High resolution timing with Silicon detectors

Is it possible to build a tracker with concurrent excellent time and position resolution?

Can we provide in one detector, or in combination
Timing resolution ~ 10 ps
Space resolution ~ 10's of μm

- Tracking in 4 Dimensions
- HL-LHC conditions
- CMS Barrel and Endcap detectors
- Review of Ultra-fast silicon detectors
- How to build a large detector

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.

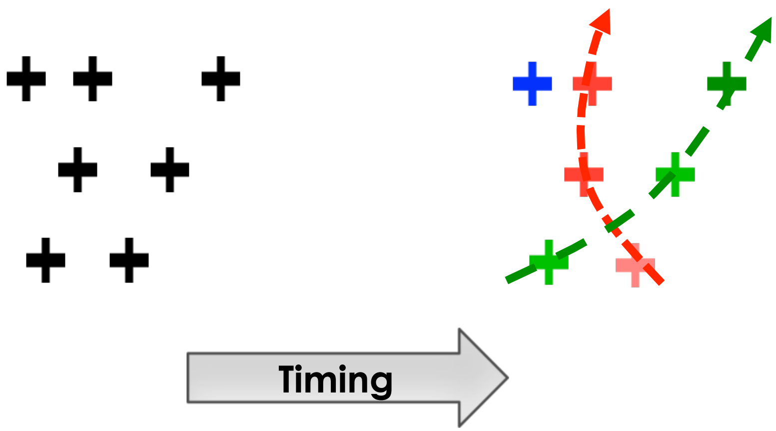
Timing can be available at different levels of the event reconstruction.

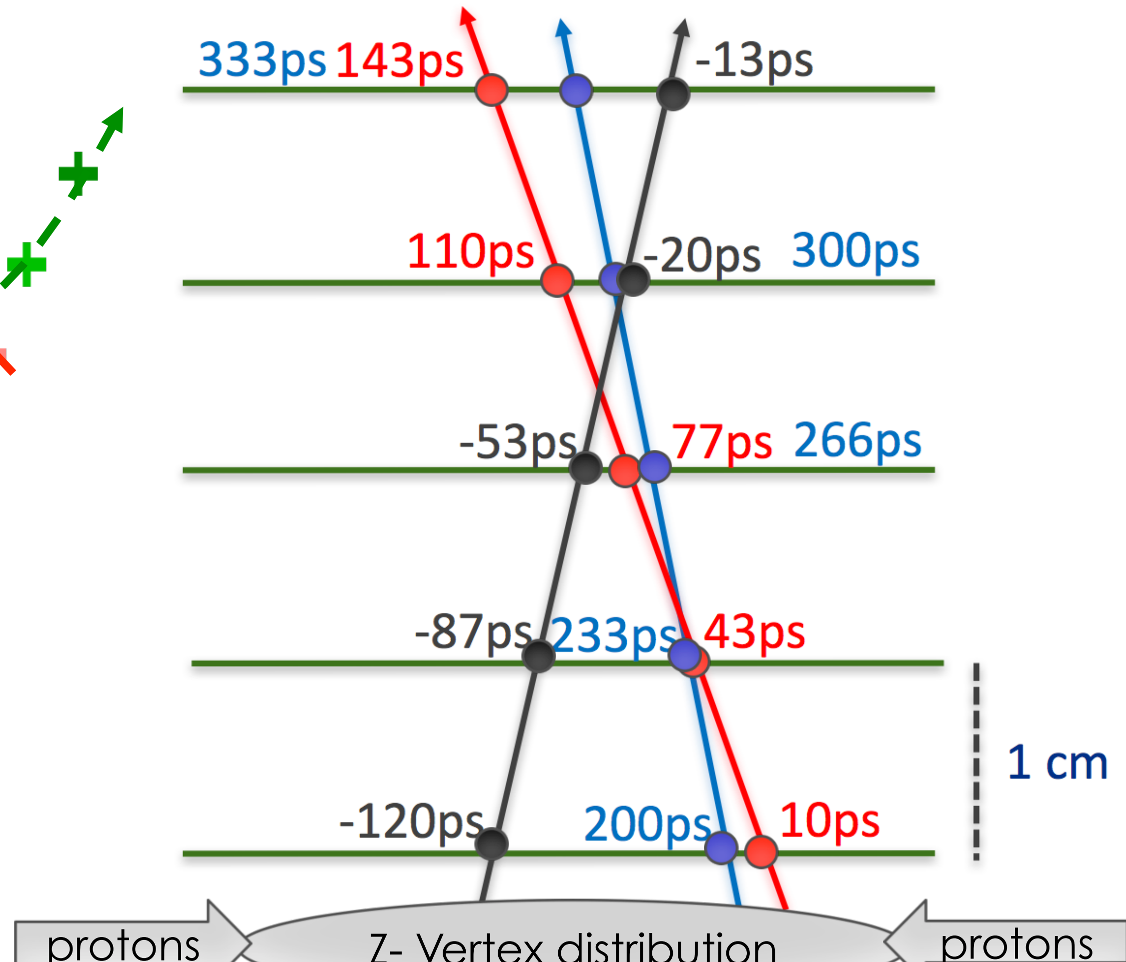
1) Timing at each point along the track
2) Timing in the event reconstruction
3) Timing at the trigger level

Timing at each point along the track

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

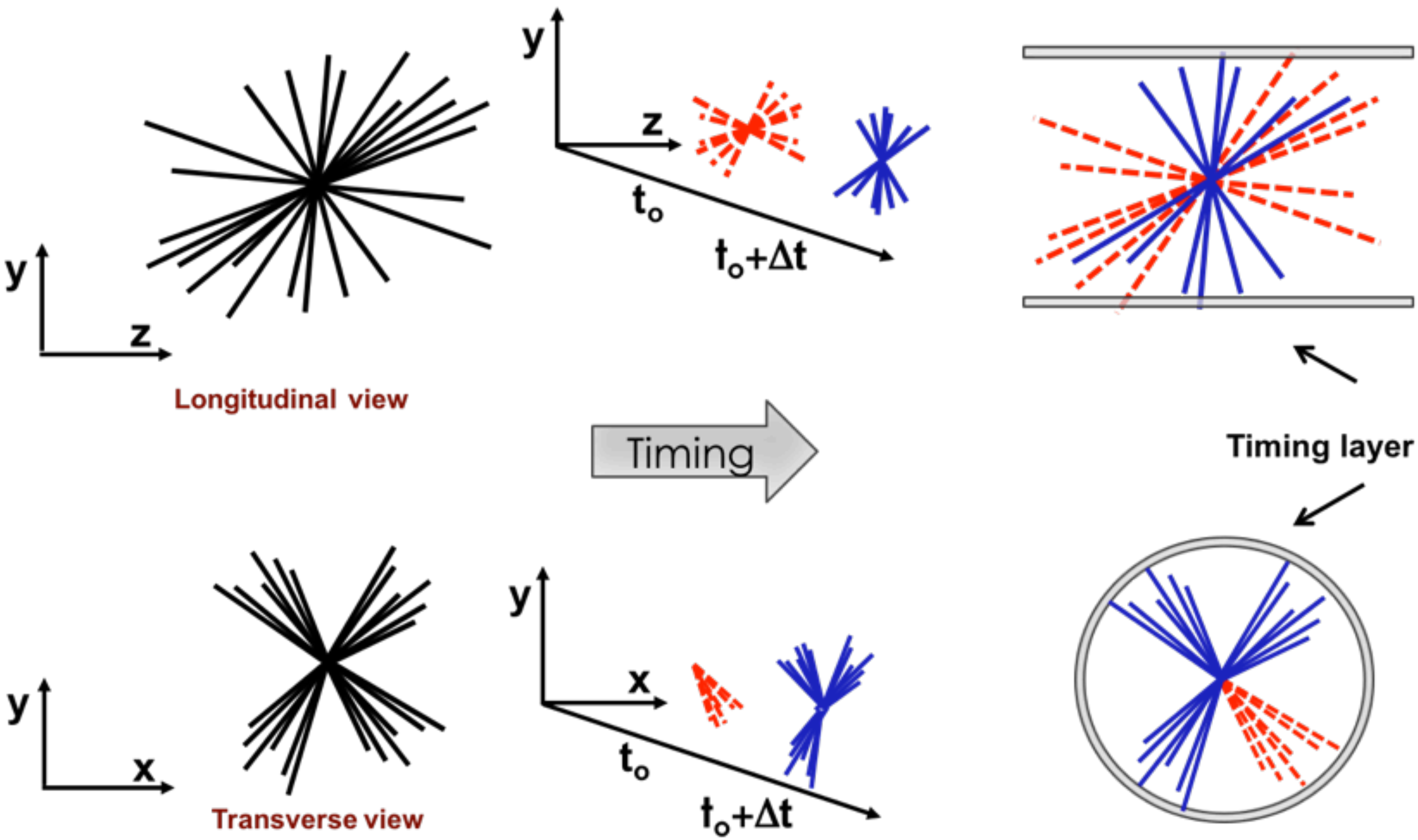
➔ Use only "time compatible points"





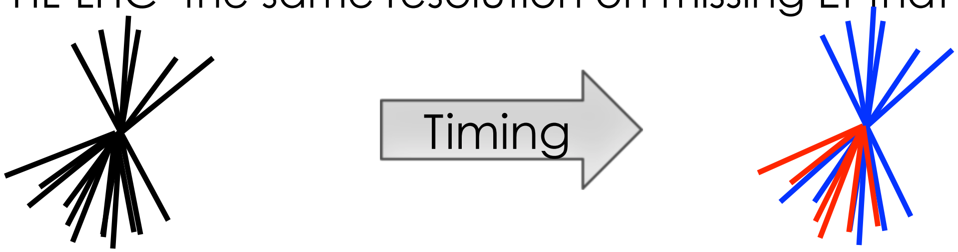
Timing in the event reconstruction - I

Timing allows distinguishing overlapping events by means of an extra dimension.

