AIDA-2020-SLIDE-2019-018

AIDA-2020

Advanced European Infrastructures for Detectors at Accelerators

Presentation

Timing layers, 4D- and 5D-tracking

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Timing layers, 4D- and 5D-tracking

Besides a few indirect signals of new physics, particle physics today faces a discovery desert.

We need to cross an **energy- cross section** desert to reach the El-dorado of new physics.

Very little help in the direction of this path is coming from nature, the burden is on the accelerator and experimental physicists to provide the means for this crossing.

Timing is one of the enabling technologies to cross the desert

erc UFSD

The effect of timing information

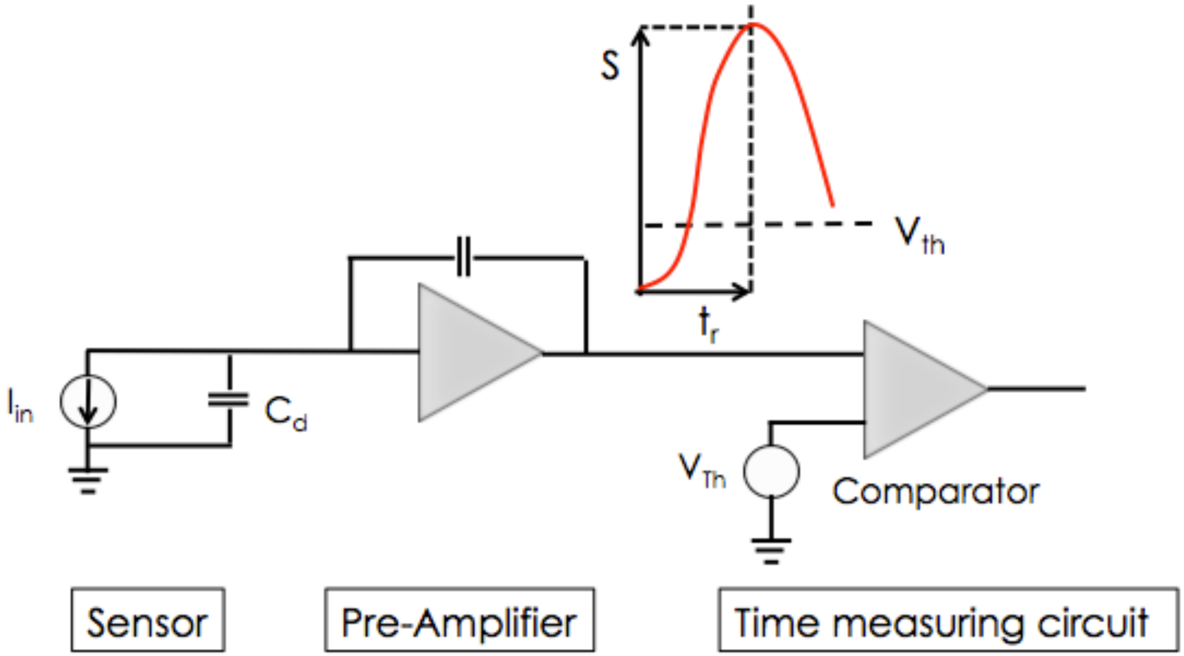
The inclusion of track-timing in the event information has the capability of changing radically how we design experiments.

Timing can be available at different levels of the event reconstruction, in increasing order of complexity:

1) Timing in the event reconstruction ➔ **Timing layers**
   - this is the easiest implementation, a layer ONLY for timing
2) Timing at each point along the track ➔ **4D tracking**
   - tracking-timing
3) Timing at each point along the track at high rate ➔ **5D tracking**
   - Very high rate represents an additional step in complication, very different read-out chip and data output organization

A time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Strong interplay between sensor and electronics

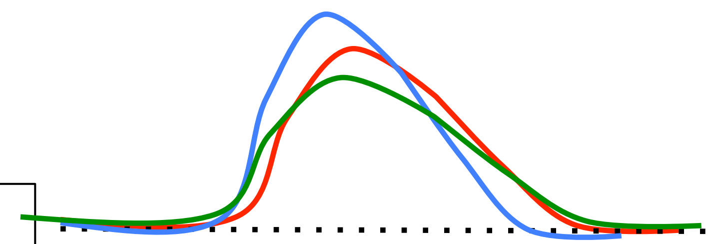
Not all geometries are possible

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity → v

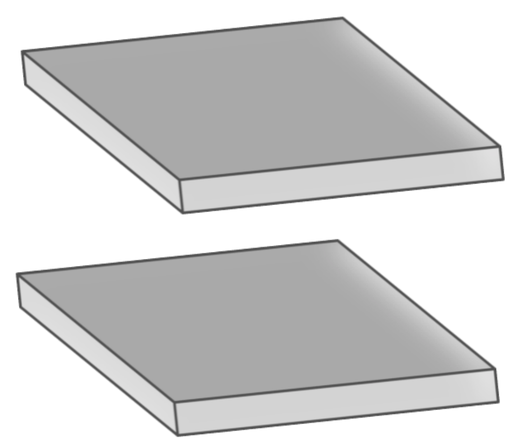
Weighting field → E_w



The key to good timing is the uniformity of signals:

Drift velocity and Weighting field need to be as uniform as possible

Basic rule: parallel plate geometry



Time resolution

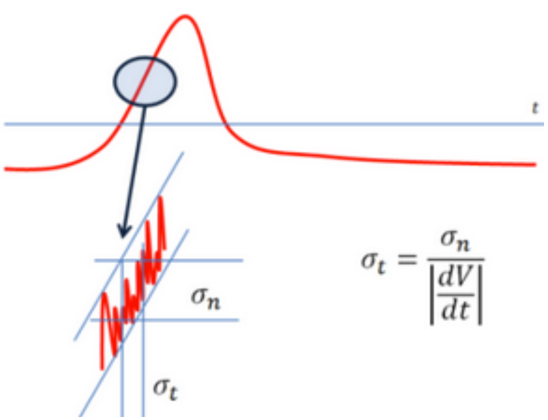
$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

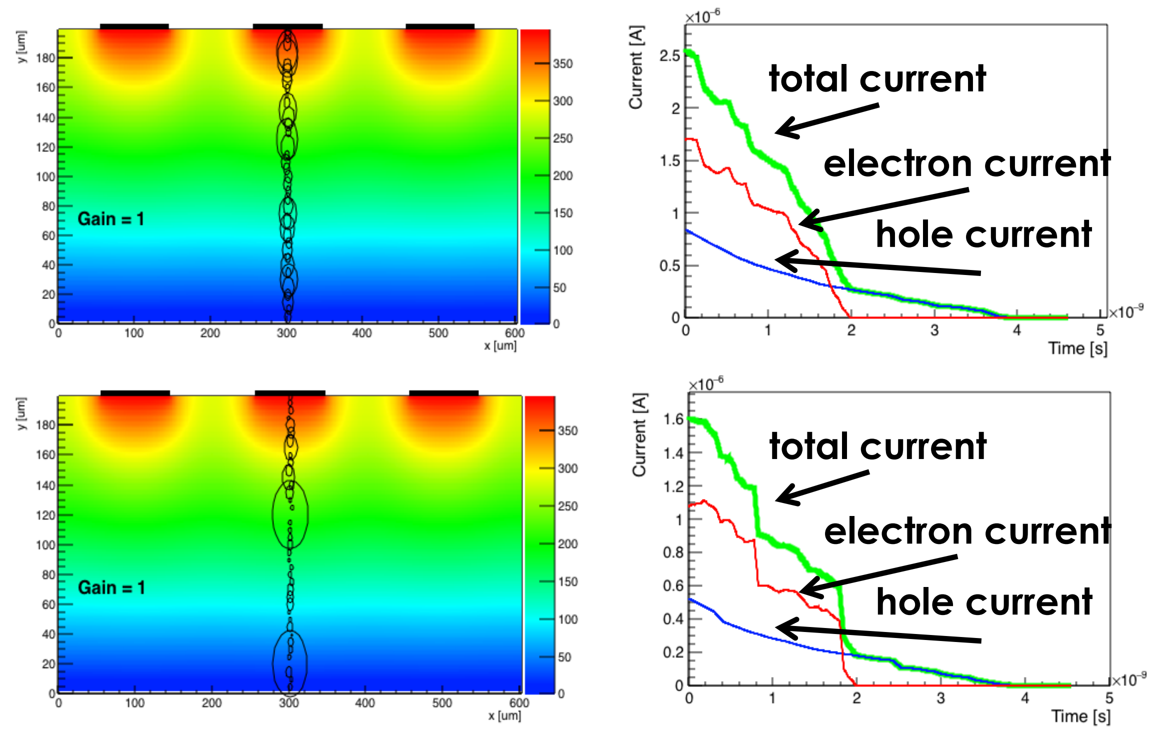
Usual "Jitter" term

Here enters everything that is "Noise" and the steepness of the signal

Time walk: time correction circuitry

Shape variations: non homogeneous energy deposition

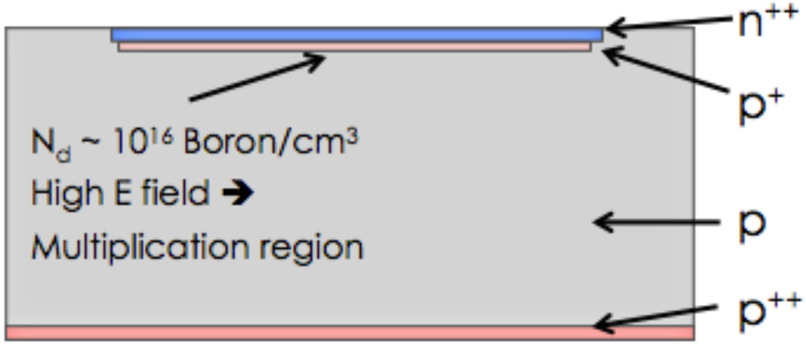




Sensors for 4D tracking

Must have:

- Large dV/dt to minimize jitter
- Segmentation
- Radiation hard



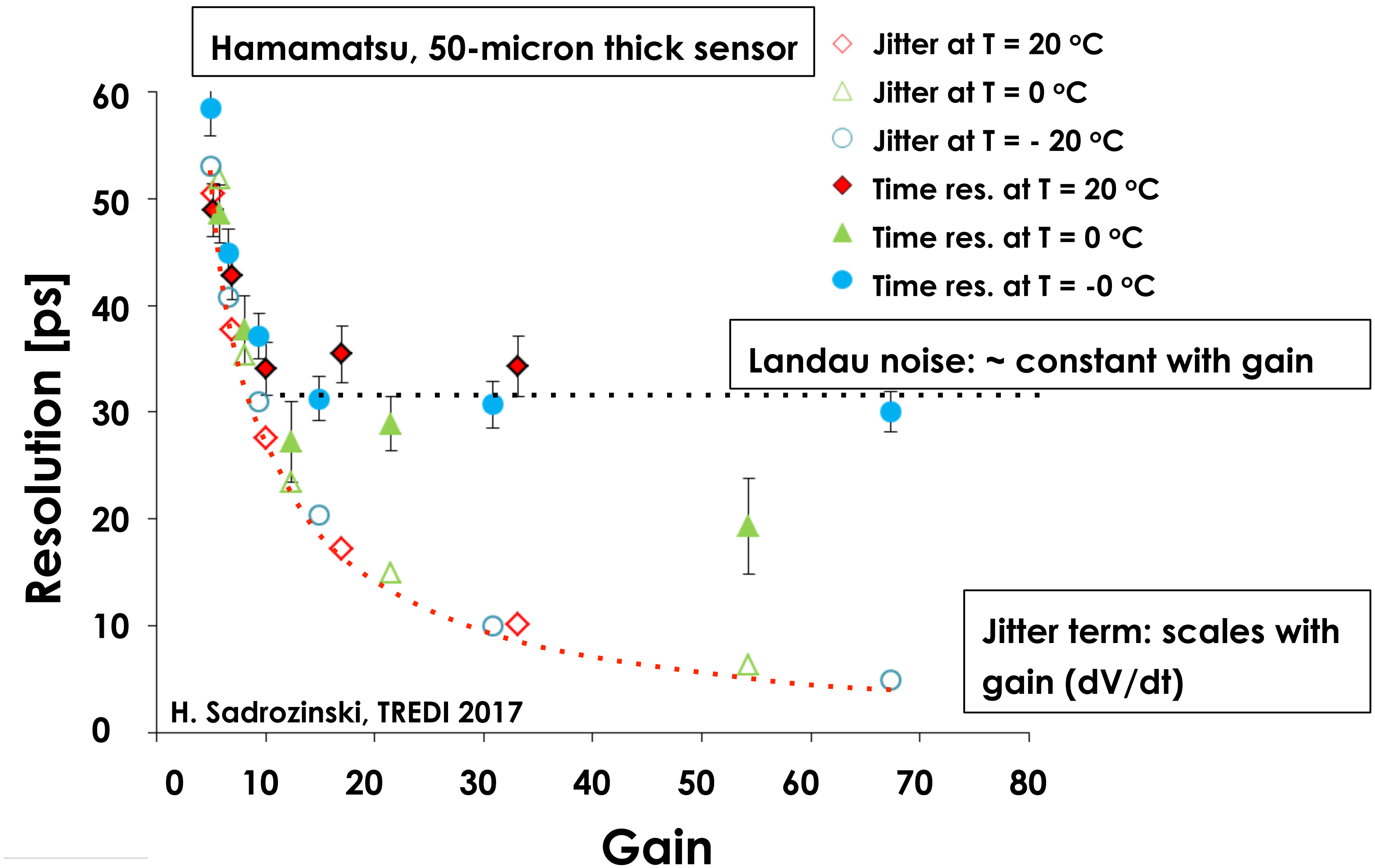
The game changer is the introduction by CNM of the **LGAD** idea:

- Add a thin layer of doping to produce low controlled multiplication.
- This idea retains almost (segmentation) the benefit of standard silicon sensors
- **UFSD:** LGAD sensors, optimized for timing

Runner up: **3D trench detectors**.

