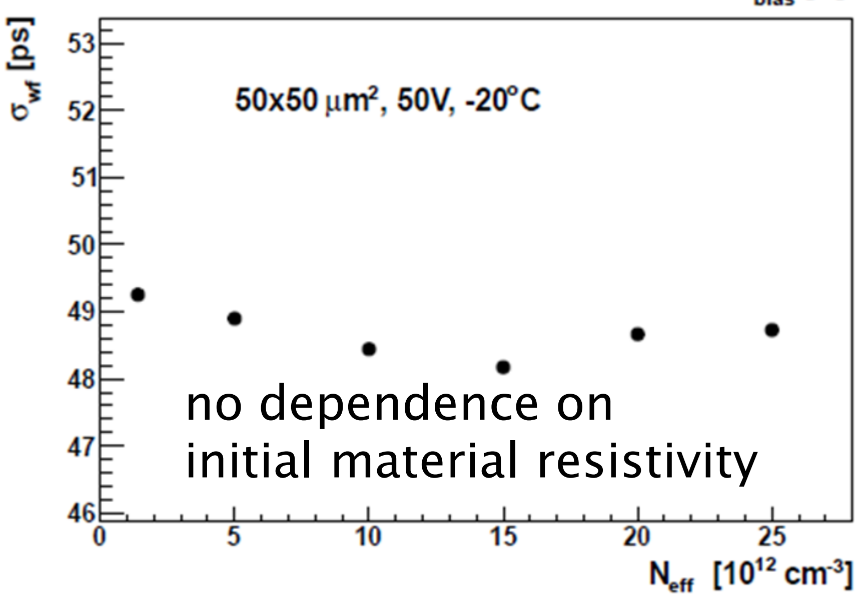


- all junction electrodes at the same weighting potential (no charge sharing between pixel cells anymore – much better performance)
- with tracks under angle (5° at r=30 cm of ATLAS-HGTD) and T=27°C.
- very good timing resolution (σ_{TW}) of 26 ps – comparable to Landau fluctuations in 50 μm LGAD ($\sigma_{Lf,LGAD} \sim \sigma_{wf,3D}$)
- at lower temperatures – this will improve even more

Cell size, bias voltage, temperature







Even for single cell operation and RMS_{wf} instead of σ_{wf} (conservative)

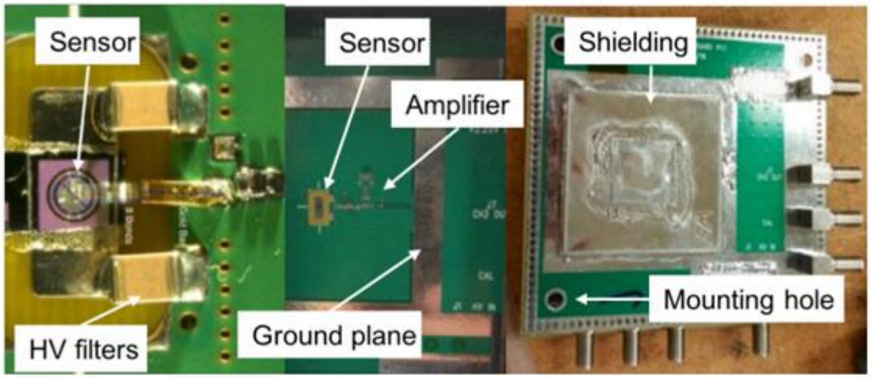
- for bias voltages of >50 V
- cell sizes <=50 μm
- low temperatures <-20°C