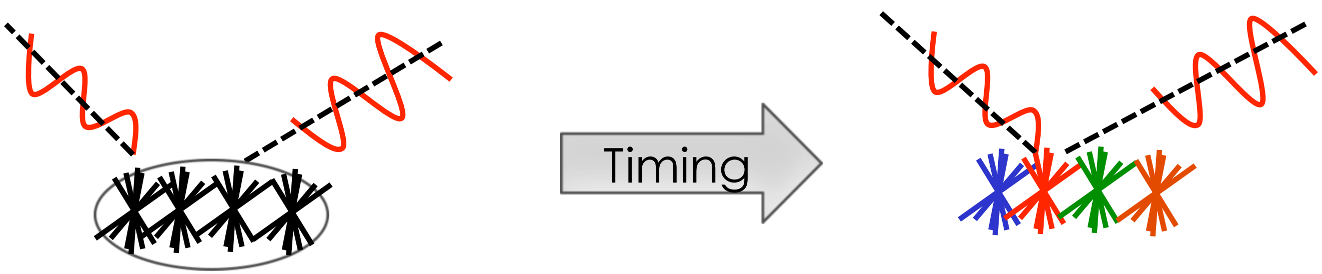


Timing in the event reconstruction - II

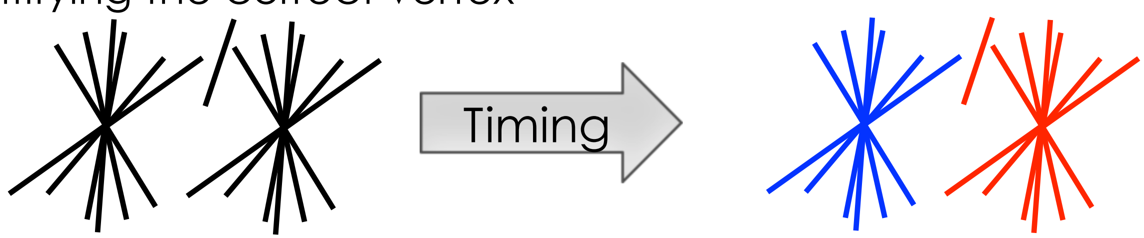
Missing Et: consider overlapping vertexes, one with missing Et: Timing allows obtaining at HL-LHC the same resolution on missing Et that we have now



H ➔ $\gamma\,\gamma$: The timing of the $\gamma\gamma$ allows to select an area 1 cm) where the vertex is located. The vertex timing allows to select the correct vertex within this area

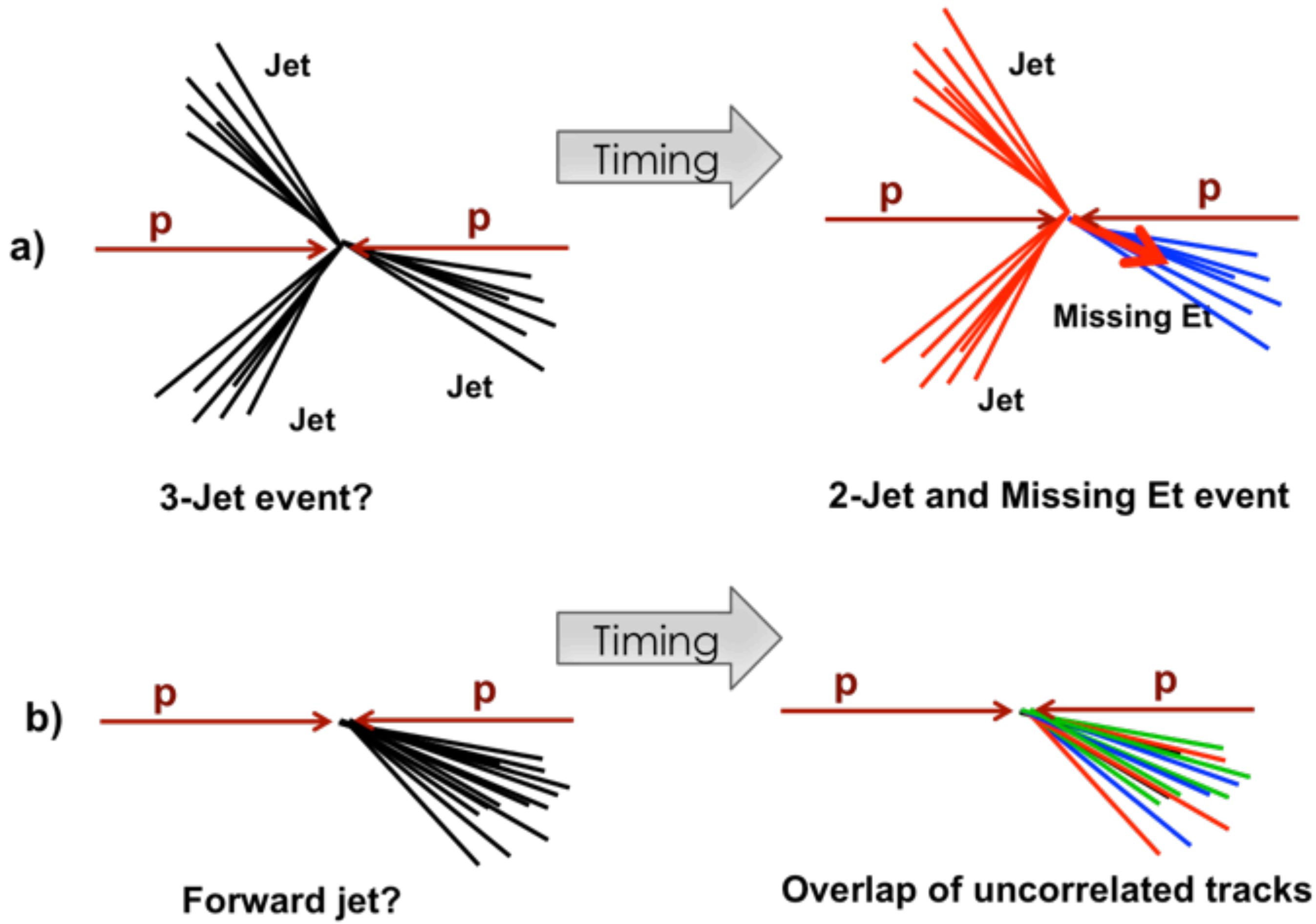


Displaced vertexes: The timing of the displaced track and that of each vertex allow identifying the correct vertex



The effect of timing information:

Timing at the trigger decision: it allows reducing the trigger rate, rejecting topologies that look similar, but they are actually different.



Why do we want a timing layer?

HL-LHC limit: 2×10^{35} cm^{-2}s^{-1} at the beginning of each fill.
Limited by luminosity leveling at 5.2 or 7.2×10^{34} cm^{-2}s^{-1}.

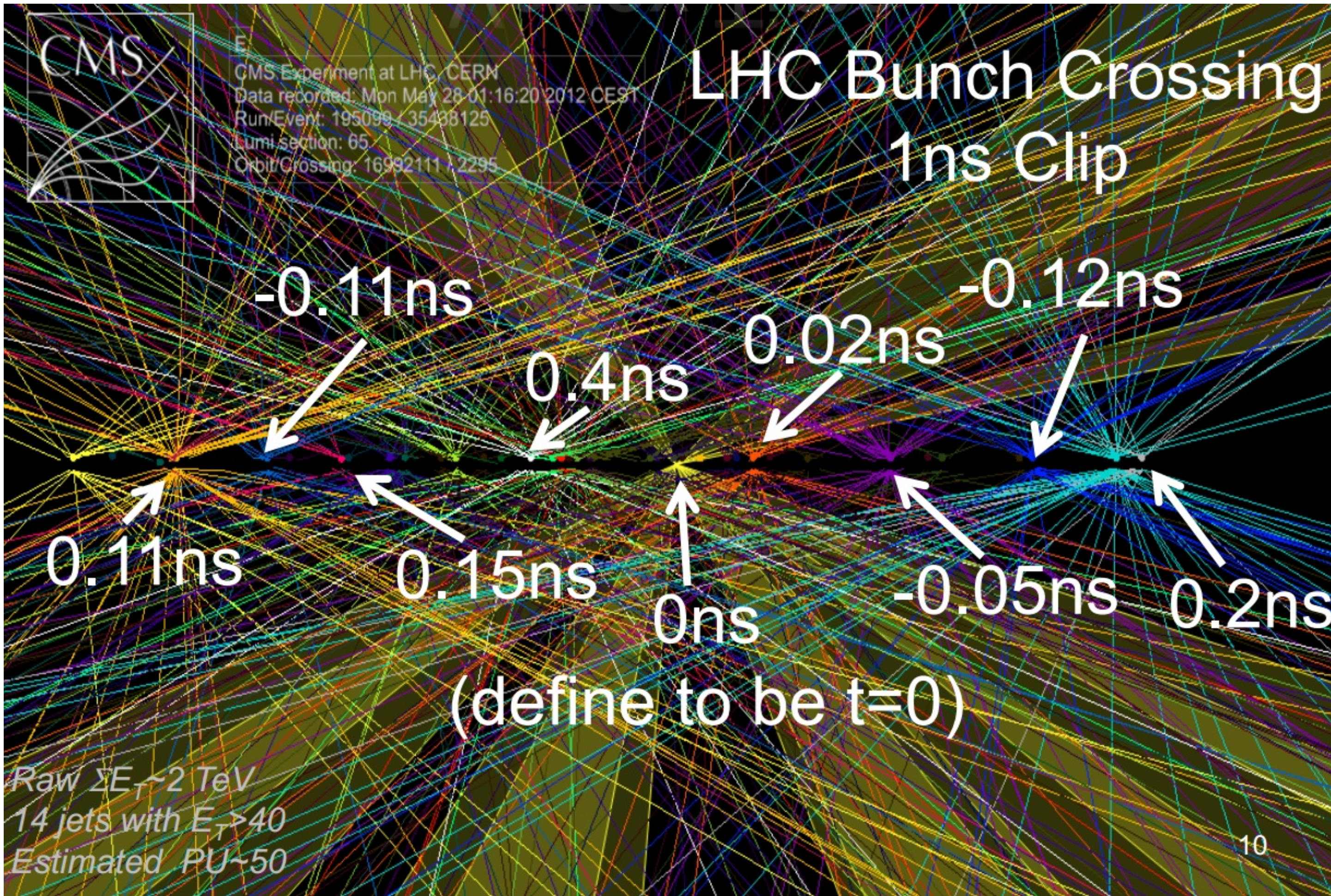
➔ Possibly LHC will be able to deliver luminosity in excess of what the experiments can take: we need to be able to take data efficiently at very high instantaneous luminosity

The purpose of a timing upgrade of the CMS detector is to consolidate the particle-flow performance at a multiplicity of 140 pileup events and to extend it up to 200 pileup events, exploiting the additional information provided by the precision timing of both tracks and energy deposits in the calorimeters.

Vertexes in space and time

Current situation, pile-up ~ 50:

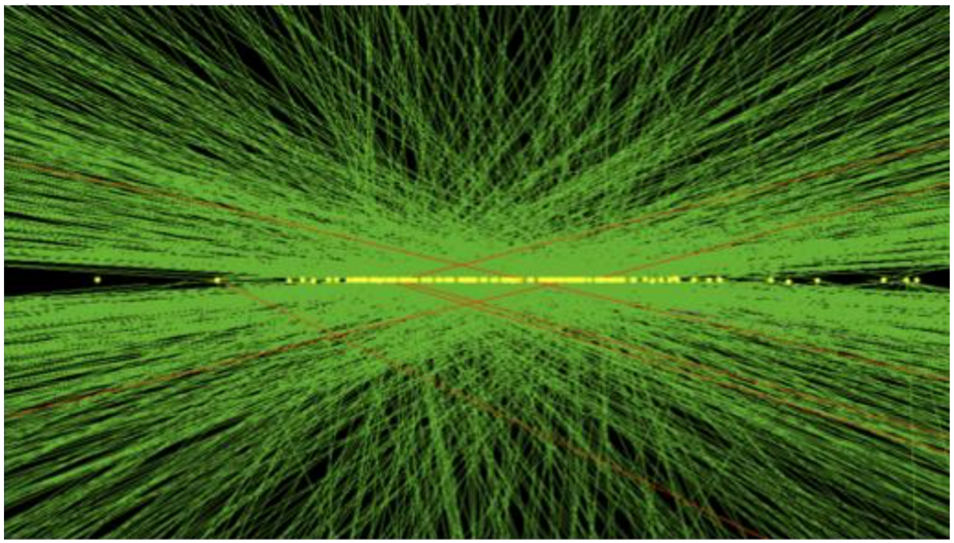
Vertexes do not overlap in space ➔ tracking resolves the vertexes

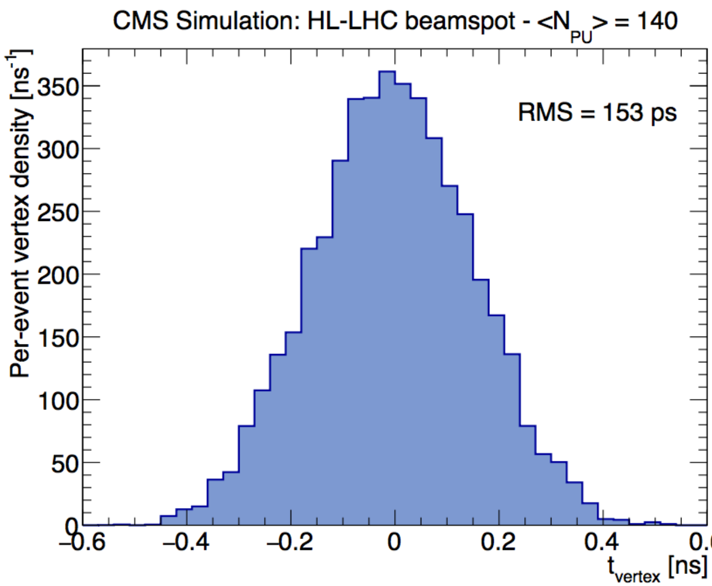


Vertexes in space and time

HL-LHC situation, pile-up ~ 150 - 200:

Vertexes **overlap** in space ➔ tracking **does not resolves** all vertexes





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

➔ Loss of events ➔ loss of luminosity

Pileup and event density

Pile-up: number of concurrent scattering processes (140 – 200).