Deep trench - 200 micron -, closed by in space – 50 micron apart, meet the above requirements.

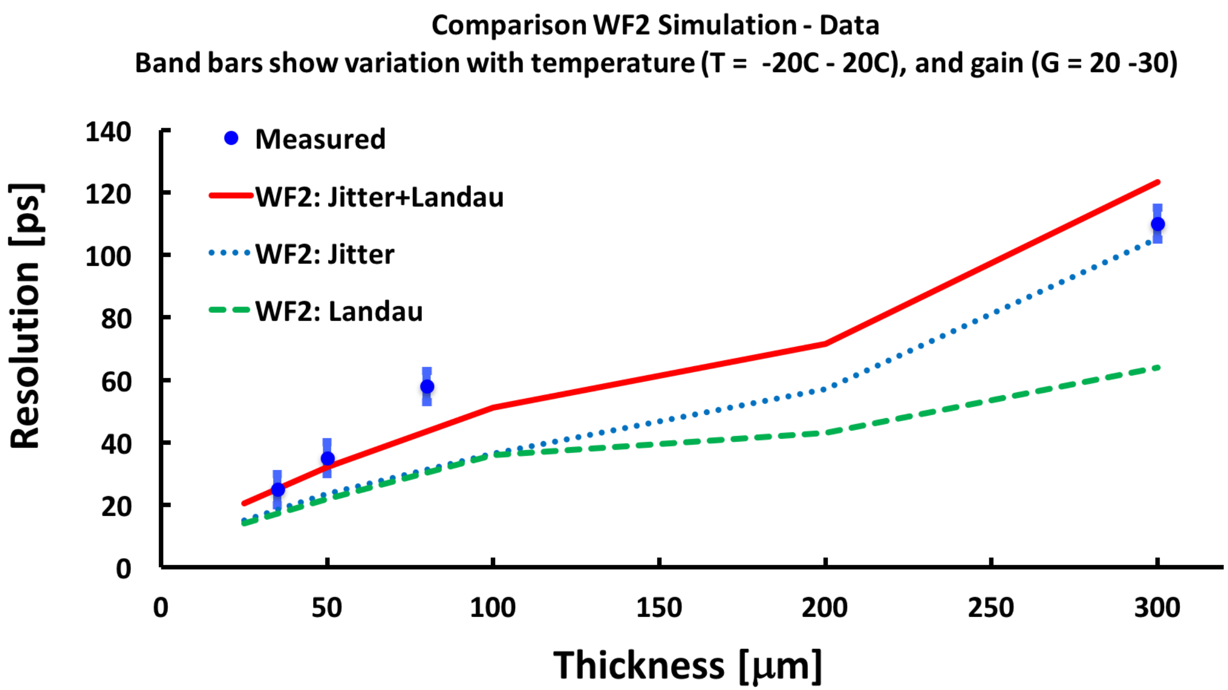
LGAD: Low Gain, what does it mean?



The time resolution is determined by charge non-uniformity

The working point is determined by the interplay with the electronics

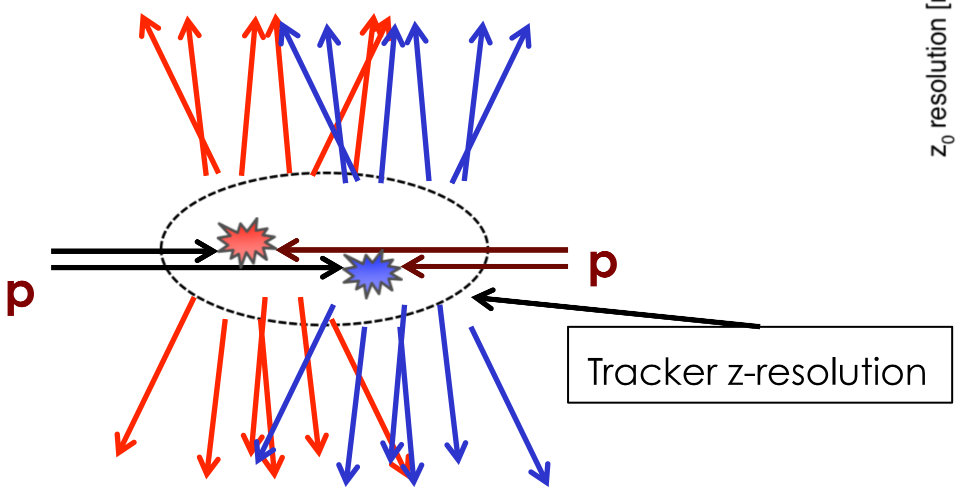
UFSD performances

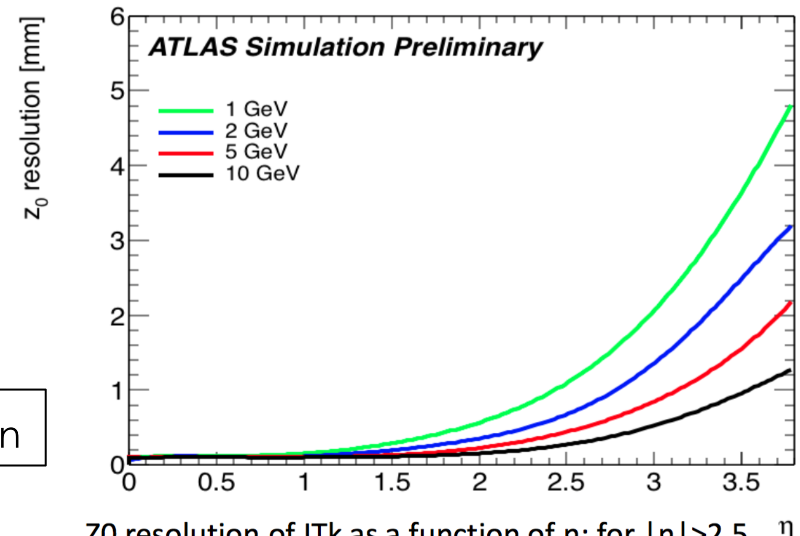


Thin sensors provide better resolution and better radiation performances.

Timing layers: the metric of the problem at HL-LHC

The problem arises when the tracking detector resolution along the z-axis is longer than the distance between vertices.





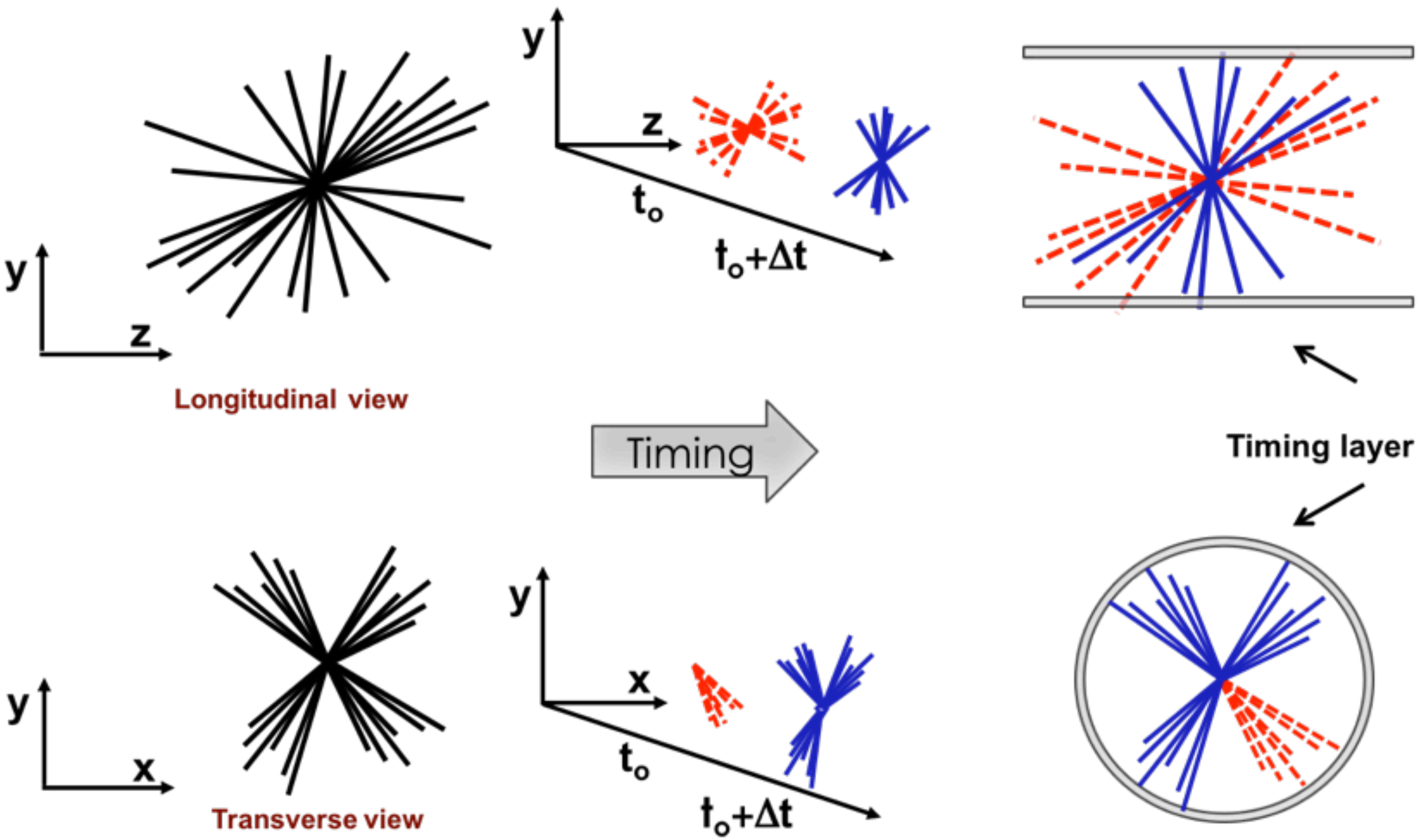
Z0 resolution of ITk as a function of η: for |η|>2.5 resolution increasing above the average vertex density (1.6vertex/mm).

Track-to-vertex association is ambiguous when the tracking z-resolution is larger than the separation between vertices

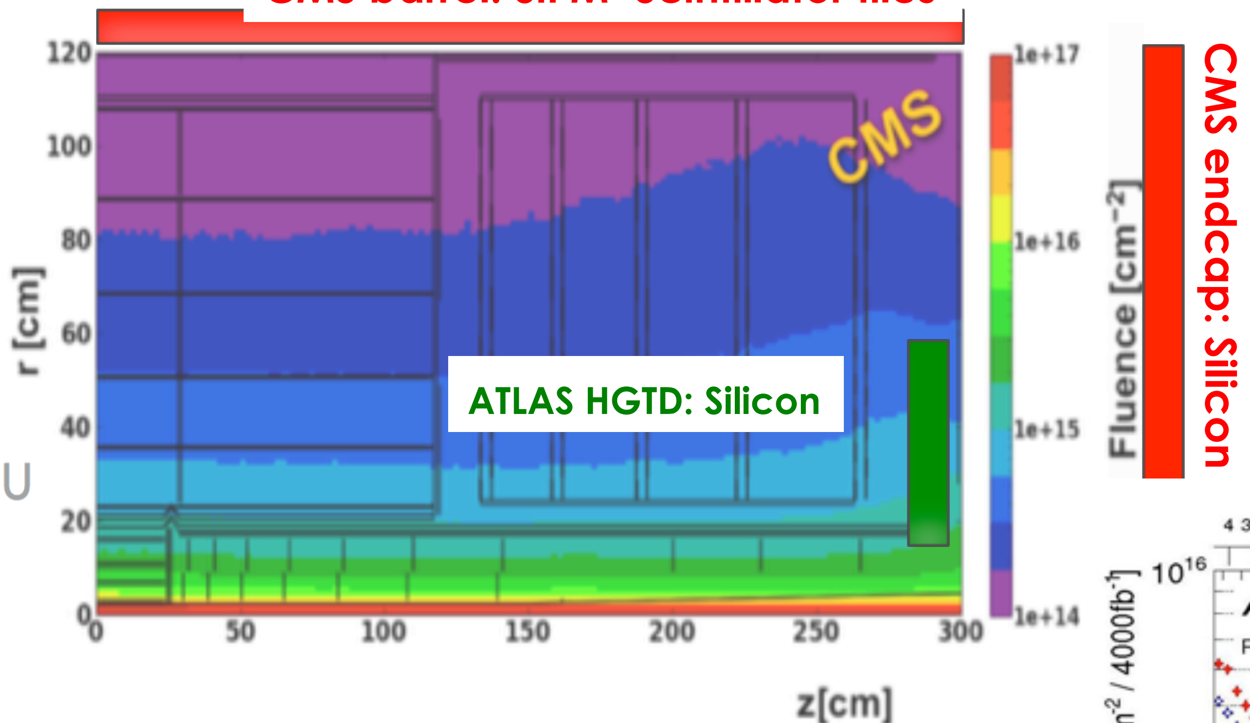
For ATLAS & CMS the target resolution is ~ 30-40 ps