time resolution ~30 ps is achievable

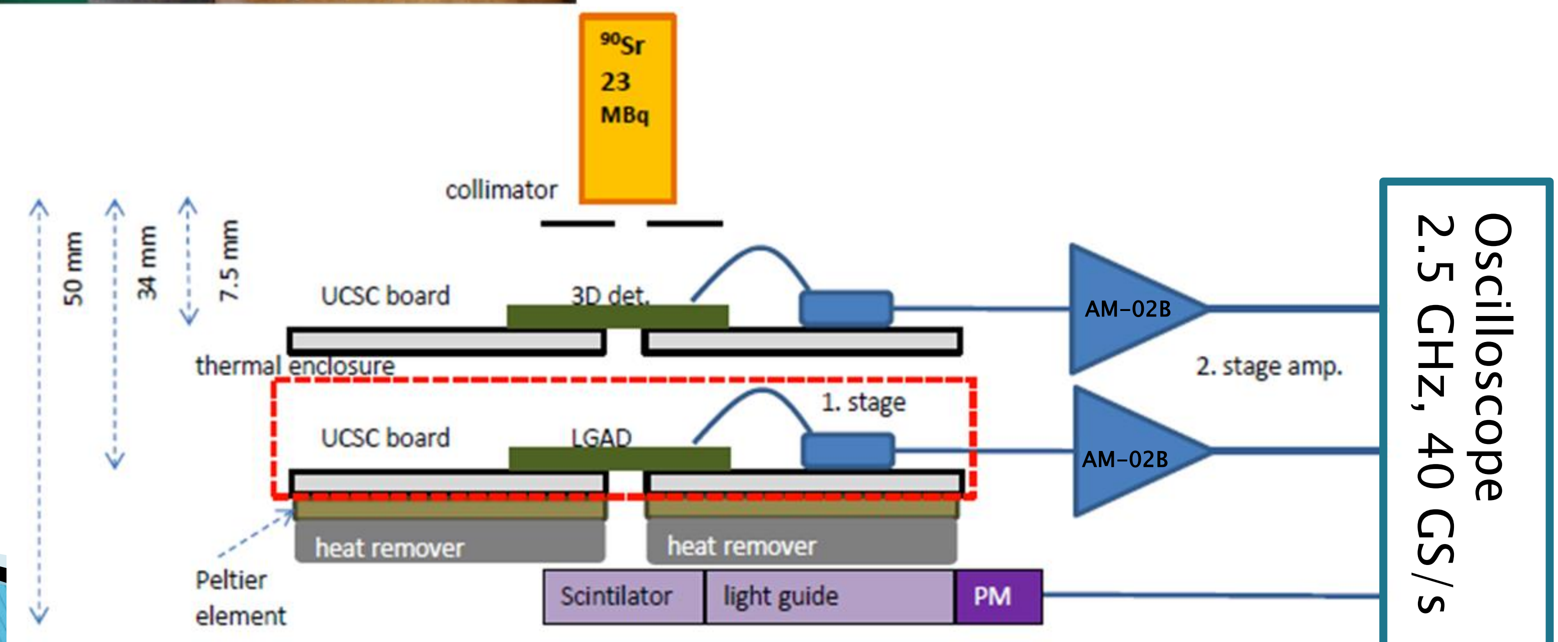
MEASUREMENT

Experimental setup

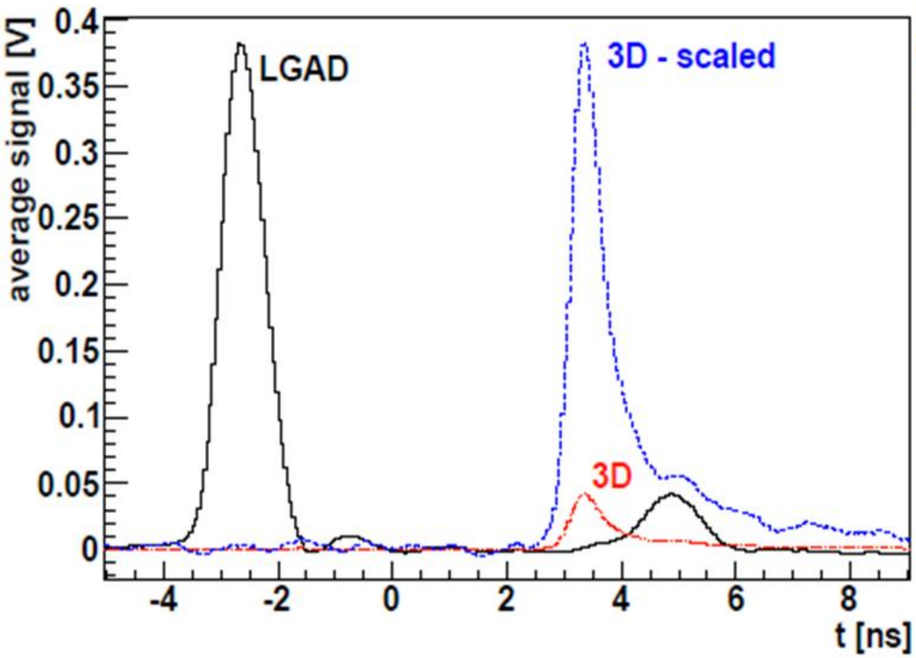
UCSC timing boards (same as for most of LGAD studies) used for measuring the signal followed by 35 dB Particulars amp

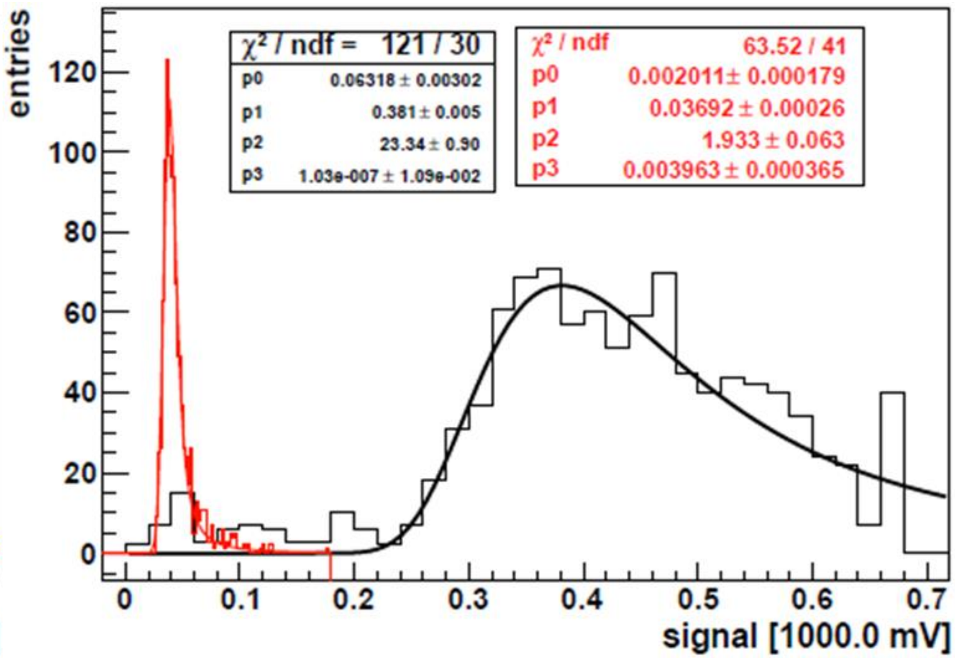


- required hits with very low threshold of 15 mV in both planes (extremely low rate ~1000/day)
- no scintillator+PM were used as this would even more reduce the rate
- 3D detectors were not cooled in these tests due to issues with rate/mounting



Signal shape and charge





- Different shape of LGAD and 3D detector
  - longer tail of 3D
  - faster rise od LGAD
- Large difference in height due to large LGAD gain (G~50-60) – HPK50-D sensor

- Peak of the signal is sampled
  - around 9-10 times larger signal for LGAD
  - Signal calibrated with pin diode and corresponds to
- Signal of both is agreement with expectations.