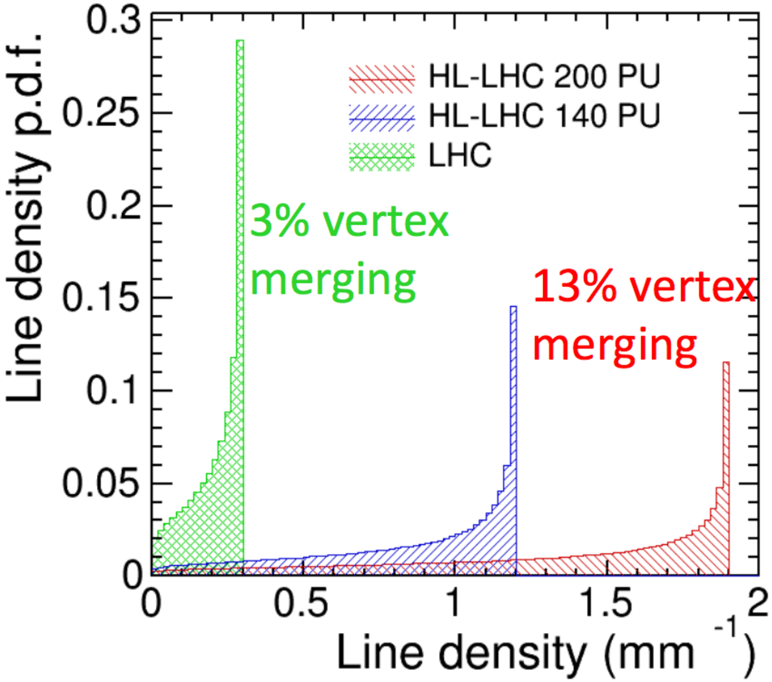
Density of events: number of events 1 mm (0.2 – 2 event/mm)

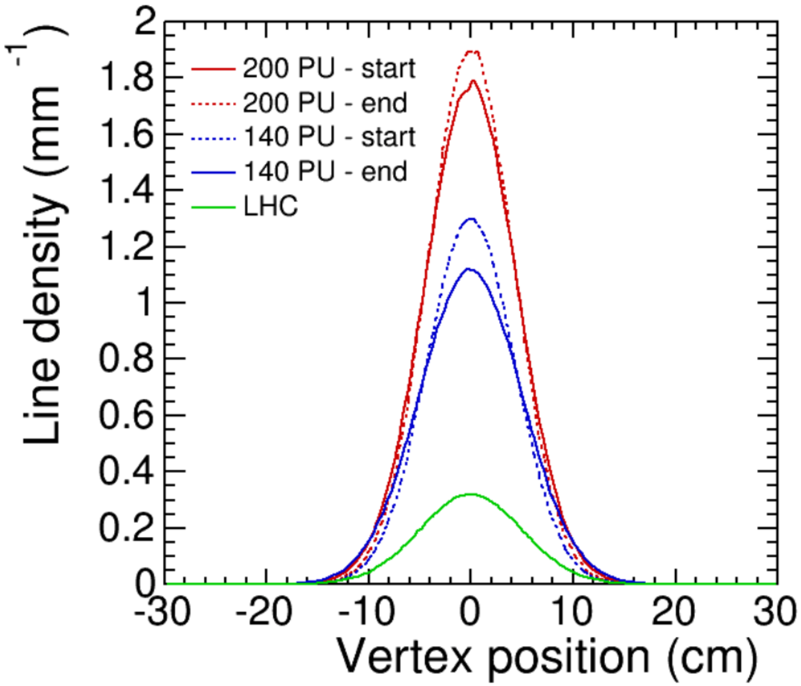
Why are they different?

Pile-up is a global quantity, and it can be fought with very high granularity. It influences, for example, the total amount of tracks and neutral clusters

Density of events: it can be fought with longitudinal resolution and timing.
➔ Charge particles

Vertex merging



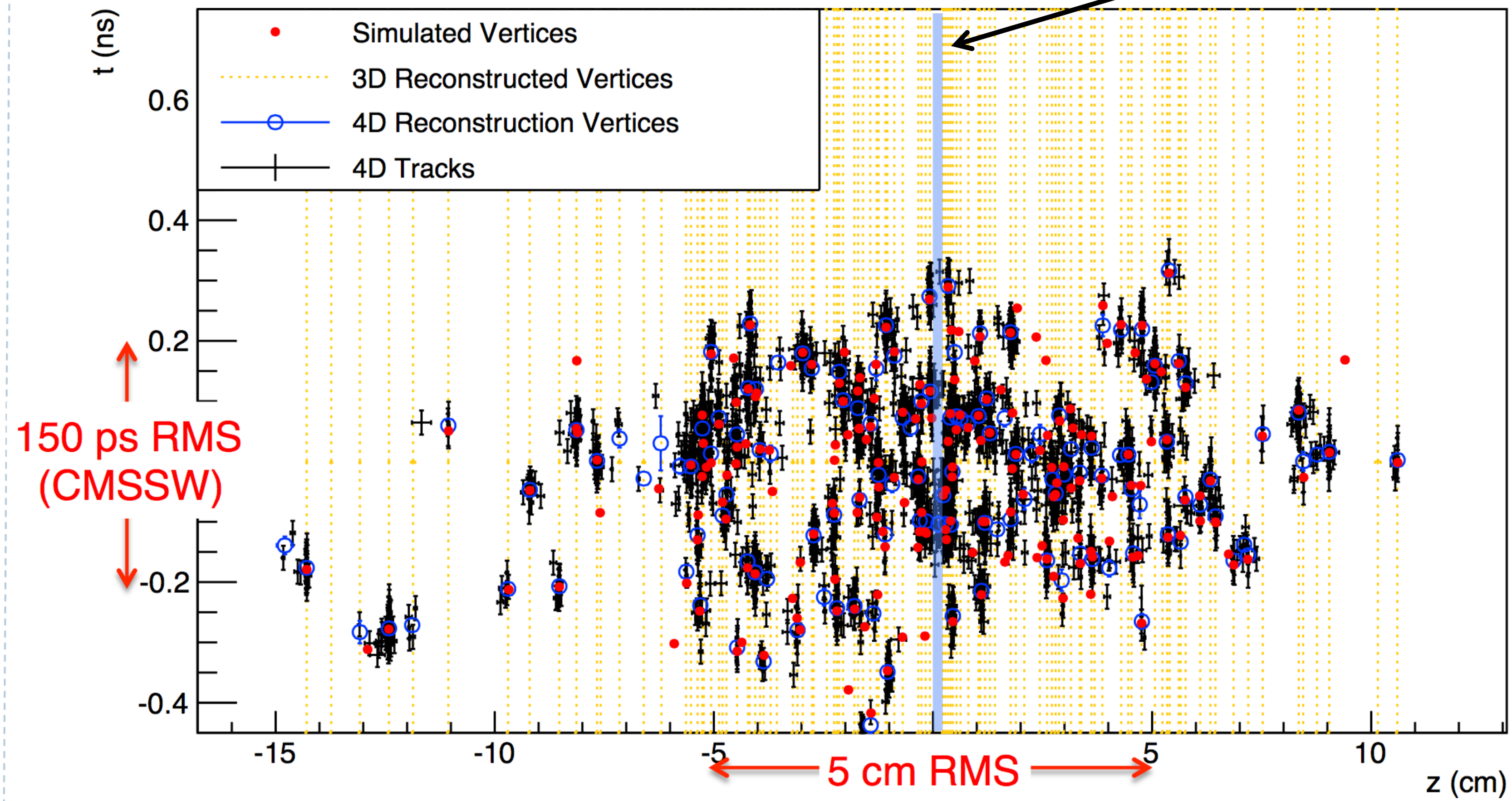


Vertexes are clustered in high density region, producing large overlaps

Position – time of each vertex

- **200 pileup collisions**

Longitudinal resolution ~ 300 micron

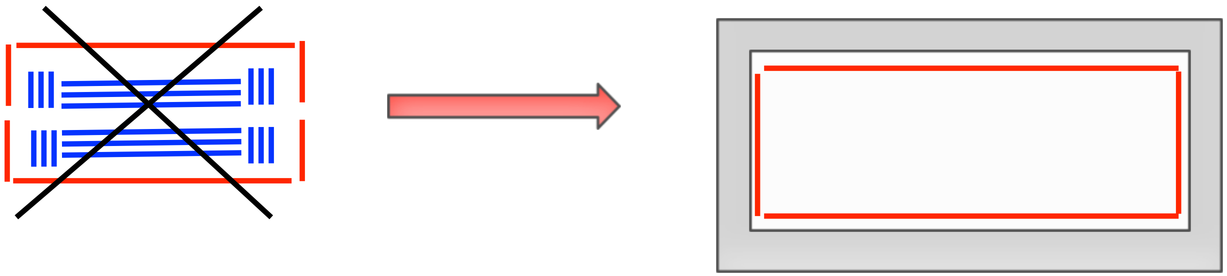


- HL-LHC baseline (as of ECFA): $t_{RMS} = 180$ ps, $z_{RMS} = 4.8$ cm

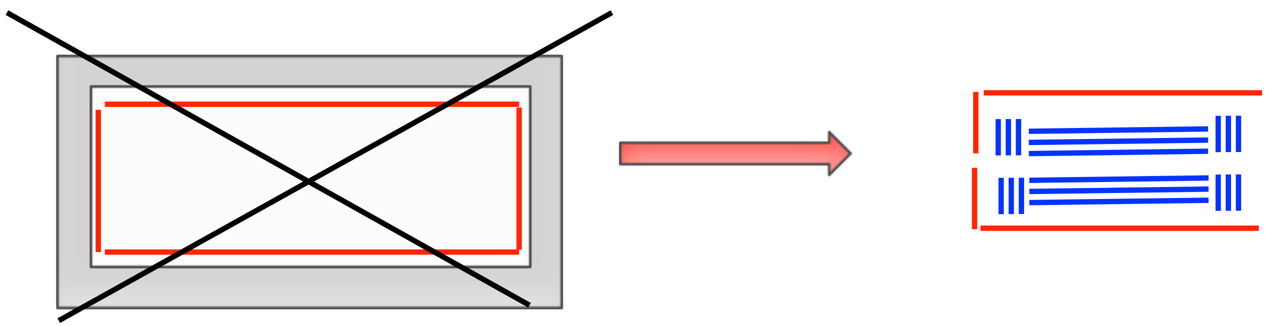
At pileup levels of 140–200, a fraction as high as 15-20% of independent vertices merges, in the absence of time information.