Timing layers: how they work

Timing layers provide a measurement of the time of a track
(most likely they won't have a key role in tracking)



Technologies and Radiation levels



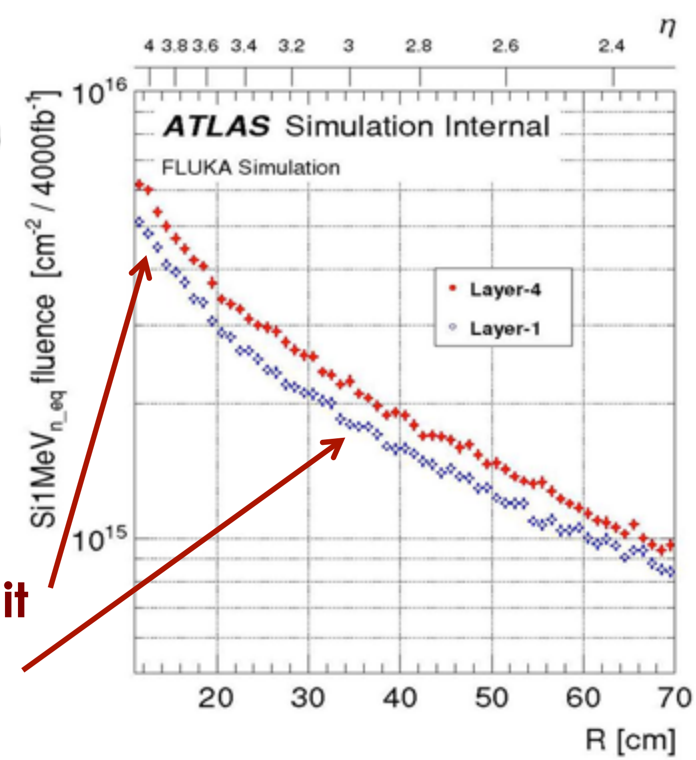
Limits (with x2 safety margin):

ATLAS: ~ 9e15 n/cm2

➔ Replace inner layer after 4.5e15 n/cm2

CMS~ 3e15 n/cm2

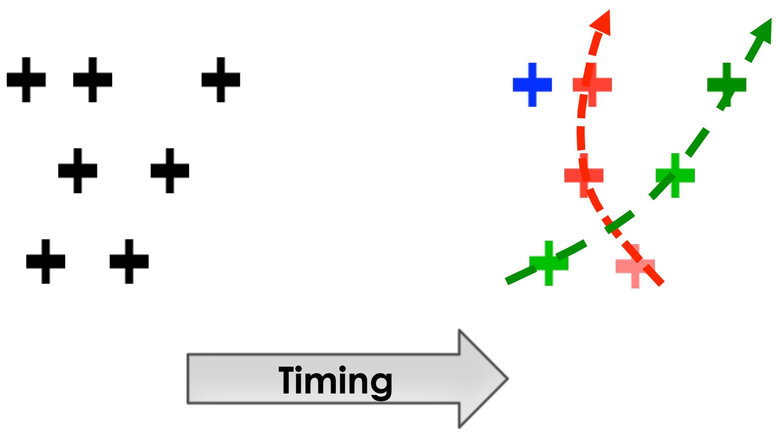
CMS~ATLAS, Almost the same number…



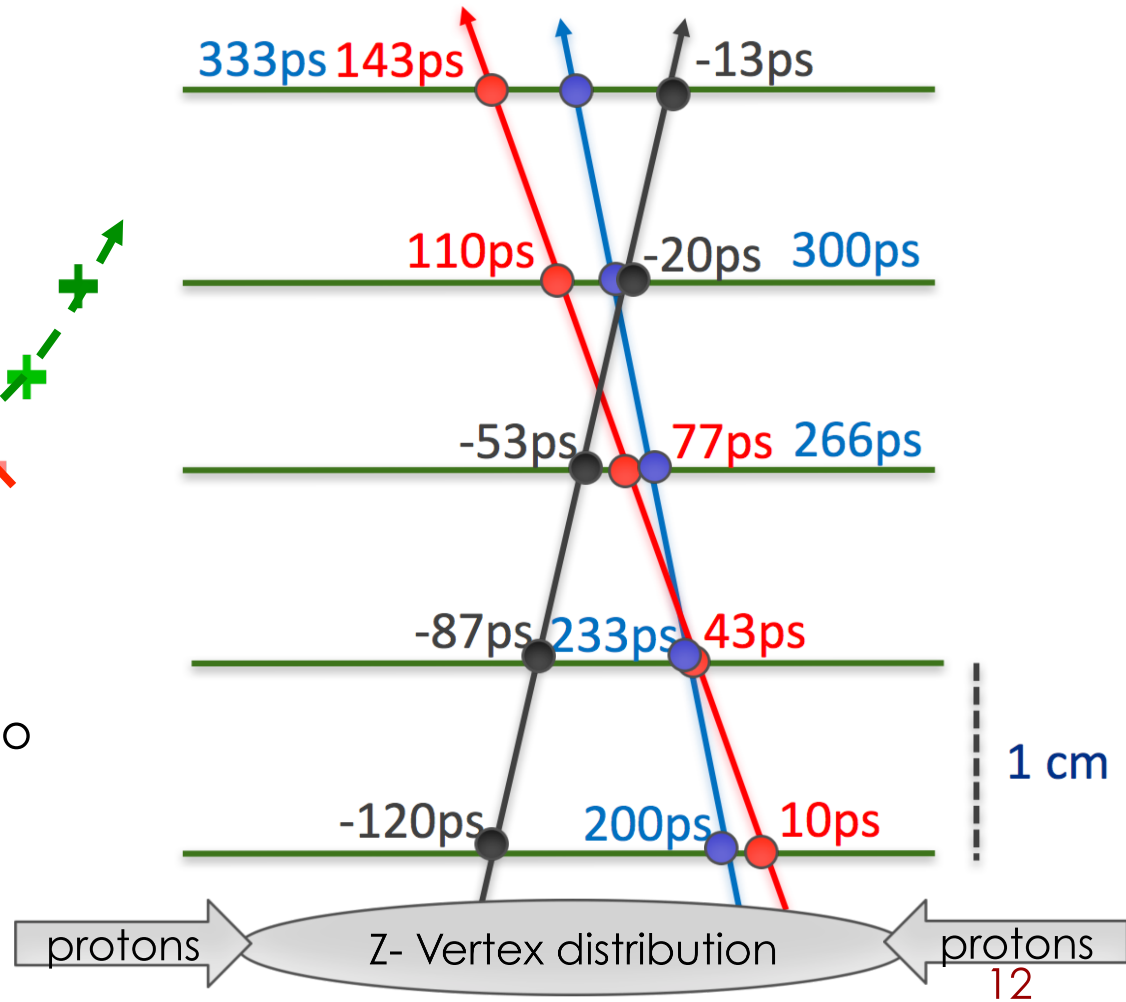
4D tracking: timing at each point along the track

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

➔ Use only "time compatible points"



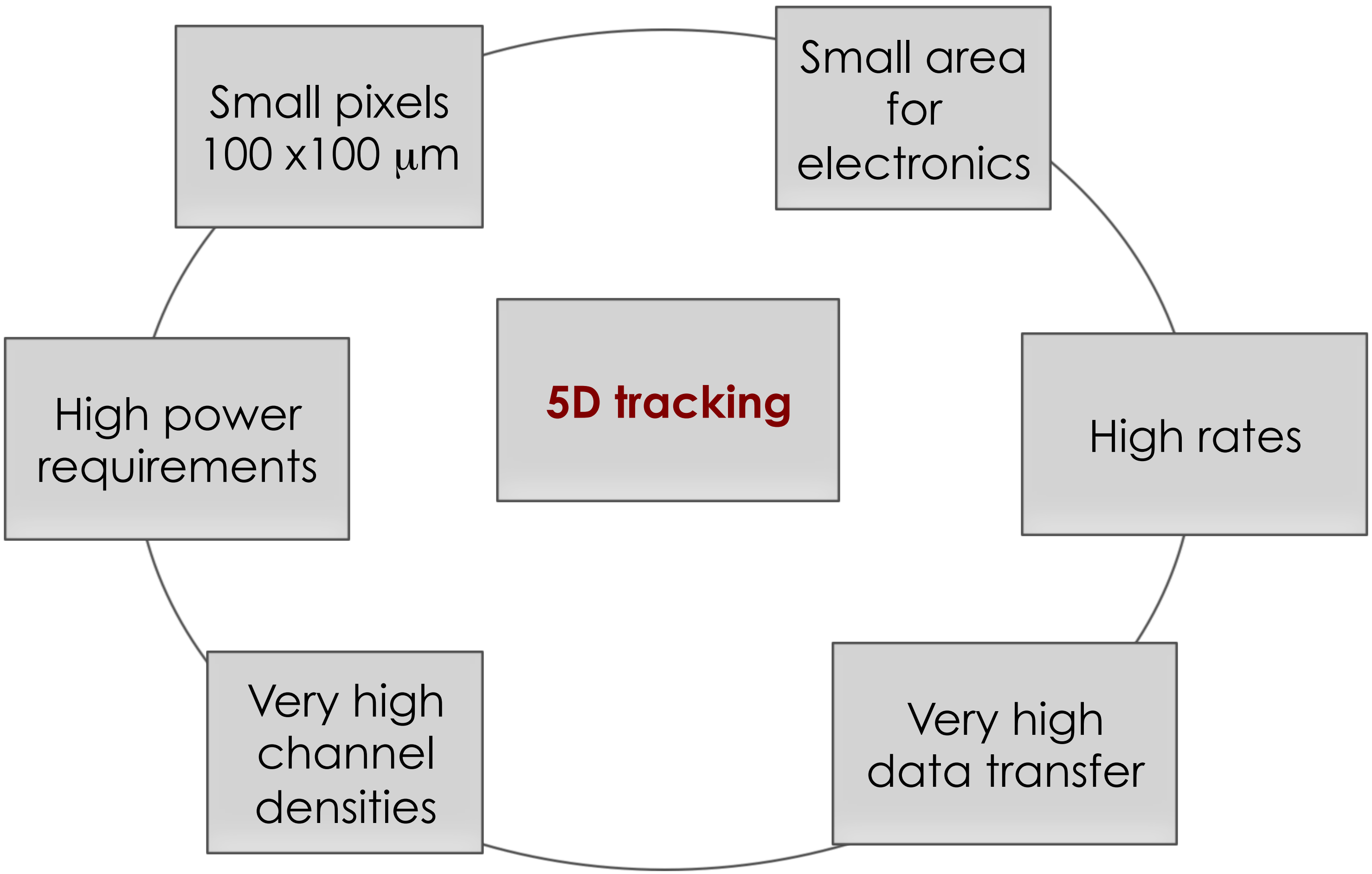
Present hypothetical LHCb Velo upgrade precision: ~ 100ps



5D-tracking: space-time at high rate

Imagine tracking with ~ 1000-2000 tracks @ 40 MHz crossing

This situation is the pinnacle of complications..



5D tracking: sensors and electronics

Let's consider a normal size pixel: 100 x 100 micron

1) Can we produce a sensor with small pixel and high fill factor?

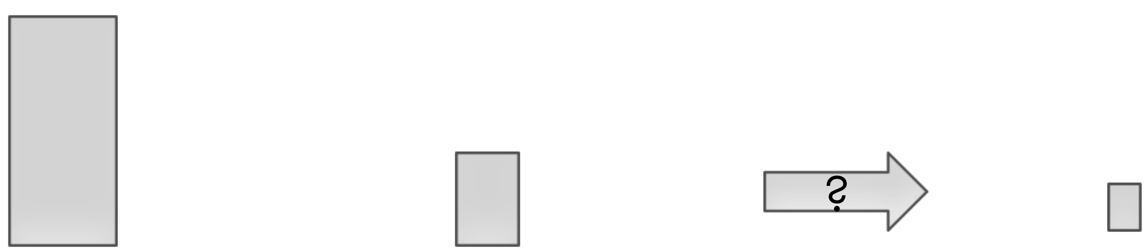
What is the "right sensor for the job?"

2) Can we fit the electronics?

➔ the preamplifier does not scale with the technological node,

➔ memory and TDC do.

Example: TDC evolution



130 nm:
70 x 150 micron

65 nm:
40 x 60 micron

28 nm:
~20 x 30 micron

5D tracking requires either 65nm or 28nm electronics

5D tracking: read-out and algorithms

Power is nothing without control

Let's suppose we have the sensors and the read-out chip:

➔ our job might be over

➔ lot's of other people need to work hard…

Taking advantage of 5D tracking requires a very complex backend:

Very fast data transfer

Real-time tracking requires the development of specific 4D tracking algorithms.