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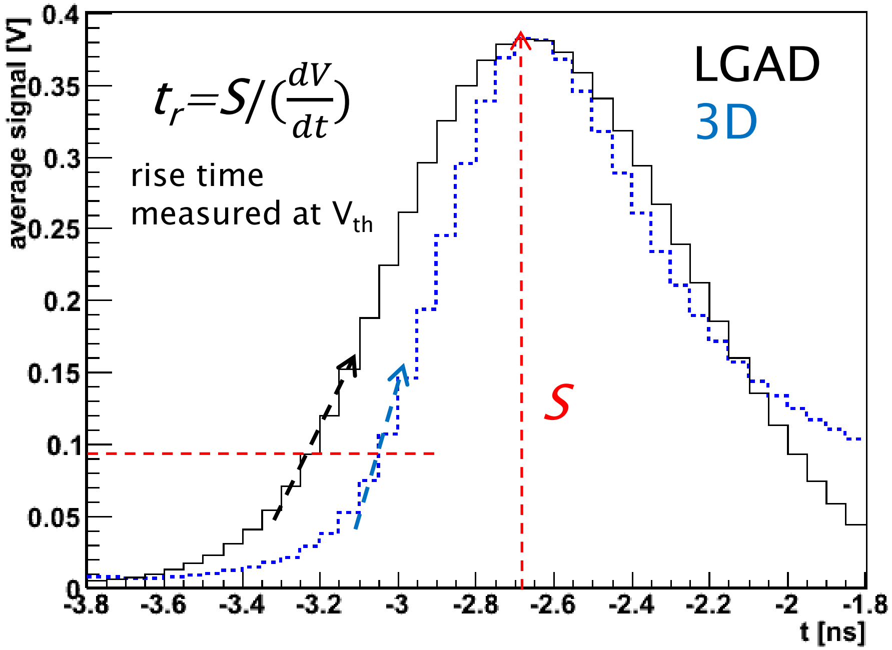