Where do we stand?

The tracking community thinks it is a wonderful idea, clearly to be implemented **outside the tracker volume**, in front of the calorimeter

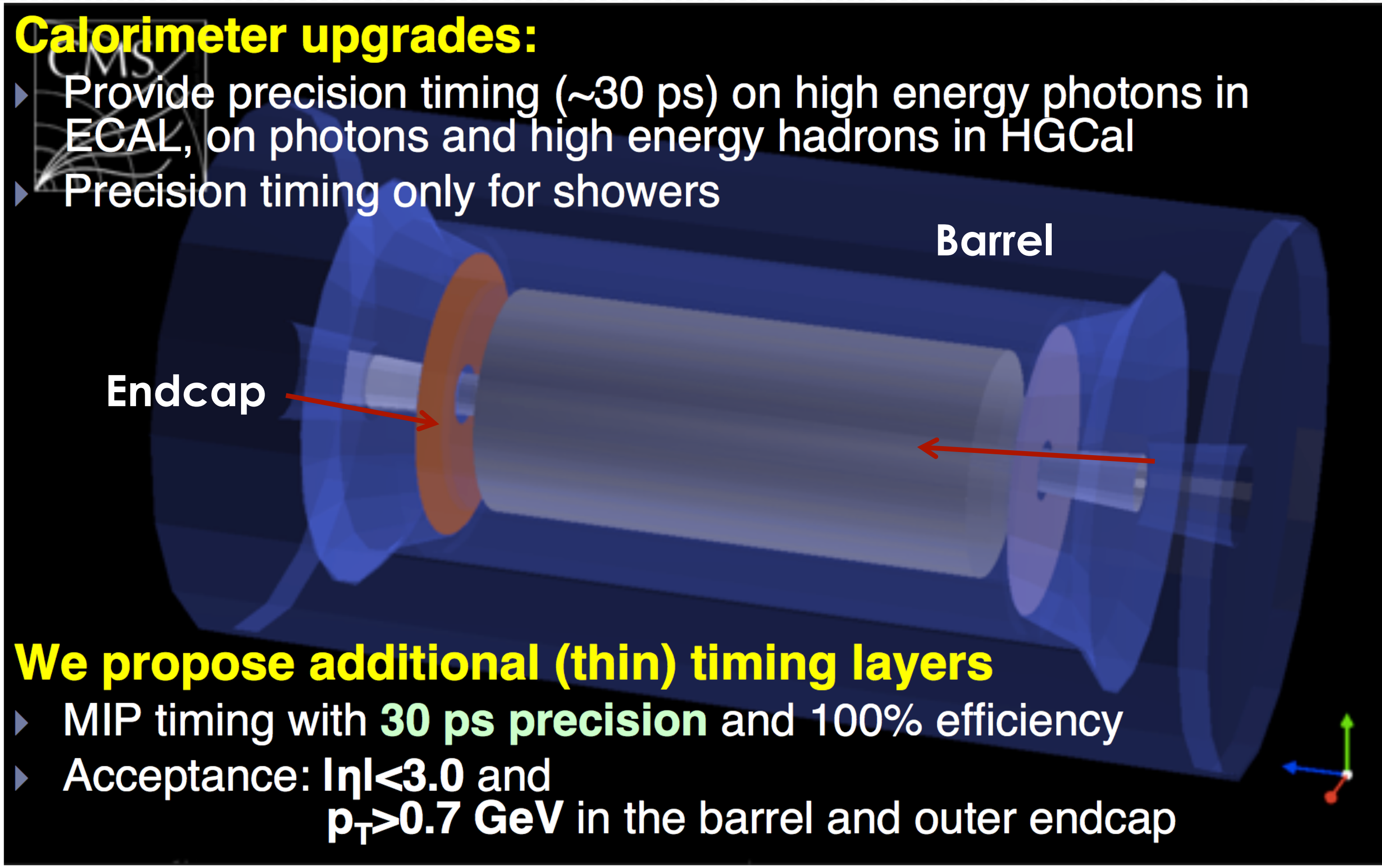


The calorimeter community thinks it is a wonderful idea, clearly to be implemented **far from the calorimeter**, in the tracker volume



We are now in contact with **the muon community….**

A timing layer for charge particles in CMS



ECAL Crystal Barrel:

Current resolution: 150 ps for E> 30 GeV

With new electronics: 30 ps for E> 30 GeV

HGCAL:

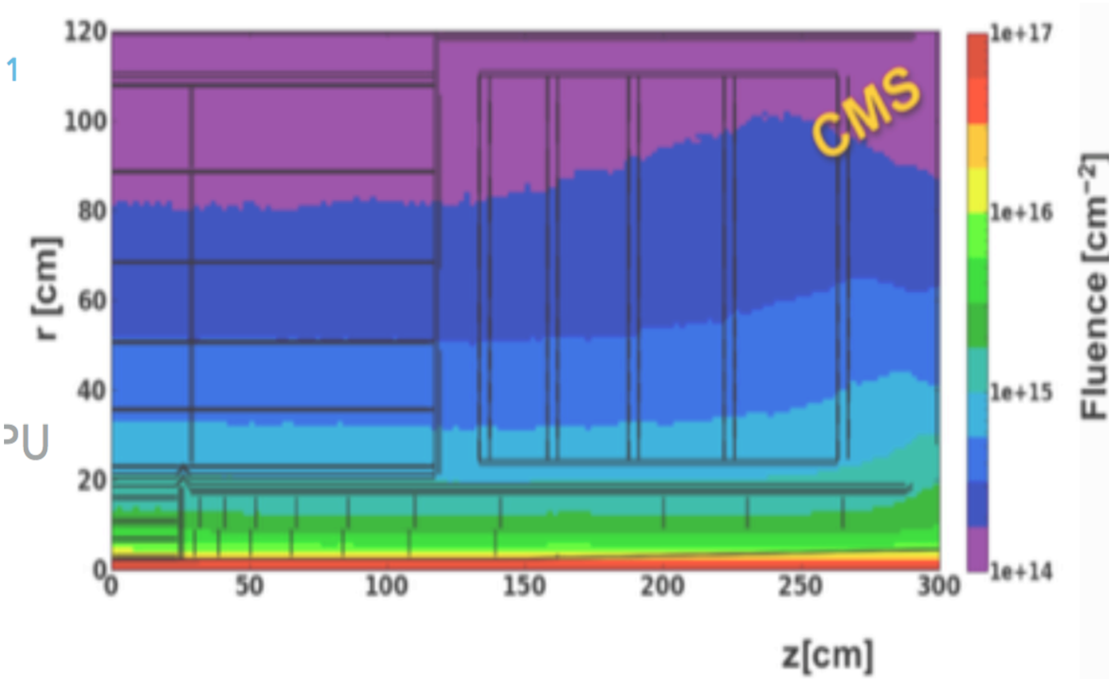
50 ps time resolution from each silicon pad for #MIPS>30

➔ Each showers covers many planes (> 5)

➔ Shower resolution limited by systematics

Radiation levels

Region	η	R (cm)	z (cm)	Fluence (cm^{-2})	Charged hardons (cm^{-2})	Dose (kGy)
barrel	0.0	130	0	1.5×10^{14}	6.7×10^{12}	11.9
barrel	1.0	130	153	1.9×10^{14}	6.9×10^{12}	15.9
transition	1.5	130	300	1.7×10^{14}	8.9×10^{12}	15.0
endcap	2.0	82.7	300	4.3×10^{14}	5.7×10^{13}	79.4
endcap	2.5	49.6	300	1.1×10^{15}	2.3×10^{14}	245.
endcap	2.7	40.5	300	1.2×10^{15}	3.3×10^{14}	337.
endcap	3.0	29.9	300	1.8×10^{15}	5.8×10^{14}	566.