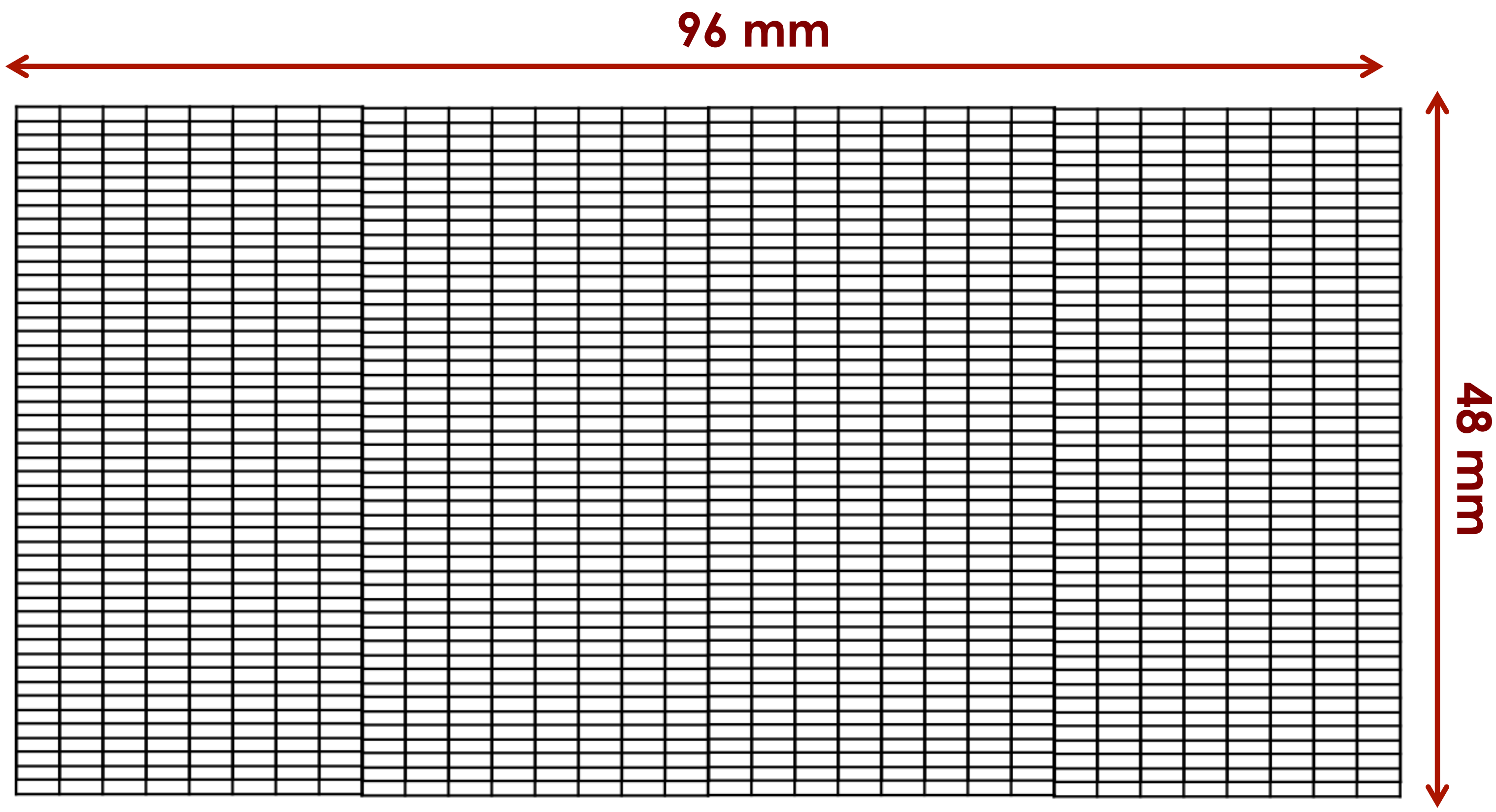
➔ Sometimes called "retina", being pursued by several groups.

CMS Sensors

Final Goal:

- CMS needs to produce 2624 sensors; each sensor is 48 x 96 mm^2, it has 1536 pads,
- Each pad is 1x3 mm^2

2624 X

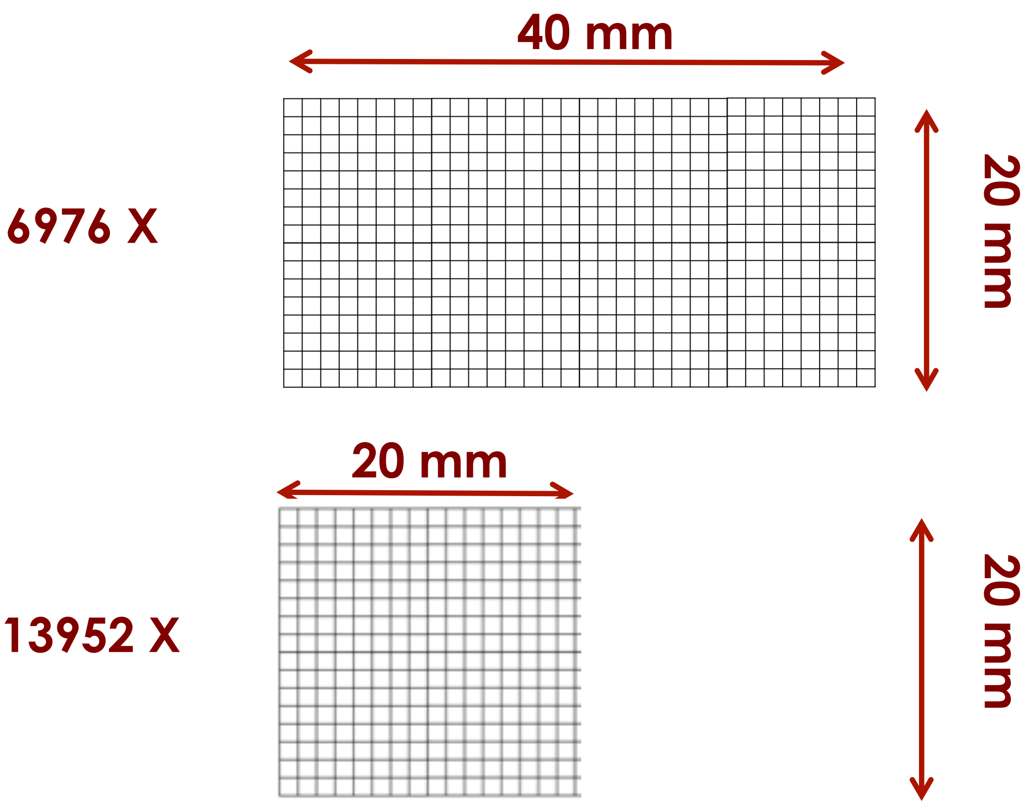


plus spares..

ATLAS Sensors

Final Goal:

- ATLAS needs to produce, assuming 2 layers, 13952 sensors 2x2 cm^2 (240 pads) or 6.976 sensors 2x4 cm^2 (480 pads)
- each pad is 1.3 x1. 3 mm^2



plus spares..

ATLAS-CMS path to construction

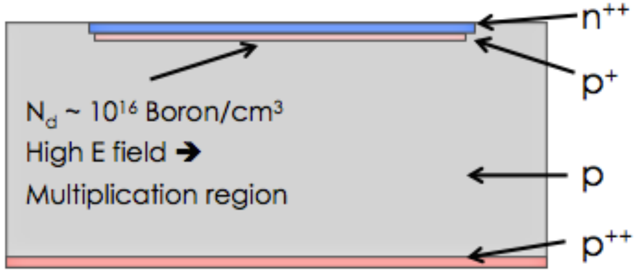
Nicolo Cartiglia, INFN, Torino HSTD11 - 11 Dec 2017

Key topics to be addressed:

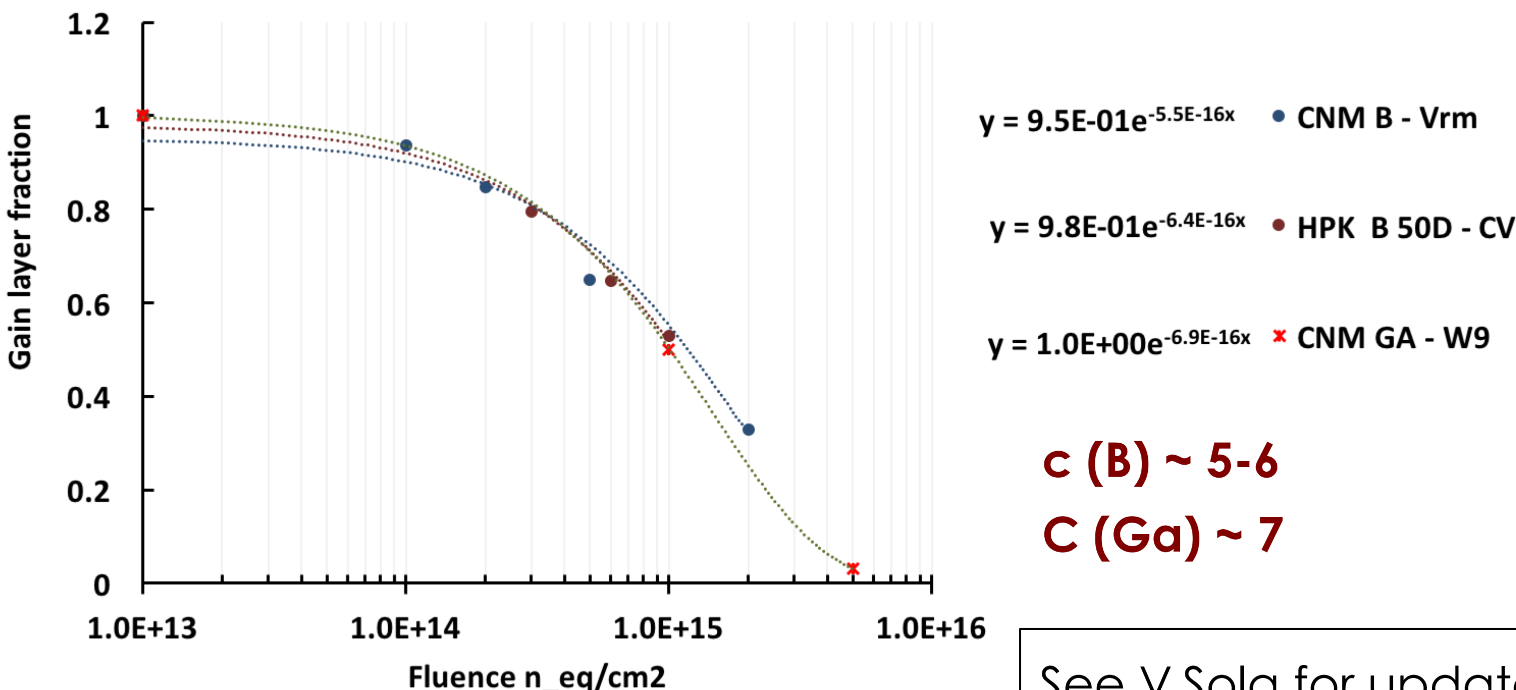
1. **Radiation hardness**: time resolution and operating conditions
   - Spoiler: the situation looks reasonable
2. **Highest possible fill factor:** dead area between pads
3. **Multi pad sensors:** pad isolation, breakdown voltage
4. **Large area:** yield, cost
5. **~ 30 ps time resolution at the end of HL_LHC lifetime**
   - 35-micron thick option
     - Looks reasonable, it is a "read-out chip" problem