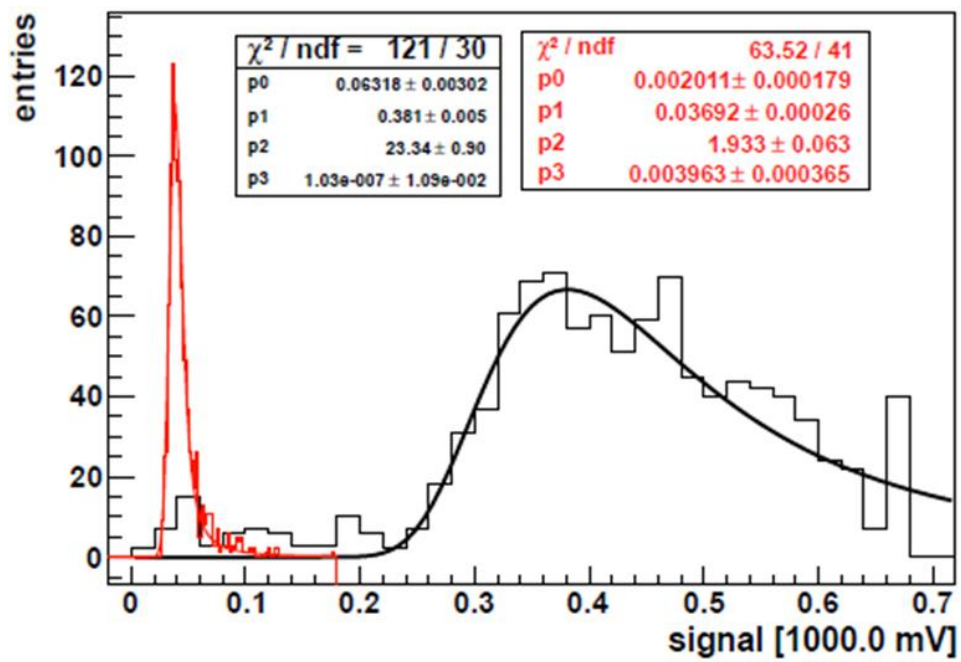

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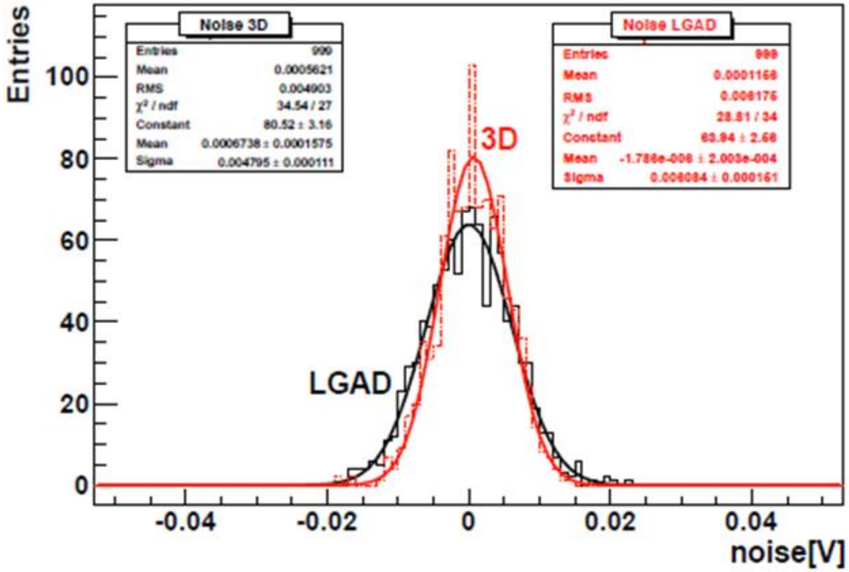
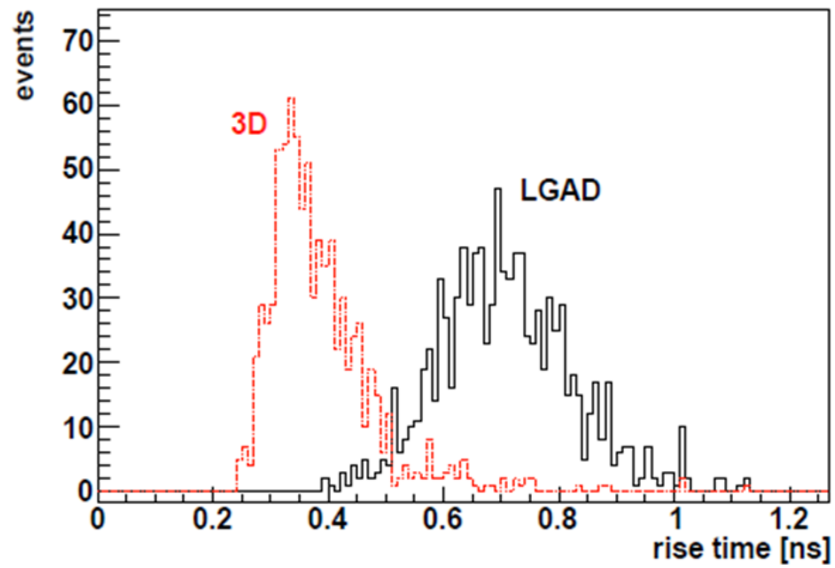
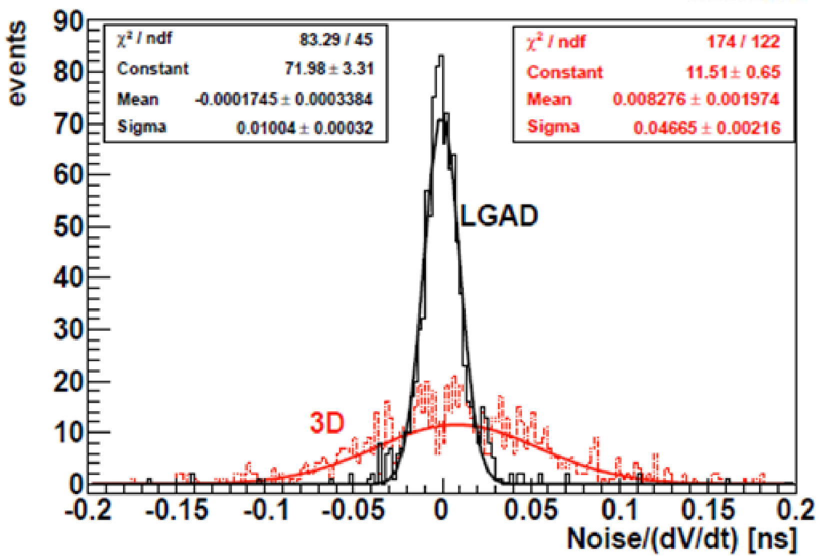
Noise, rise time, jitter