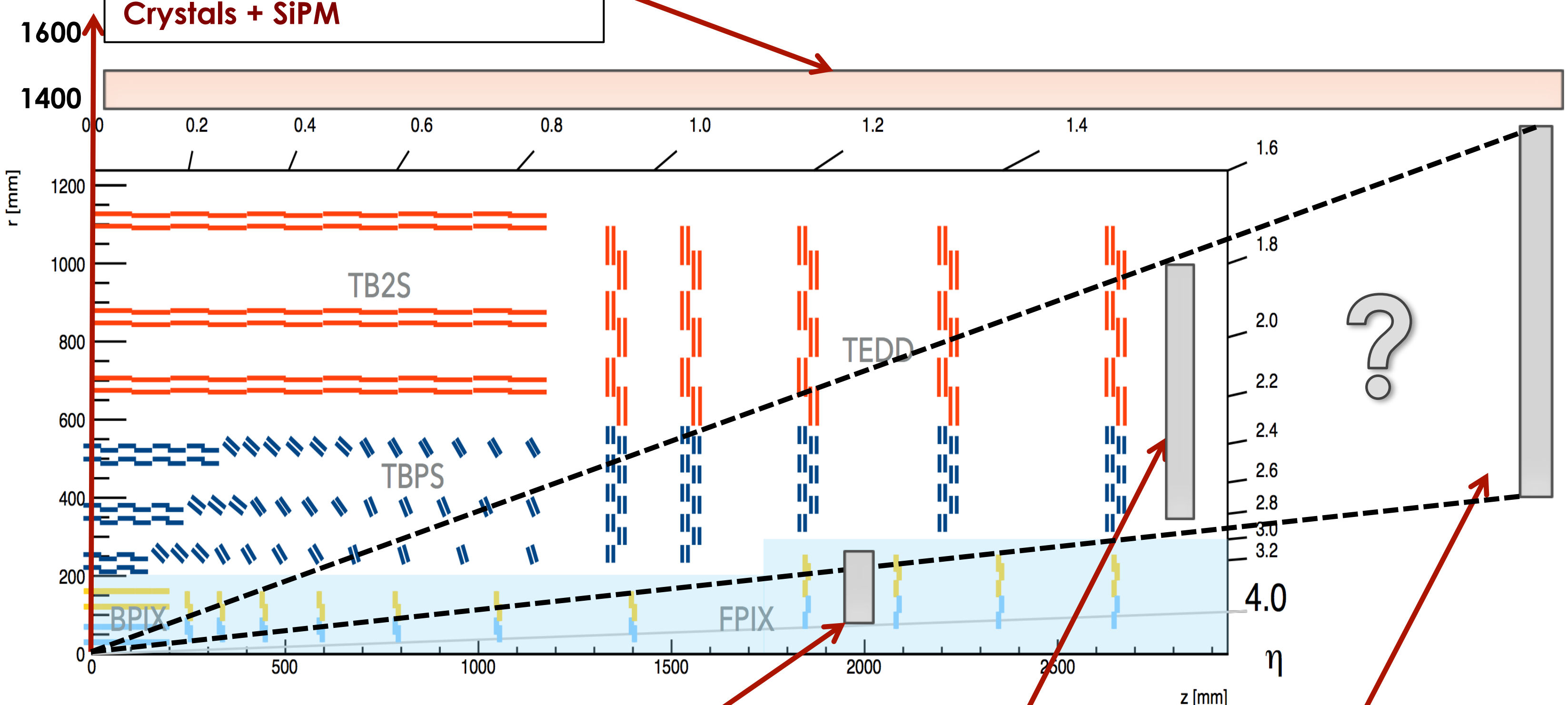


Barrel is a much easier environment

Endcap will be driving the radiation aspects of the project

CMS Timing layer position

Between tracker and ECAL
Crystals + SiPM



Silicon detector

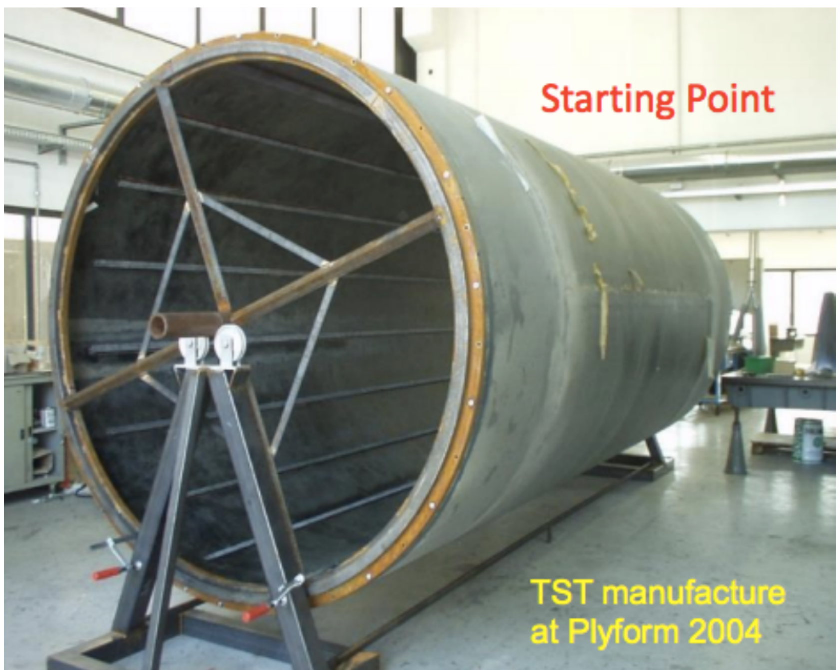
High rapidity Option:
Inside Forward pixel
3.5 m^2
0.7 ml Channel

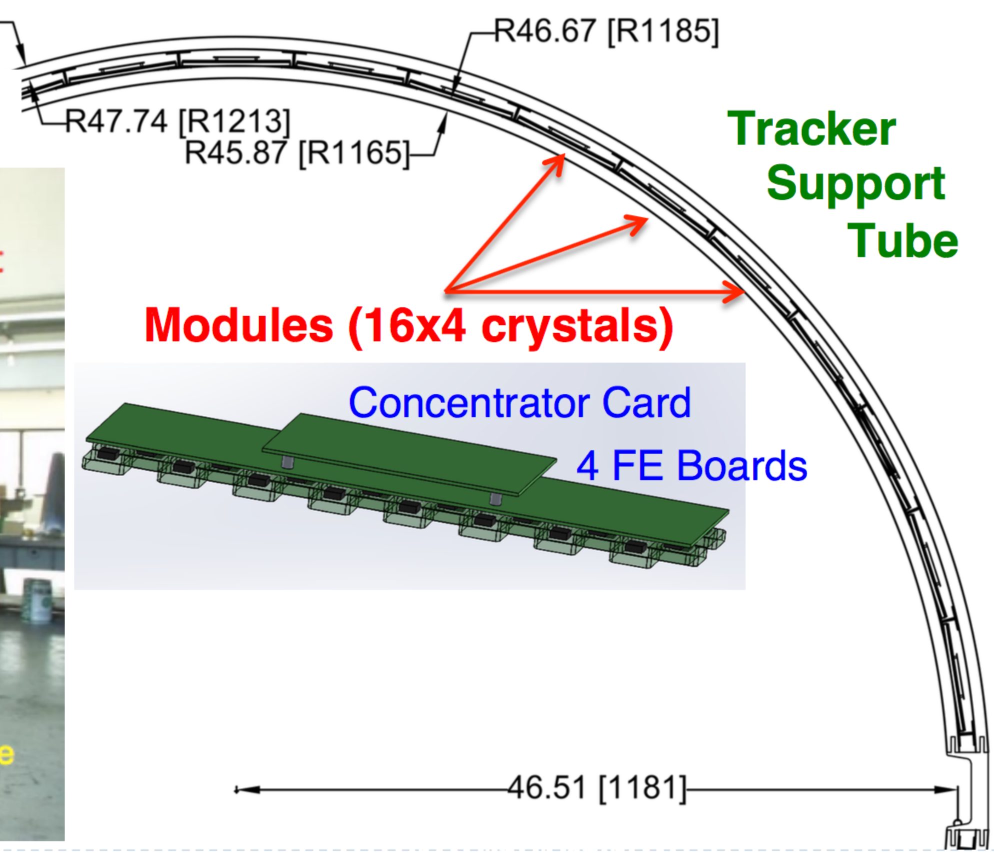
Option 1:
Inside Tracker
3.5 m^2
0.7 ml Channel

Option 2:
In front HGCAL
7.2 m^2
1.2 ml Channel

Barrel Timing layer: on the Tracker Support Tube

- **LYSO crystals + SiPM embedded in the TST**
  - Be ready before TK installation: 2022
  - → Select production ready sensors and electronics



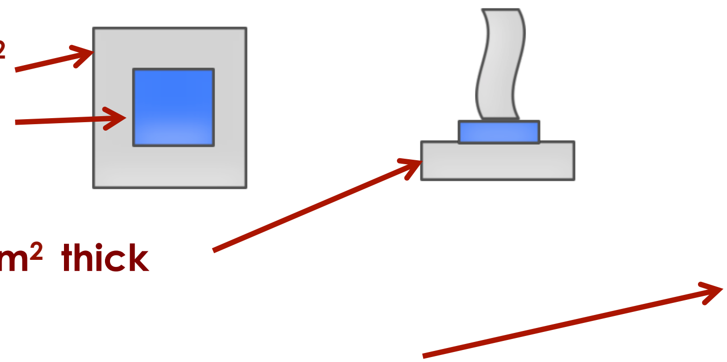


Barrel design: crystals read-out by SiPM

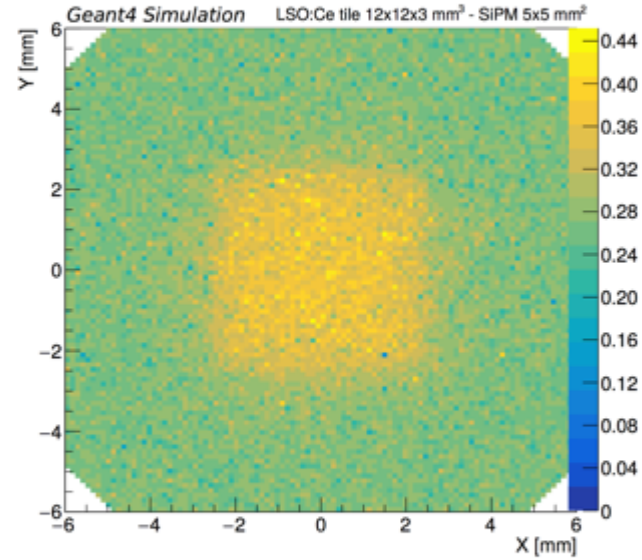
Crystal: 1.2 x 1.2 cm^2

SiPM = 0.5x0.5 cm^2

Crystal: 0. 3 cm^2 thick



Single photon efficiency as a function of position



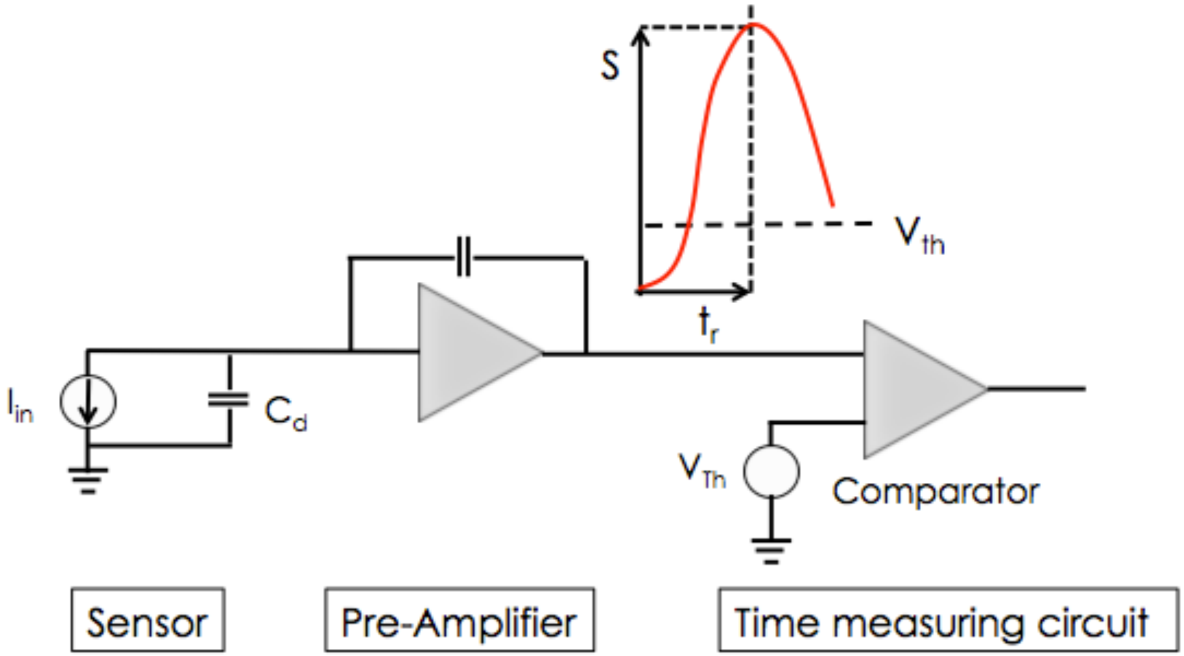
- **Based on LYSO:Ce crystals read-out with silicon photomultipliers (SiPMs)**
- **1.2x1.2 cm^2 crystal, 3 mm thick, read-out by a 0.5x0.5 cm^2 SiPM**
- **time resolution in the order of 10-20 ps.**

➔ A MIP traversing 3mm of LYSO produces 90,000 photons and with a 5mm x 5mm SiPM per cm^2 tile yields a S/N of above 100 throughout the entire HL-HLC program.

- Use the design of the present Tracker Support Tube (TST) and rails to instrument the region outer tracker ring and the ECAL front-end cooling plates with a thin standalone detector
- Both the crystals and the SiPM are proven to be radiation tolerant up to neutron equivalent fluence 3×10^{14} cm^{-2}, when cooled to -30^{o}C.
- We do not foresee to use time information in the level-1 trigger decision.