Radiation resistance

Radiation changes the doping level of the device, so it changes the way the devices work



$$N(\phi) = N(0)e^{c\phi}$$



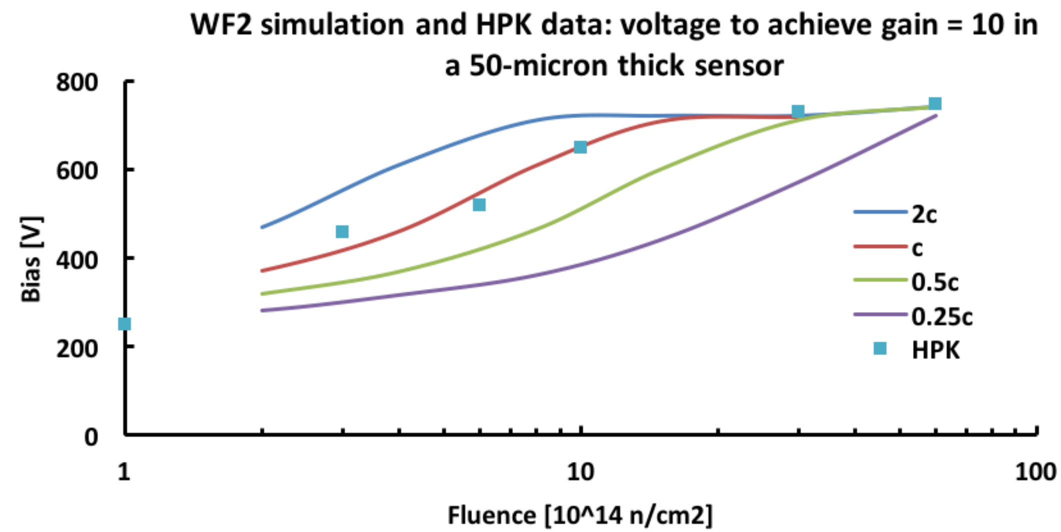
c (B) ~ 5-6

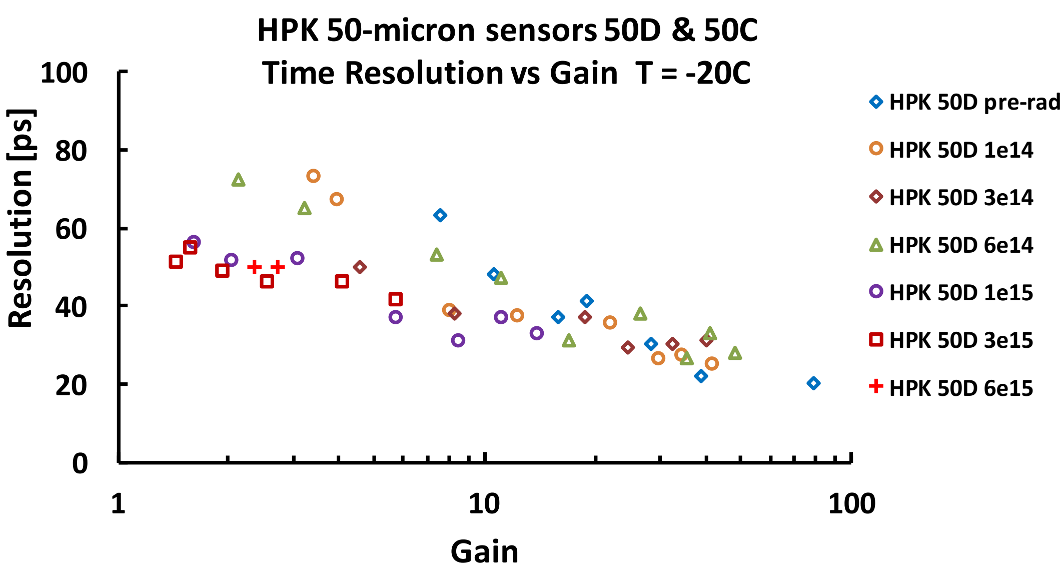
C (Ga) ~ 7

See V.Sola for update

Consequences of radiation damage

Increase bias to compensate doping loss



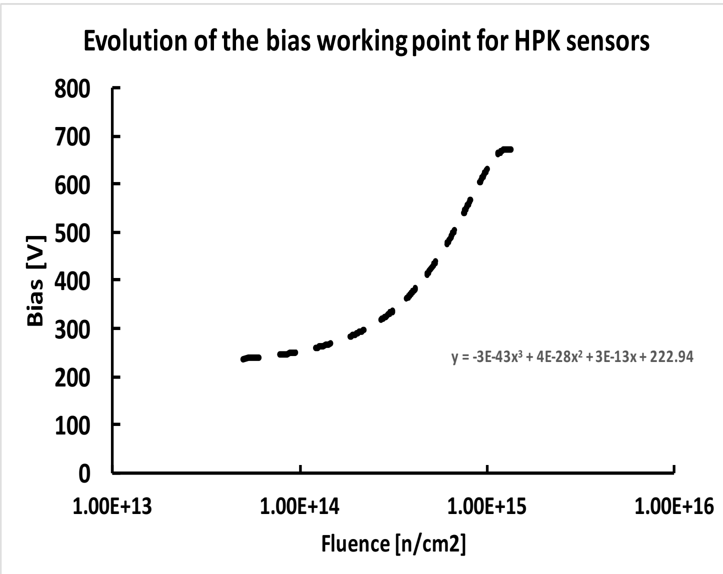


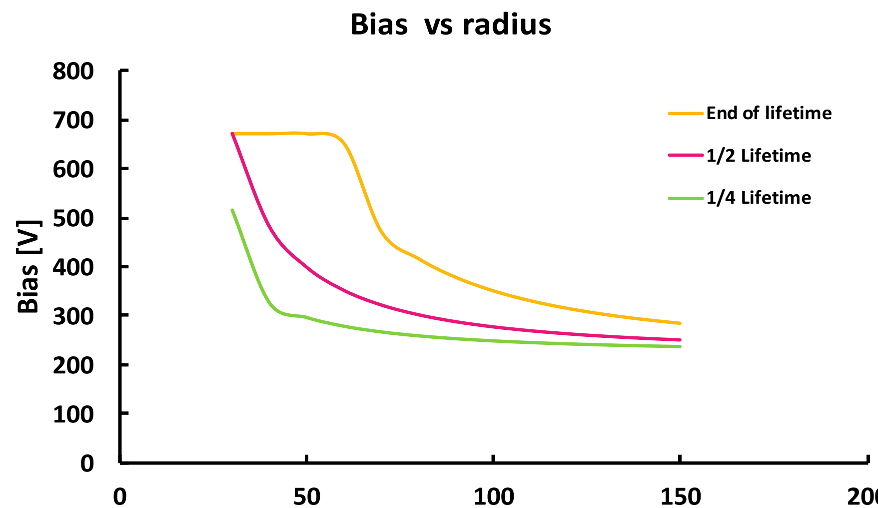
Good time resolution up to 3(6)e15 n/cm2

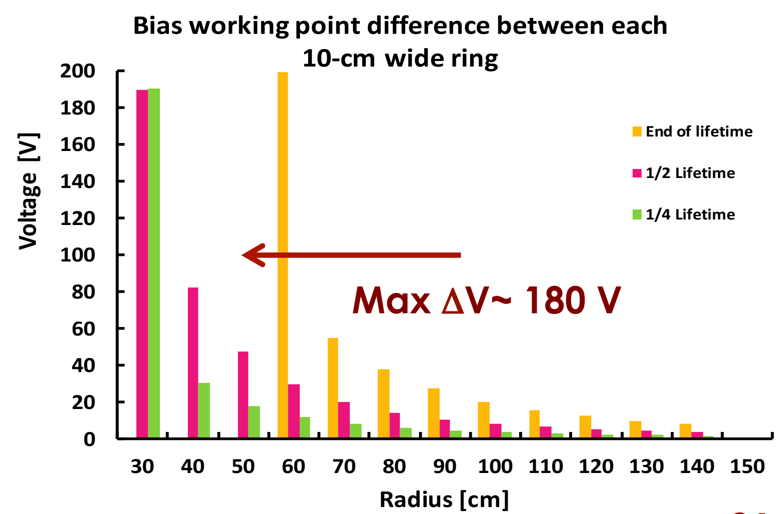
Radiation hardness: operating conditions

To keep the gain ~ constant (to keep the time resolution high) ➞ increase Vbias

Operating conditions should be adjusted as a function of fluence







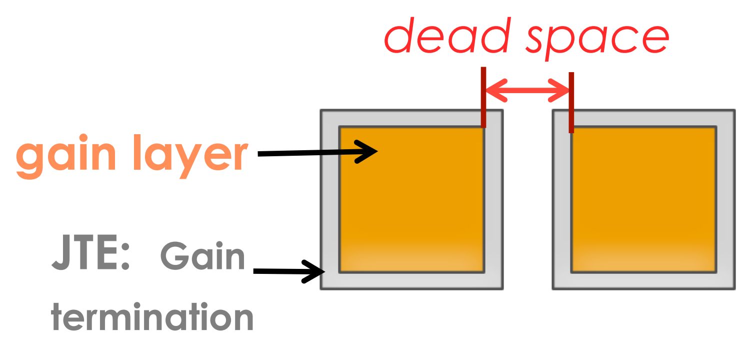
➔ the ideal biasing point differs by ~ 180V at the two side of a 10-cm long detector.

Highest possible fill factor

The fill factor is mainly determined by the inactive gap between sensors.

Current measured gap size:

- ~ 70 micron for CNM
- ~ 100 micron for HPK
- ~ 70 micron for FBK



This gap affects directly the detector acceptance as we (CMS) have only one layers

Goal: 30 micron gap = 96% fill factor

Currently under study, looks possible…

Reduction of gap between pads

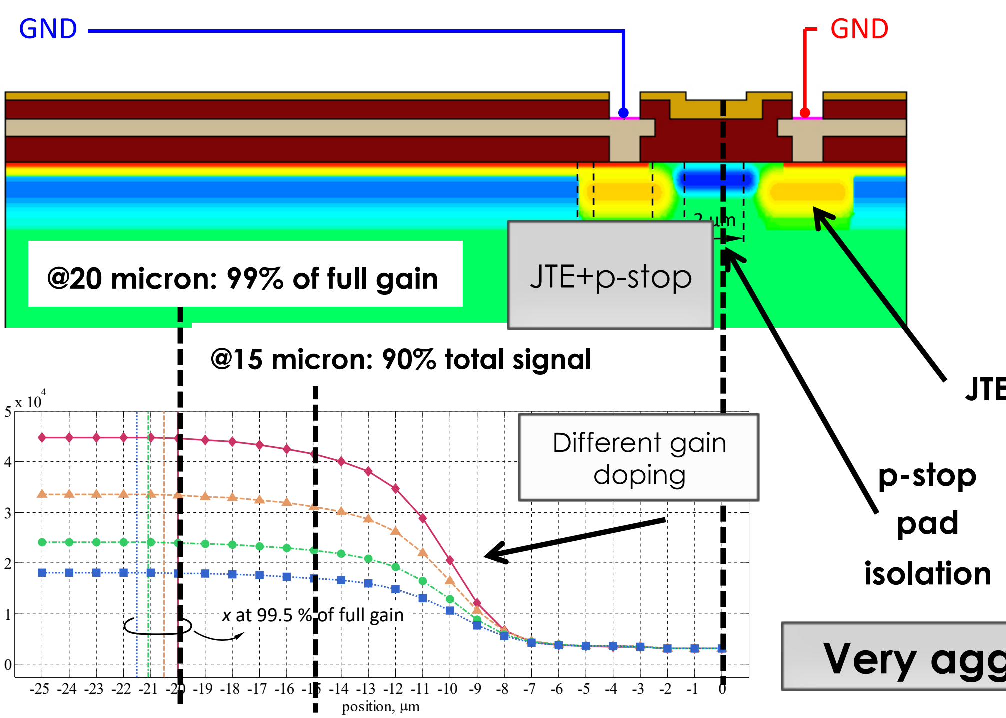
The gap is due to **two components**:

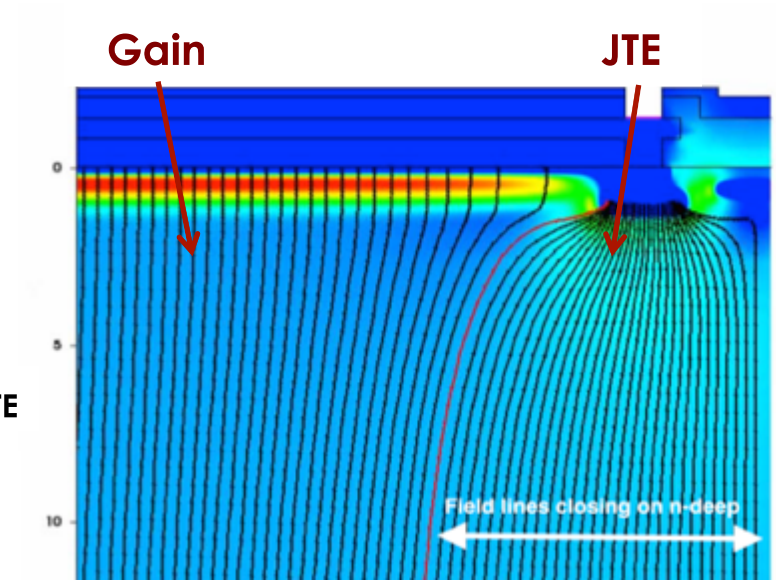
1) Adjacent gain layers need to be isolated (**JTE & p-stop**)