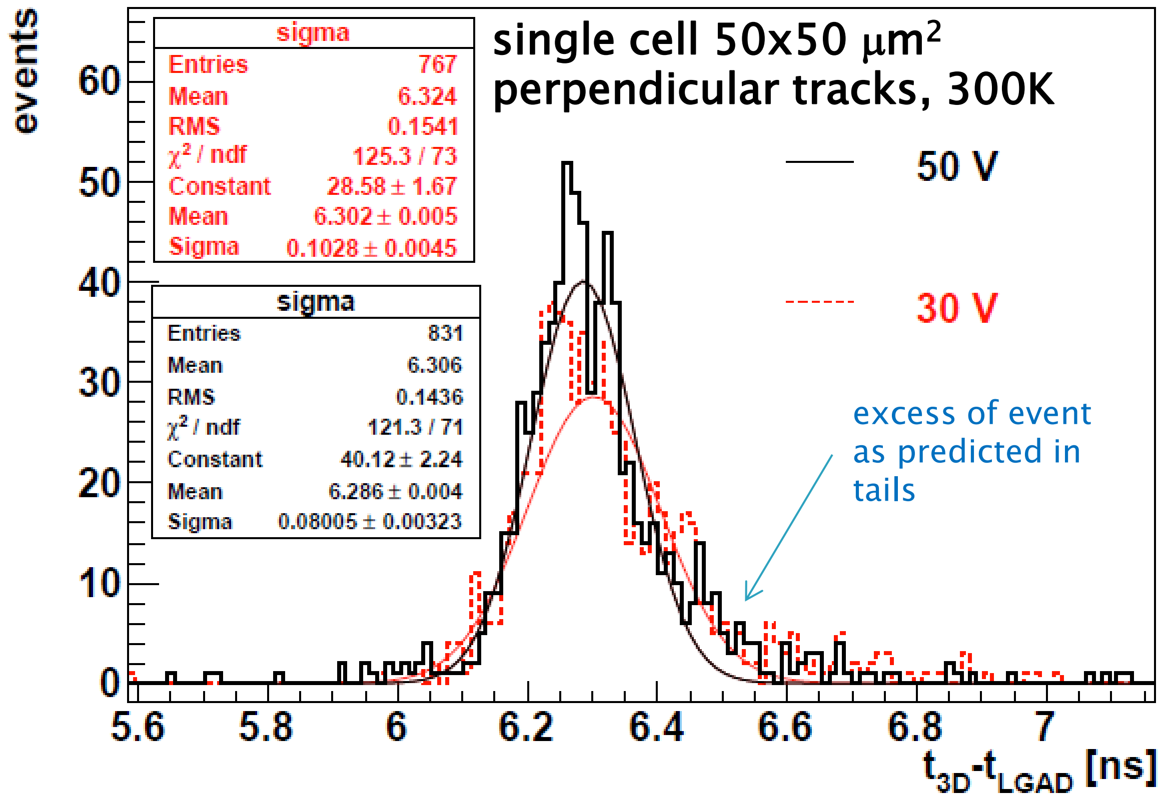




- Noise is compatible with larger capacitance of LGAD (σ=6.0 mV), wrt to 3D (σ=4.8 mV)
- 3D detector is around twice faster than LGAD and that should reflect in the noise jitter:
  - difference in signal rise time ~2
  - difference in signal ~ 9-10
  - similar noise