Silicon time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

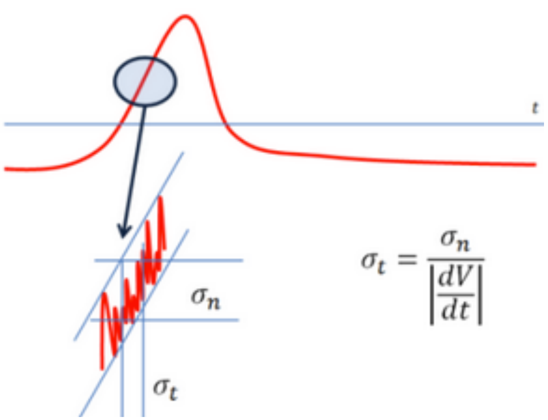
The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

Strong interplay between sensor and electronics

Time resolution

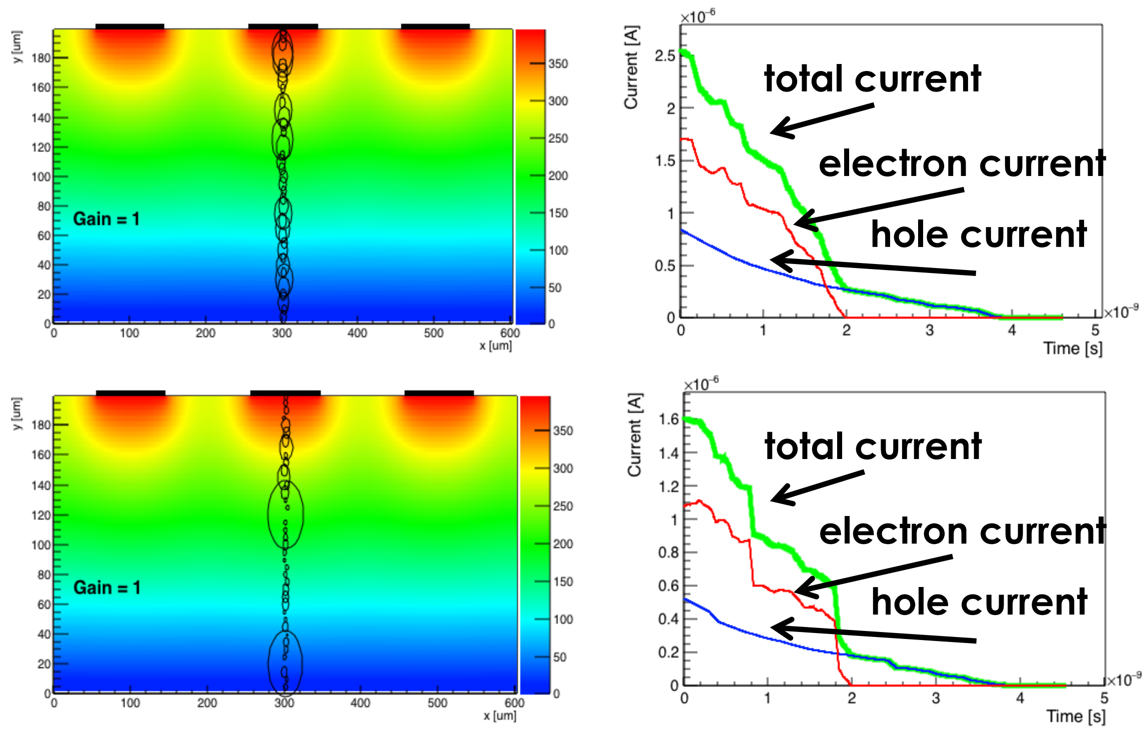
$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

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



Time walk: Amplitude variation, corrected in electronics

Shape variations: non homogeneous energy



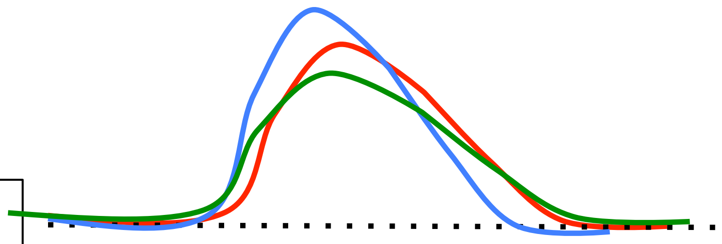
Not all geometries are possible

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity

Weighting field

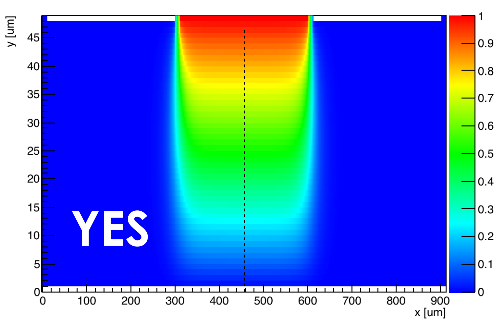


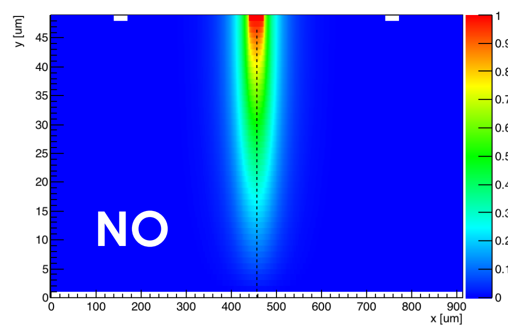
The key to good timing is the uniformity of signals:

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

Basic rule: parallel plate geometry: strip implant ~ strip pitch >> thickness

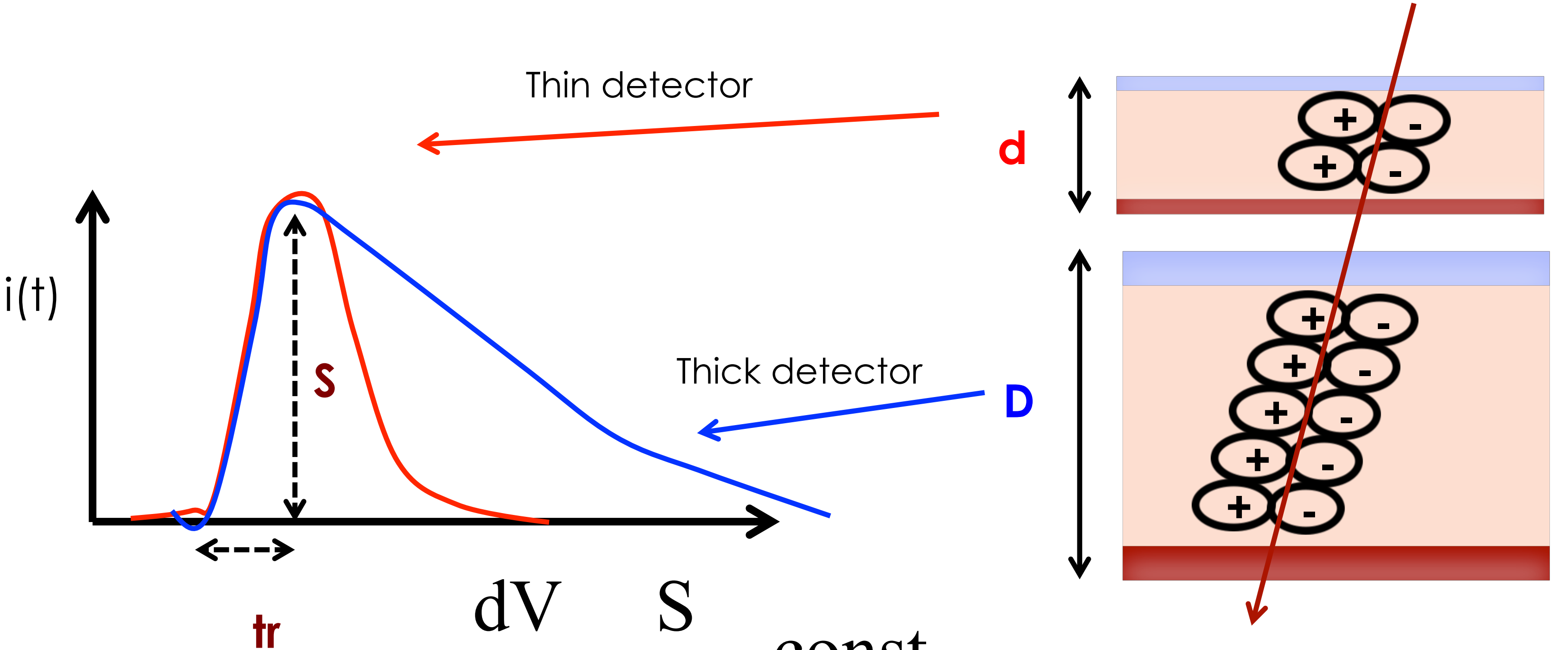
Everything else does not work





dV/dt in Thin and Thick silicon detectors

(Simplified model for pad detectors)



$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim const$$

Thick detectors have longer signals, not higher signals

Best result : NA62, 150 ps on a 300 x 300 micron pixels

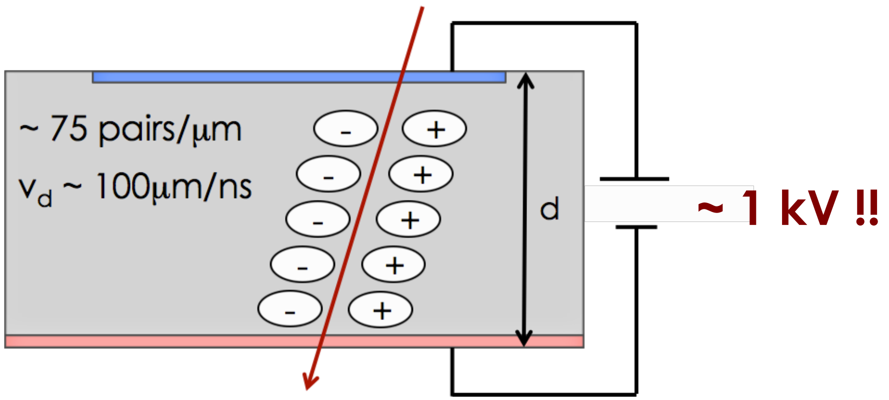
How can we do better?

➔ Add internal gain

Gain need E ~ 300kV/cm. How can we do it?

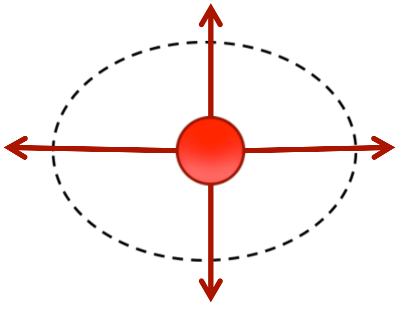
1) Use external bias: assuming a 50 micron silicon detector, we need **V_{bias} = ~ 1 kV**

Possible, but really difficult



2) Use Gauss Theorem:

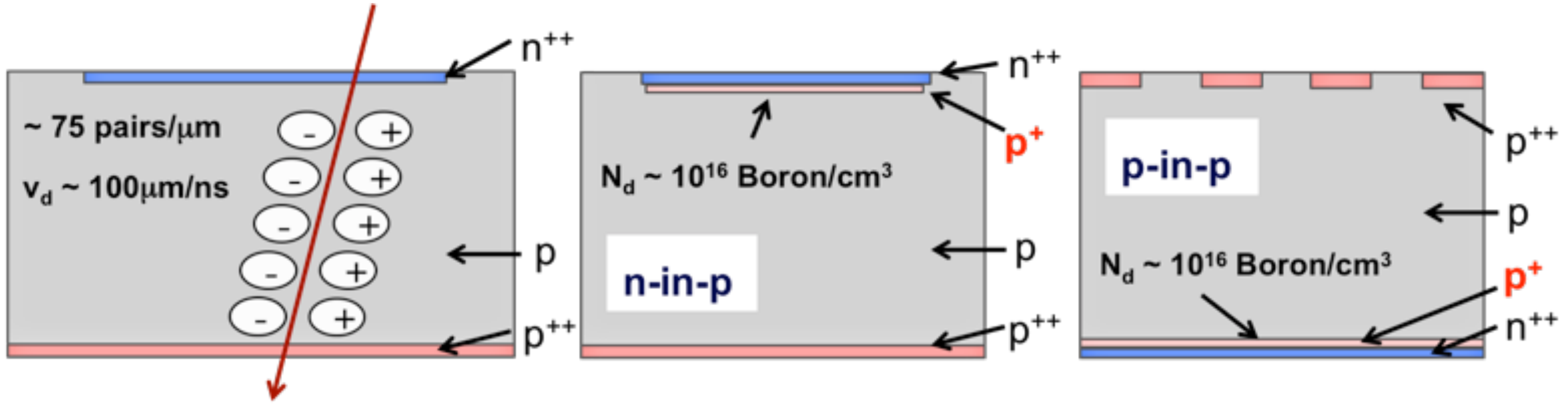
$$\sum q = 2\pi r * E$$



E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

Need to have 10^{16}/cm^3 charges !!