2) Bending of the E field lines in the region around the JTE area

Both under optimization   Different junction termination/p-stop design

- ➢ **CMS Goal: 30 micron gap = 96% fill factor**





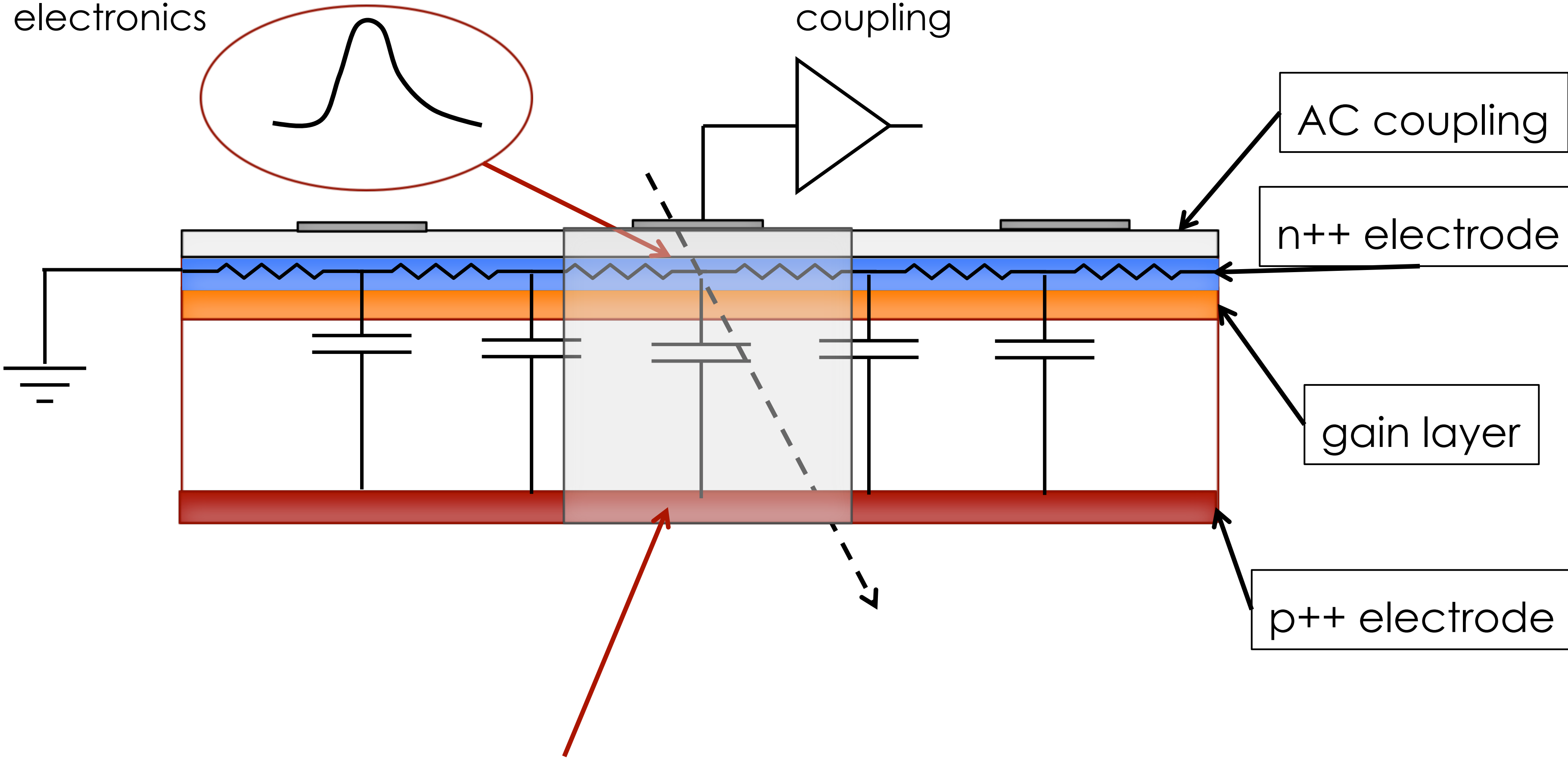
Very aggressive design: <10 micron per side

100% fill factor: AC-UFSD

The signal is frozen on the resistive sheet, and it's AC coupled to the electronics

➔ E and E_w fields are very regular

➔Segmentation is achieved via AC coupling



The AC read-out sees only a small part of the sensor:

small capacitance and small leakage current.

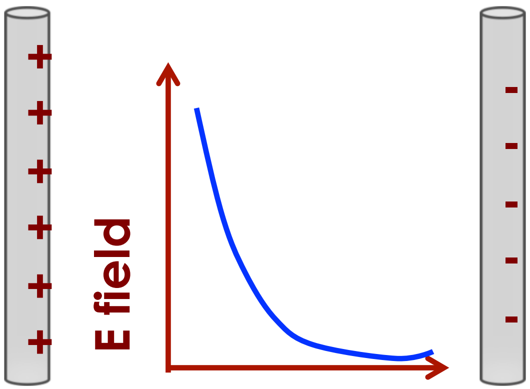
3D sensors for timing applications

3D sensors enjoy good performance even at fluences $\phi \sim 10^{16}$ n/cm^2

Can they be used in 4D-tracking?

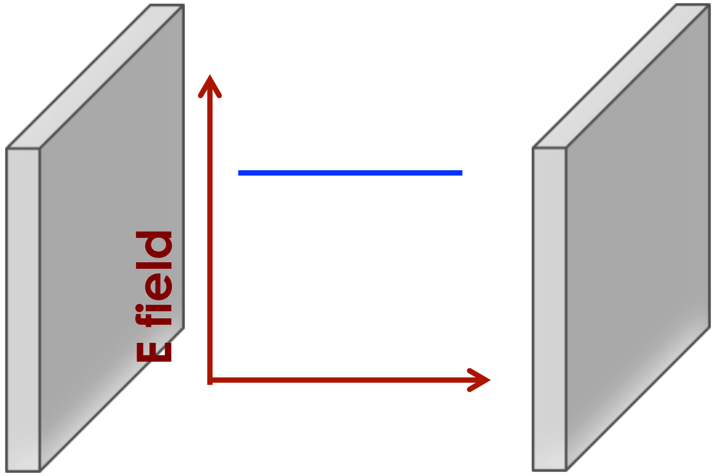
Can diamond 3D work?

In their "column" geometry, they cannot, the Efield is not uniform enough



However, using trenches gives a parallel plate geometry, and a weighting field ~ 1/d

➔ Insensitive to non-uniform charge deposition **GOOD!**

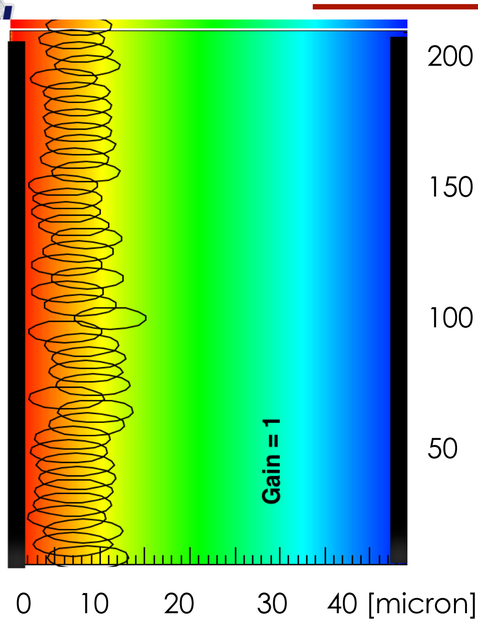


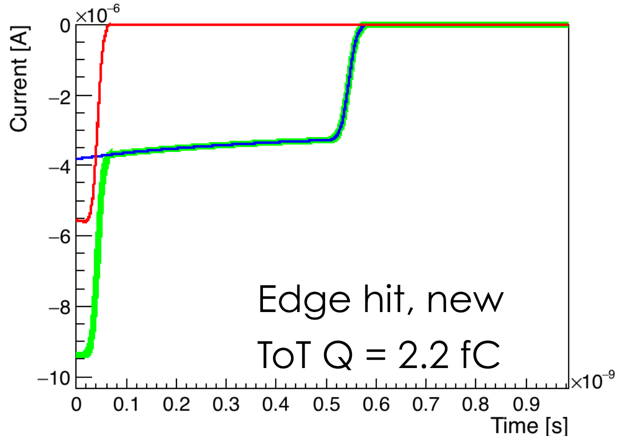
Challenges:

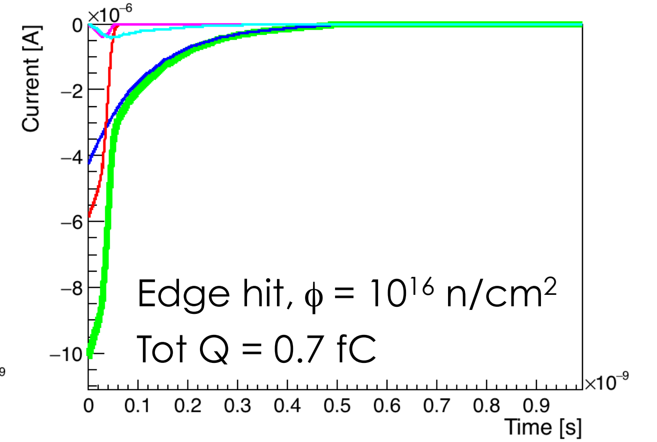
- Position dependent current shape
- Strong signal reduction with irradiation

Pulse shape in 3D – trench detectors

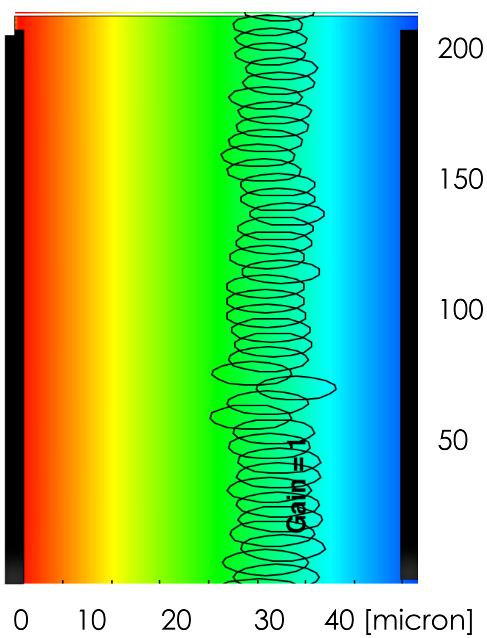
Assume: 3D silicon, 50 micron separation, 200 micron thick

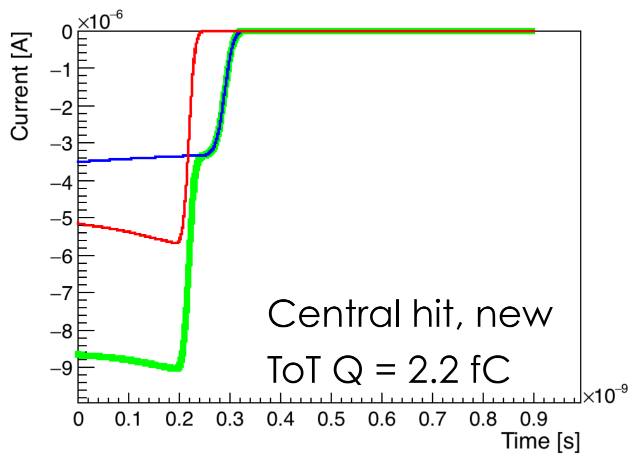


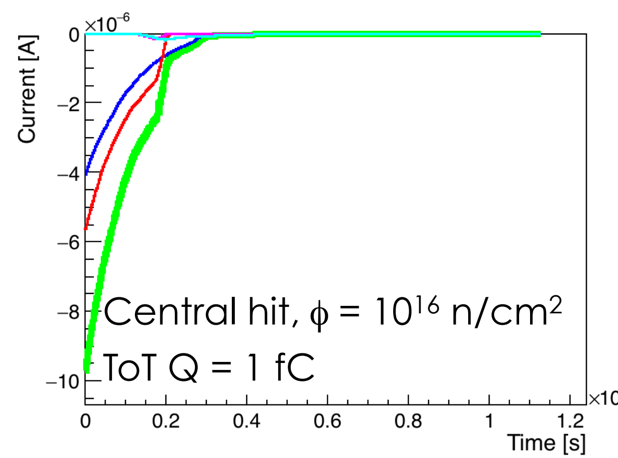




Different signal length







Very challenging, similar to UFSD @ ϕ = 5 10^{15} n/cm^2

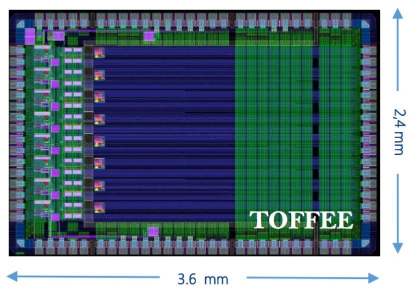
Two examples of UFSD and read-out chips

Single pad + TOFFEE

Multipad + TDCPix

TOFFEE: a chip for timing applications

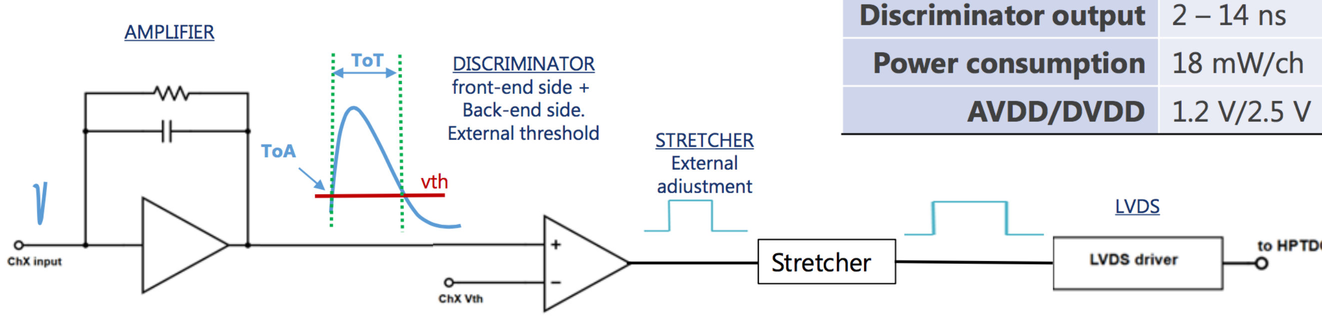
INPUTS



LVDS OUTPUTS

Technology	CMOS 110 nm
Channels	8
Sensor capacitance	2-10 pF
Input dynamic range	3 fC – 60 fC
Analog gain	7 mV/fC
GBW	14 GHz
RMS noise (C=6pF)	800 μV
Discriminator output	2 – 14 ns
Power consumption	18 mW/ch
AVDD/DVDD	1.2 V/2.5 V