  Around 5 times larger jitter is expected for 3D and this is also confirmed (47 ps for 3D and 10 ps for LGAD)

Timing resolution of 3D detectors



50 V:

$\sigma_{wf,meas}$=58 ps

$\sigma_{wf,sim}$=54 ps

$RMS_{wf,sim}$=64 ps

30 V:

$\sigma_{wf,meas}$=81 ps

$\sigma_{wf,sim}$=89 ps

$RMS_{wf,sim}$=89 ps

that confirms simulated results – within 10%

$$\sigma_t^2 = \sigma_{LGAD}^2 + \sigma_{3D}^2 \rightarrow \sigma_{3D} = \sqrt{80^2\mathrm{ps}^2 - 26^2\mathrm{ps}^2} = 75 \text{ ps}$$

$$\sigma_{wf}^2 \approx \sigma_{3D}^2 - \sigma_{3D,j}^2 \rightarrow \sigma_{wf} \approx \sqrt{75^2\mathrm{ps}^2 - 47^2\mathrm{ps}^2} \approx 58 \text{ ps}$$

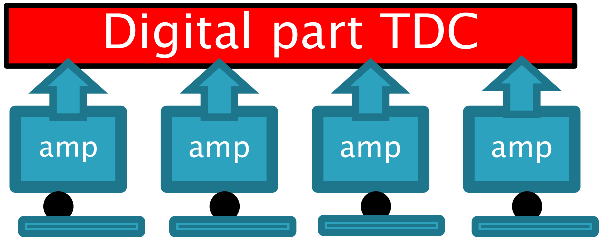
DISCUSSION

What does that mean for HL-LHC?

Can they be considered as a replacement for LGAD in harshest environments?

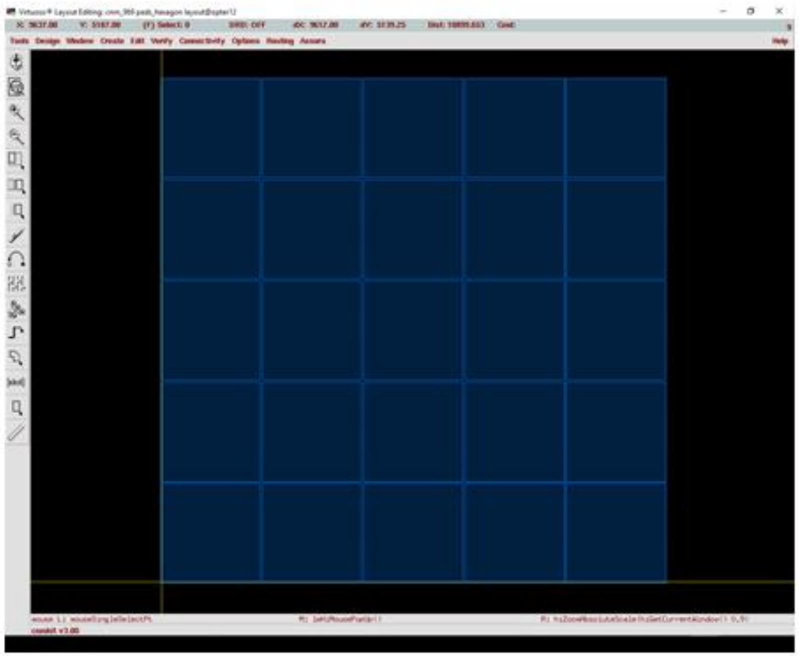
- We expect to have threshold (ALTIROC chip of ATLAS HGTD) of ~2 fC (~12600 e) for LGADs so the signal would large enough MPV~18000e at $5\cdot10^{15}$ cm^{-2} at $V_{bias}<150$ V.
- However the capacitance will be much larger (~50x50 um2 pads 35 pF/cell -> 1 mm^2 cell has ~14 pF instead of ~3 pF for LGAD)
  - that means lower gain of preamp or equivalent say larger ENC which will spoil the jitter
  - faster rise time will partially compensate for increase of jitter, but not entirely
  - also the threshold can change – this is yet to be seen with latest chip
- A way to prevent a problem with capacitance would be simply splitting a pixel into smaller ones. If floor-plan is to small then only analog part can be separated.