LGAD - Ultra-Fast Silicon Detector

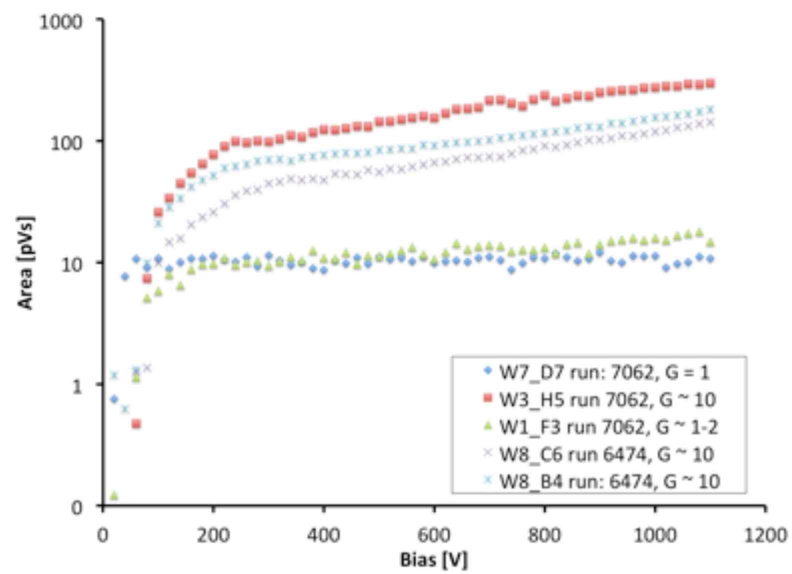


Traditional Silicon Detector **Ultra-Fast Silicon Detector**

Adding a highly doped, thin layer of of p-implant near the p-n junction creates a high electric field that accelerates the electrons enough to start multiplication. Same principle of APD, but with much lower gain.

Gain changes very smoothly with bias voltage.

Easy to set the value of gain requested.



Simulation

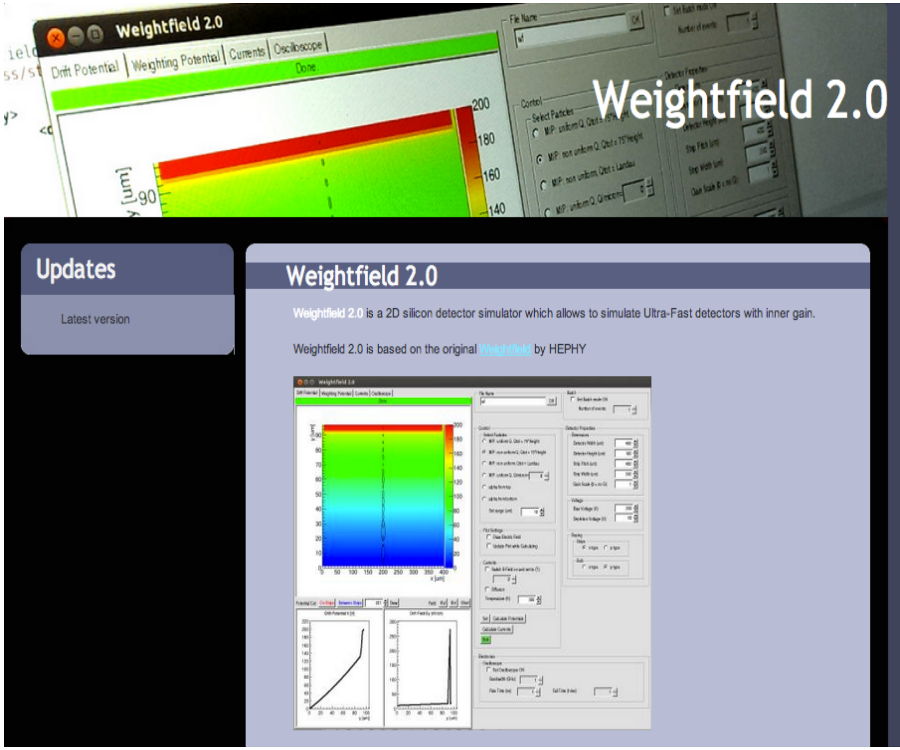
We developed a full sensor simulation to optimize the sensor design

WeightField2, F. Cenna, N. Cartiglia 9th Trento workshop, Genova 2014

Available at http://personalpages.to.infn.it/~cartigli/weightfield2

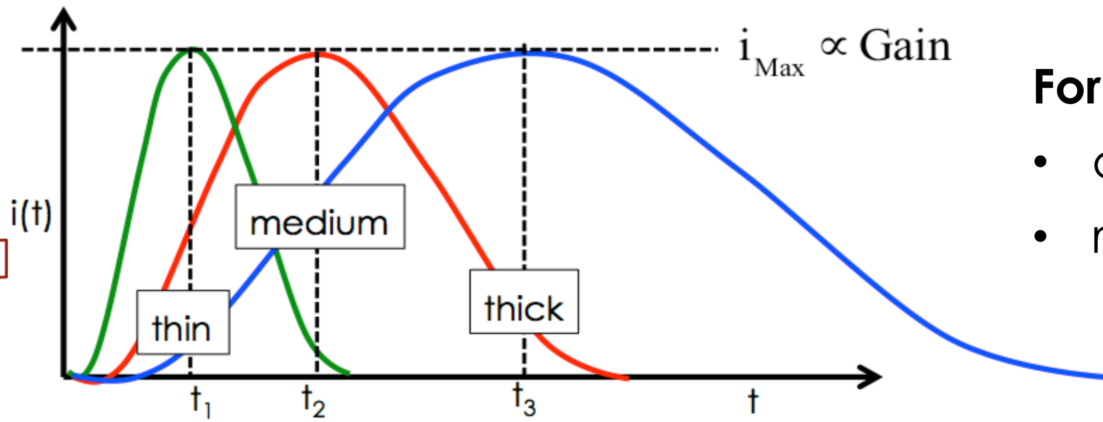
It includes:

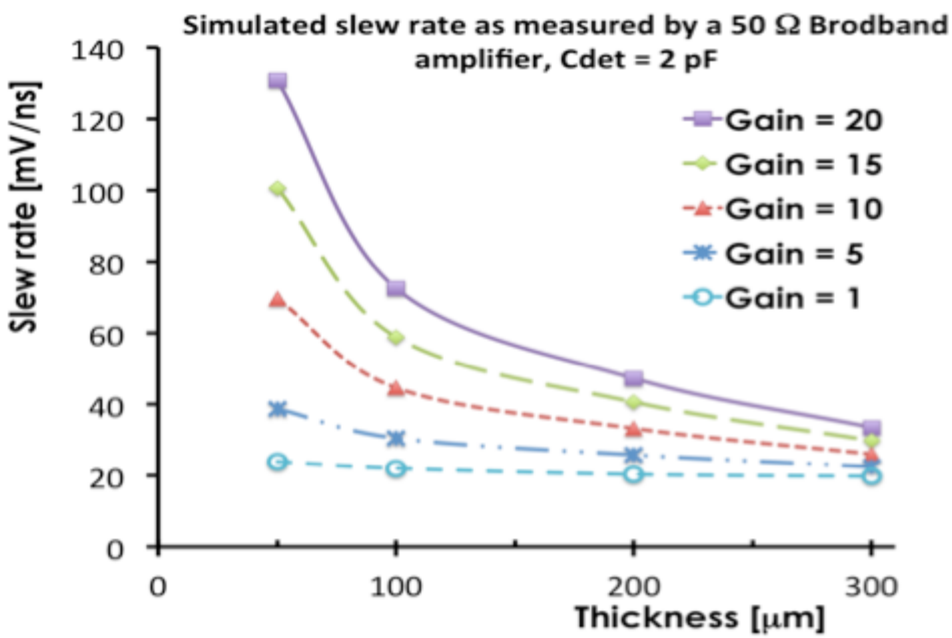
- Custom Geometry
- Calculation of drift field and weighting field
- Currents signal via Ramo's Theorem
- Gain
- Diffusion
- Temperature effect
- Non-uniform deposition
- Electronics



For each event, it produces a file with the current output that can be used as input in the simulation of the electronic response.

Gain and slew rate vs thickness





For a fixed gain:

- amplitude = constant
- rise time ~ 1/thickness

The slew rate:

- Increases with gain
- Increases ~ 1/thickness

➔ **Go thin!!**

Significant improvements in time resolution require thin detectors

Ultra Fast Silicon Detectors

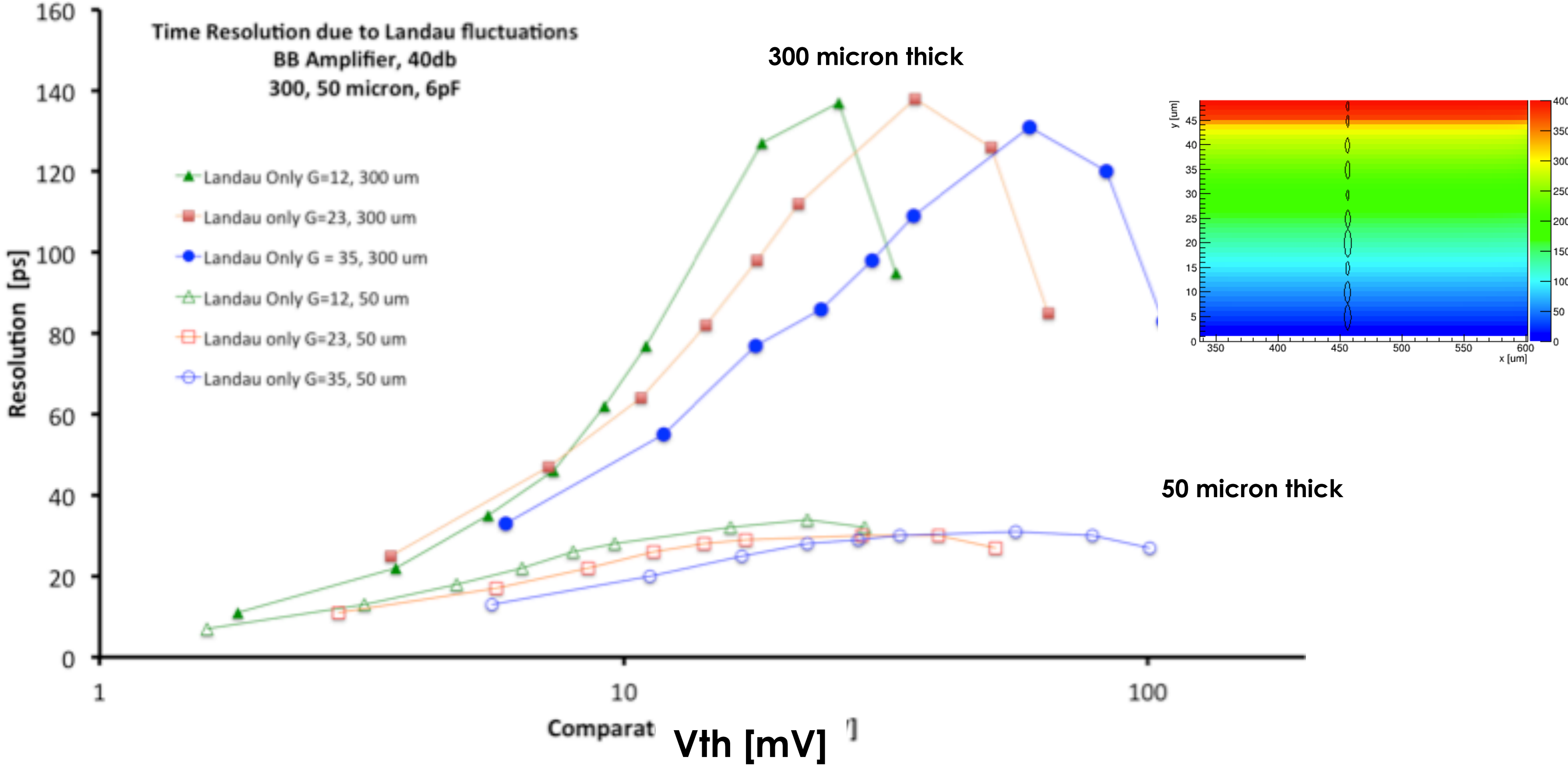
UFSD are LGAD detectors optimized to achieve the best possible time resolution