The channel architecture

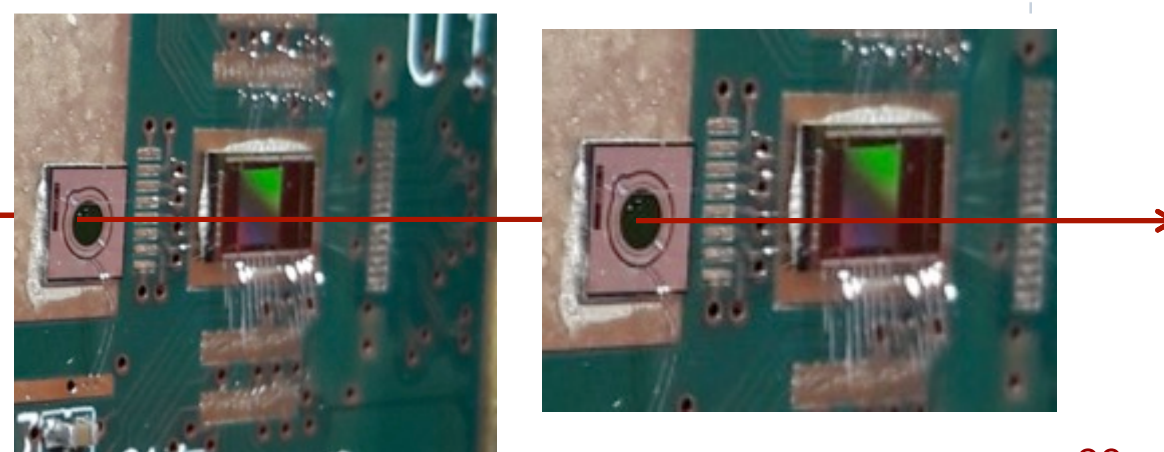


LVDS OUTPUT

The LVDS output is meant for time digitization with HPTDC (rising and falling edges). **A Strecher is required**.

Beam test at

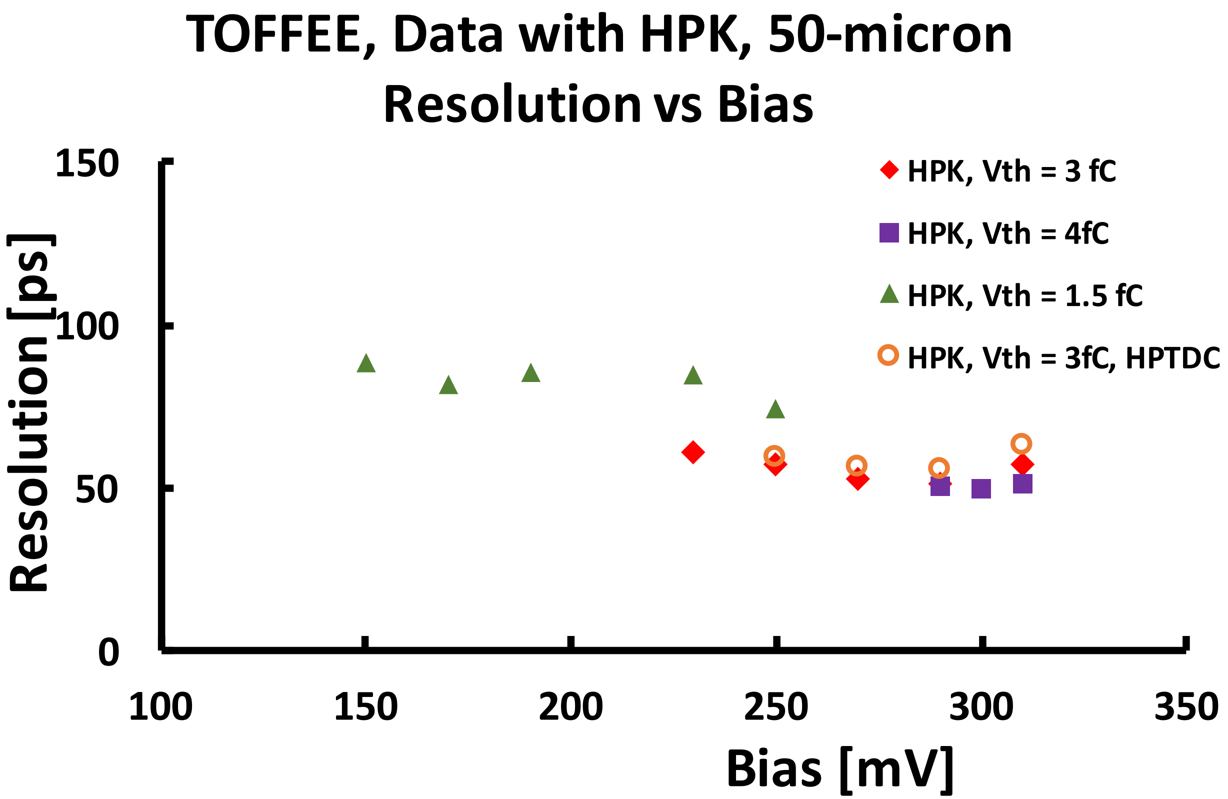
CERN north area



TOFFEE: beam test results

TOFFEE is the first version of a multipurpose 8-channel chip with Time-over-Threshold time-walk correction.

It achieves a resolution of 55 ps, including the digital part.

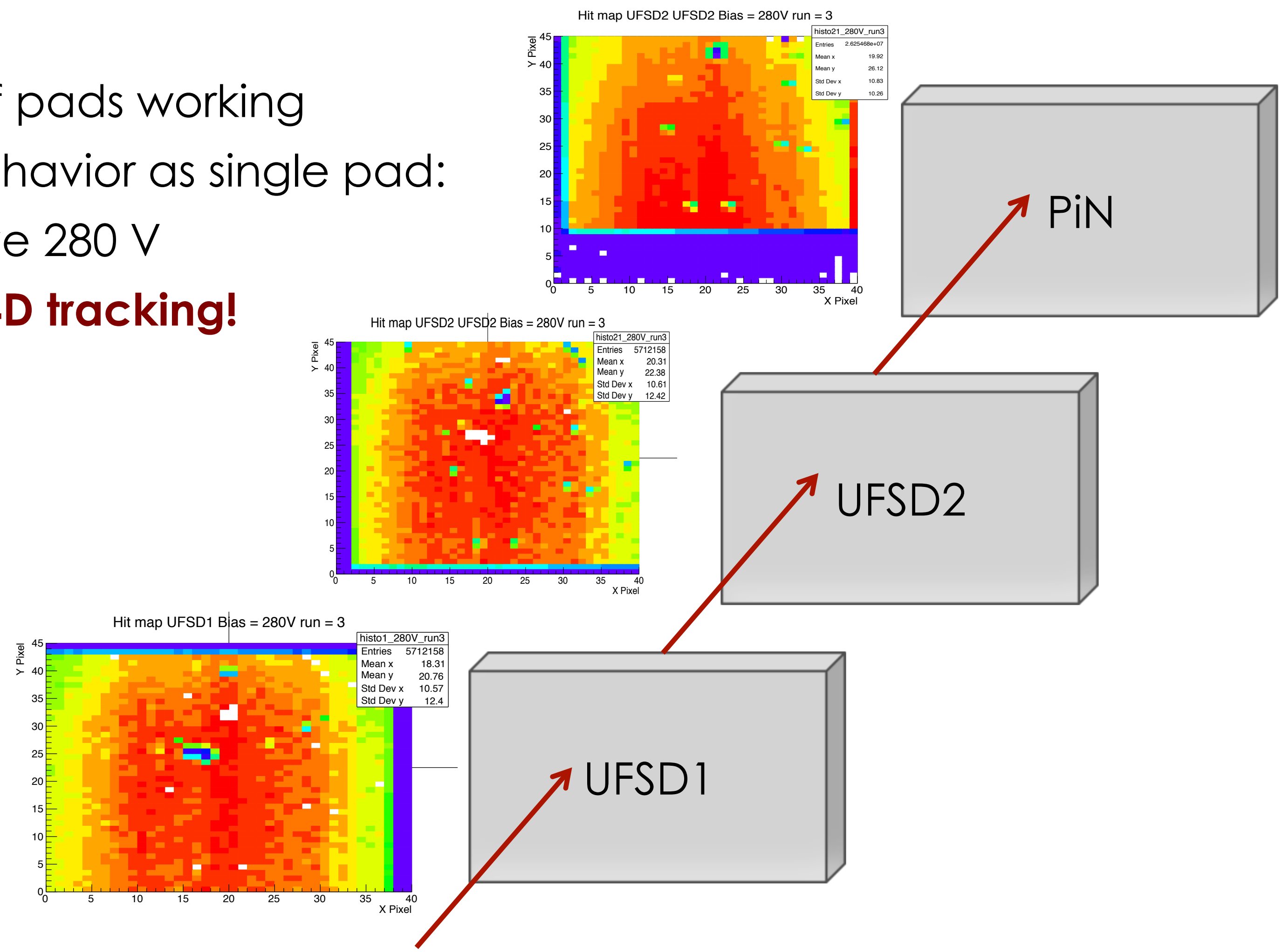


Multi-pad sensors: TDCpix & FBK-UFSD

Bump-bonded NA62 TDCpix ROC to FBK-UFSD sensor

NA62 ROC: 40x45 pads, each 300x300 μm^2 (1800 pads)

- More than 99% of pads working
- Same voltage behavior as single pad: breakdown above 280 V
- **First example of 4D tracking!**



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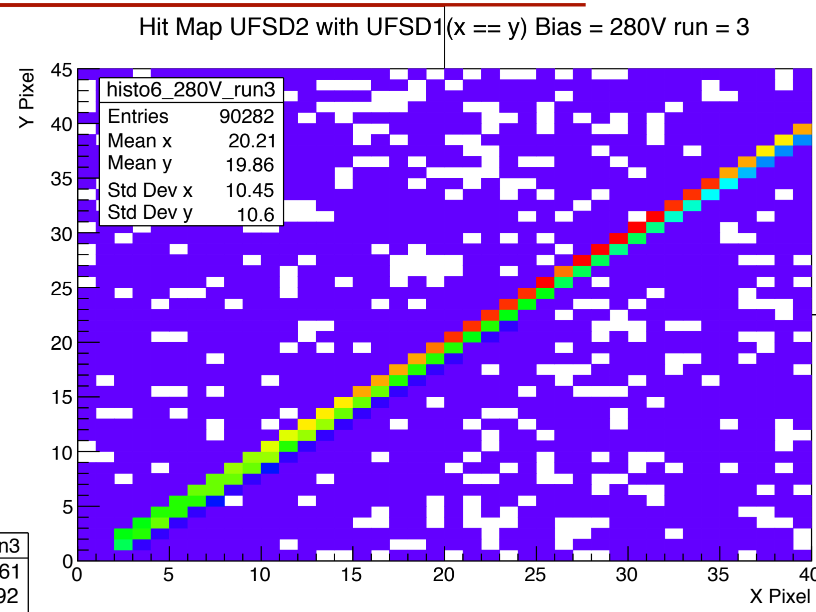
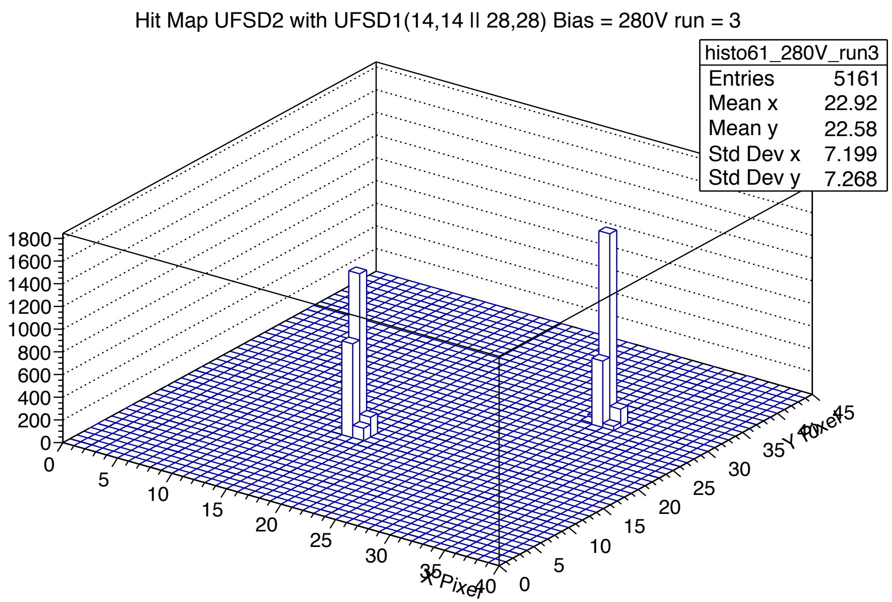
TDCPix & UFSD