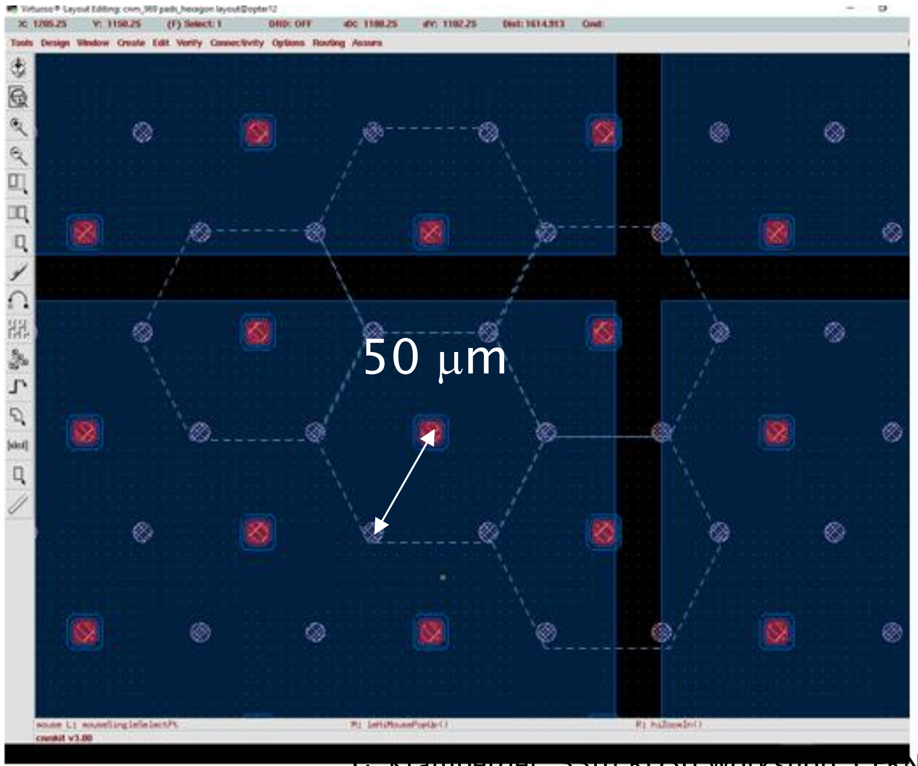
  There is no problem with fill factor.
- Also other pixel designs can reduce the capacitance.



HL-LHC backup design

- less capacitance – hexagonal with cell dimenssion 50 μm for ganged cells – exact numbers will be subject to optimization
- more uniform fields – smaller breakdown
- better ratio low field/total area
- Can be thicker – 500 μm wafers will require larger holes diameters (maybe 15 μm). The new Deep RIE available at the end of 2019 may solve the problem for CNM.





Conclusions

- Timing in small cell 50x50 μm^2 3D detectors was measured and simulated.
- Very good agreement between simulated and measured results was found, within 10%.
- Contribution to the timing resolution due to different hit positions is found to be comparable to landau fluctuations in LGAD at high gain
  - For multi-cell operation the resolution of 26 ps at room temperature is predicted. Lowering the temperature improves timing even more
- Measurements open possibilibilities for backup solution for HL-LHC timing detectors providing that capacitance can be kept under controll:
  - larger cells
  - smaller pads
  - multiple amplifiers per pad with common digital part to save floor space on the electronics