Hit map on UFSD2 requiring x=y on UFSD1





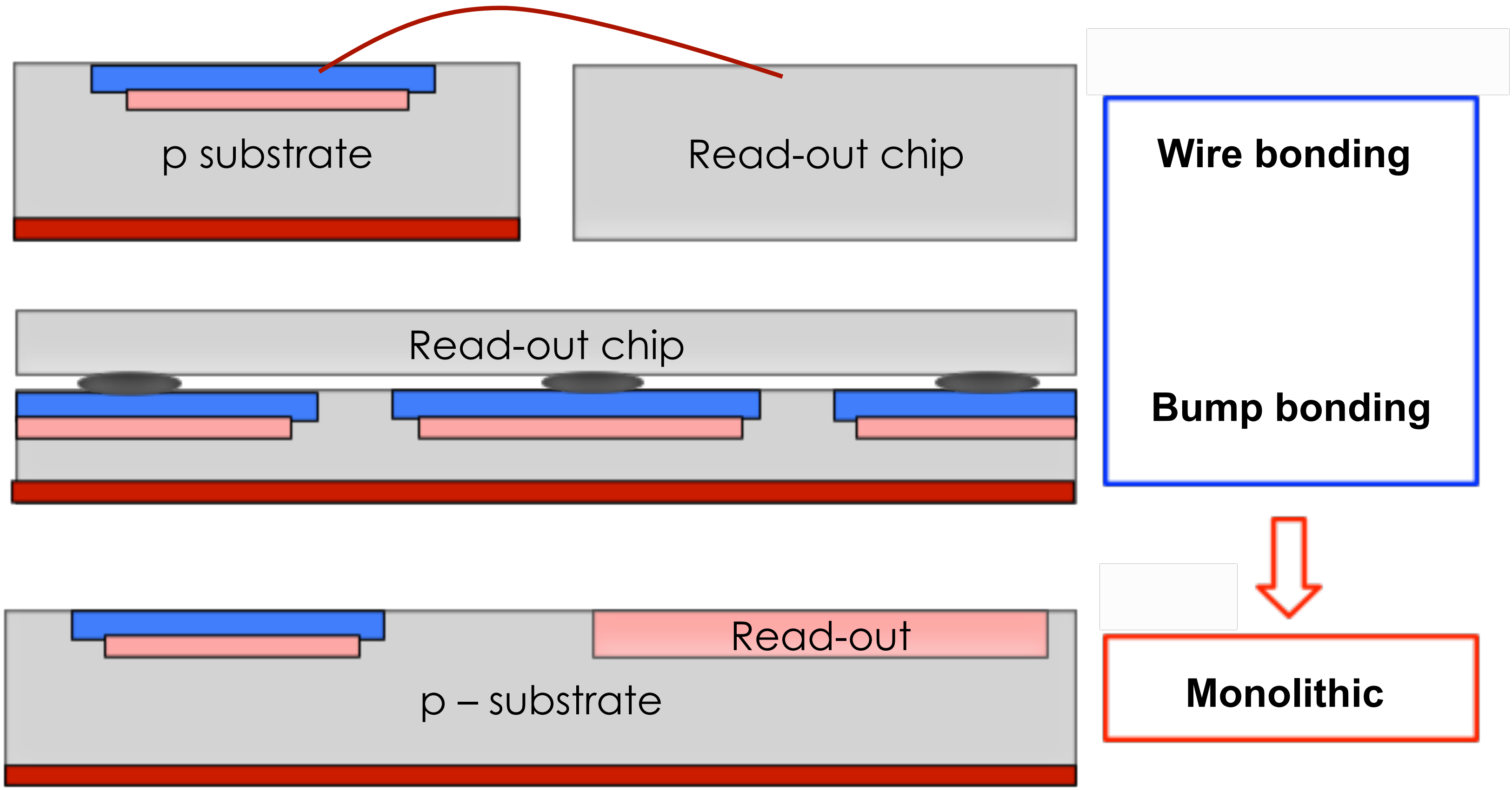
Hit map on UFSD2 requiring

x=y=14 || x=y=28

on UFSD1

We see sharp and clear correlations, no cross talk at the sensor level

R&D: Can we use Monolithic technology?



Summary and outlook

Timing layers, 4D- and 5D- tracking are being developed for the next generation of experiments

It is a challenging and beautiful developments, that requires a collective effort to succeed.

There is no "one technology fits all": depending on segmentation, precision, radiation levels and other factors the best solution changes.

It would be great if in our journey we stumble upon a highway, to take us out of the desert

Acknowledgement

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Part of this work was developed in the framework of the CERN RD50

The work is supported by HORIZON2020 Grants AIDA2020 and UFSD ERC grant UFSD669529

CMS timing layer

The CMS hermetic timing layer provides a diffuse improvement in many quantities, that allows higher analysis efficiencies.

- **Lepton isolation:** 60% improvement in background rejection for constant signal efficiency
- **B-tagging:** reduction of spurious secondary vertexes and decrease mis-identification
  - ➔ di-Higgs acceptance increases by ~ 20% (mostly barrel)
- **Pile-up jet**: 20% (barrel), 40% (endcap)
  - ➔ MET tails reduced by 40% for MET>150 GeV
- **Long lived particles:** possible only with hermetic timing layer

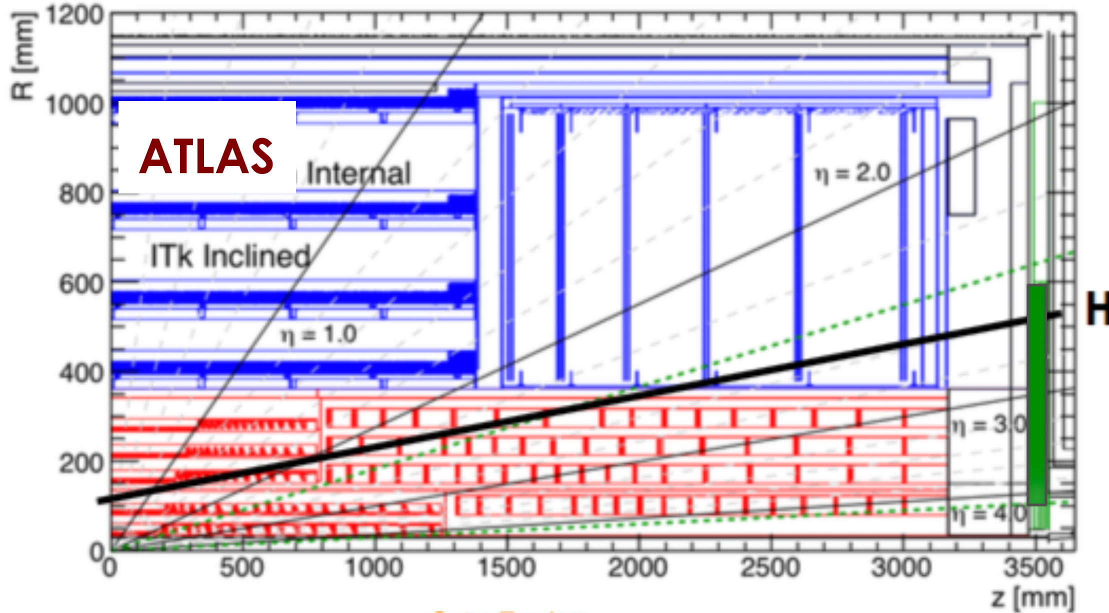
Sum of all effects:

Equivalent to an additional 2-3 years of HL-LHC running

Timing layers: ATLAS and CMS

ATLAS instruments the forward region,

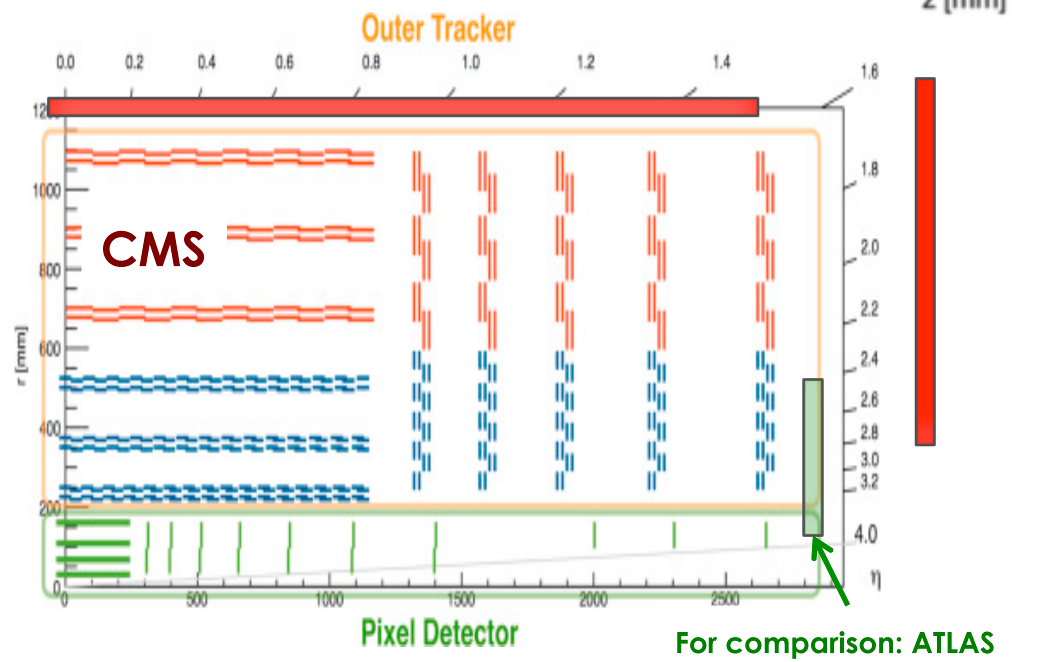
coverage: 2.4 < eta < 4



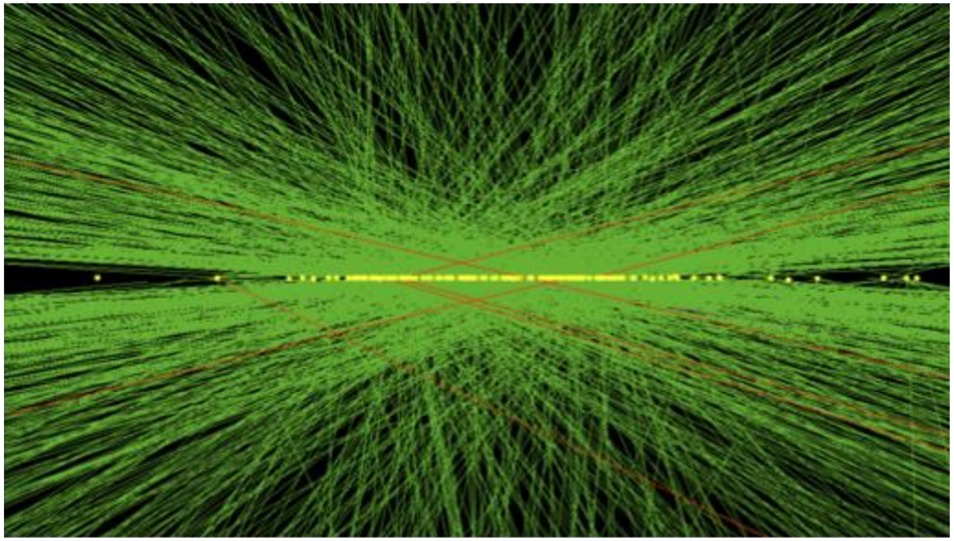
CMS instruments the central part:

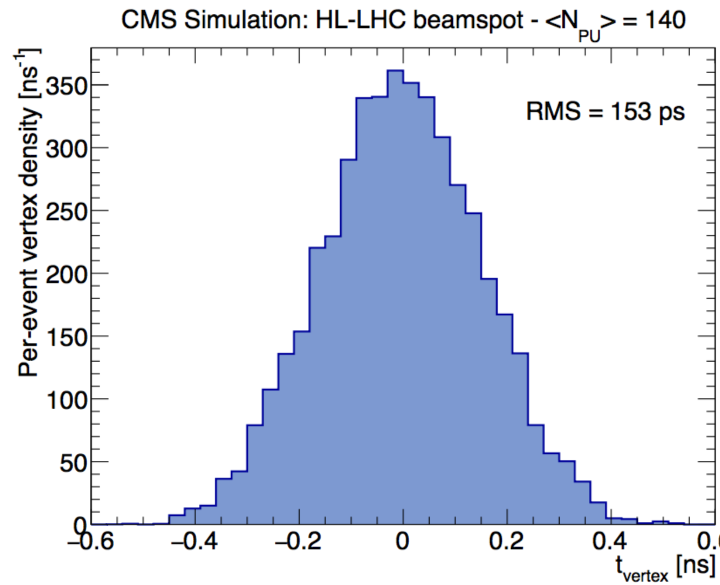
coverage: 0 < eta < 3

(MTD: Mip Timing Detector)



Vertexes in space and time in CMS & ATLAS





There are between 15-20% of tracking vertexes (longitudinal resolution ~ 200 micron) that are actually composed by 2 or more interaction

For ATLAS & CMS the target resolution is ~ 30-40 ps