Specifically:

1. Thin to maximize the slew rate (dV/dt)
2. Parallel plate – like geometries (pixels..) for most uniform weighting field
3. High electric field to maximize the drift velocity
4. Highest possible resistivity to have uniform E field
5. Small size to keep the capacitance low
6. Small volumes to keep the leakage current low (shot noise)

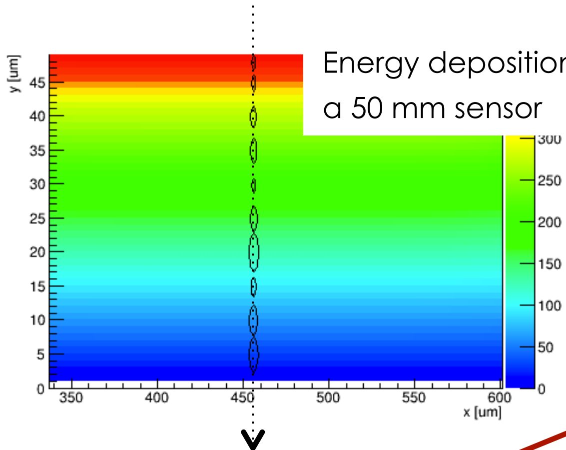
Non uniform charge deposition along the track

This is a physical limit to time resolution: beat it with thin detectors and low comparator threshold.



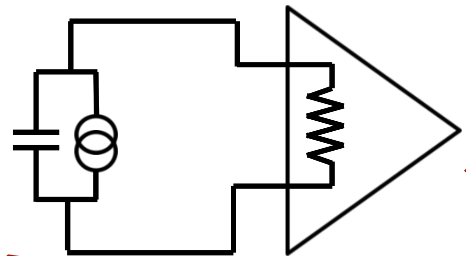
- ➔ Set the comparator threshold as low as you can
- ➔ Use thin sensors

What is the best pre-amp choice?

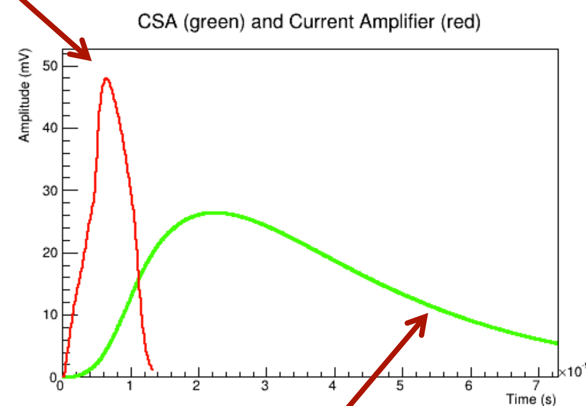


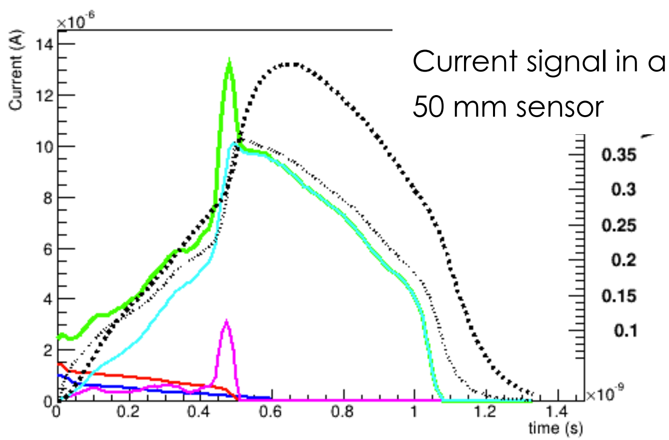
Energy deposition in a 50 mm sensor

Current Amplifier



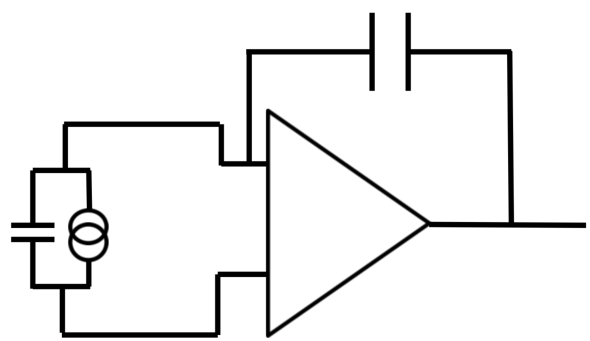
- Fast slew rate
- Higher noise
- Sensitive to Landau bumps
- More power





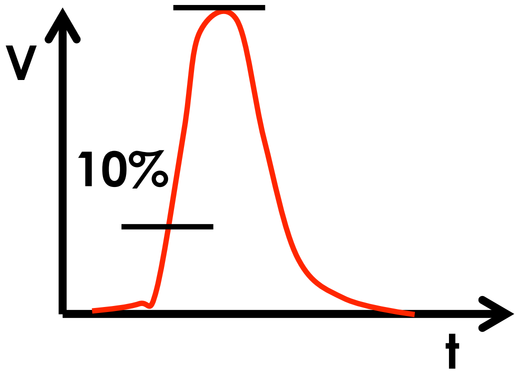
Current signal in a 50 mm sensor

Integrating Amplifier



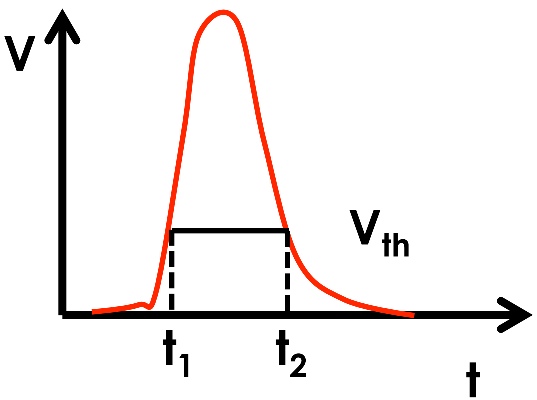
- Slower slew rate
- Lower noise
- Signal smoothing
- Less power

What is the best "time measuring" circuit?



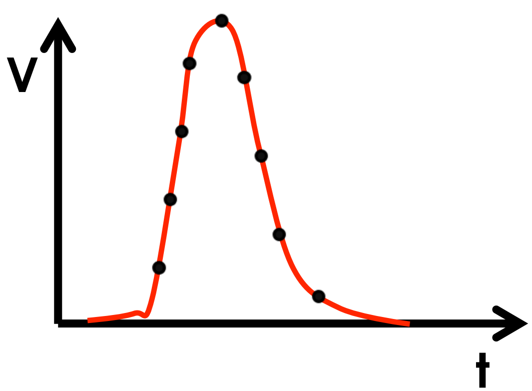
Constant Fraction Discriminator

The time is set when a fixed fraction of the amplitude is reached



Time over Threshold

The amount of time over the threshold is used to correct for time walk



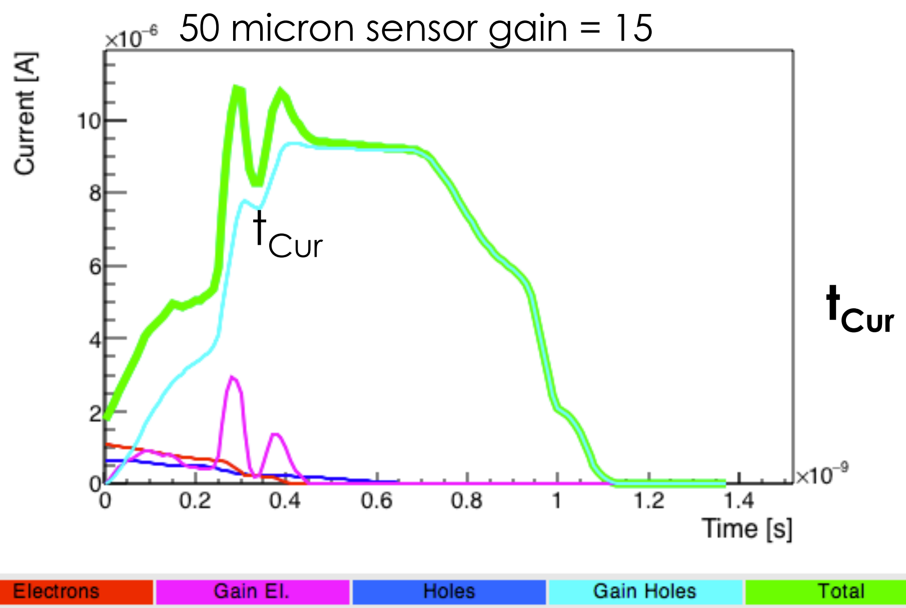
Multiple sampling

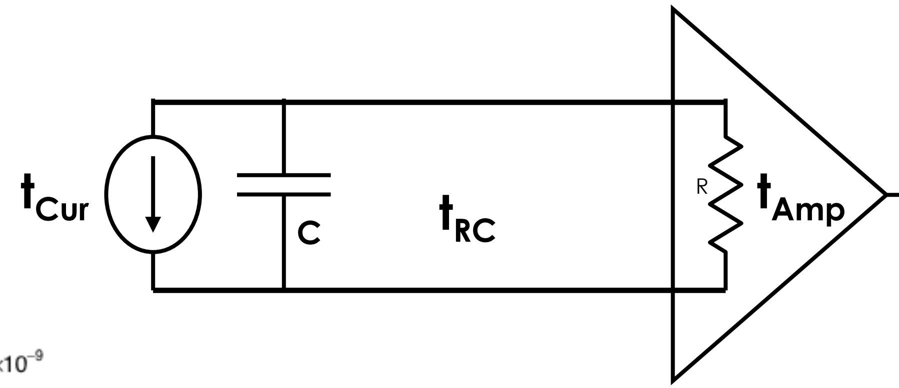
Most accurate method, needs a lot of computing power.

Possibly too complicated for large systems

The players: signal, noise and slope

Signal dV/dt | Landau Noise | Shot Noise | Electronic Noise



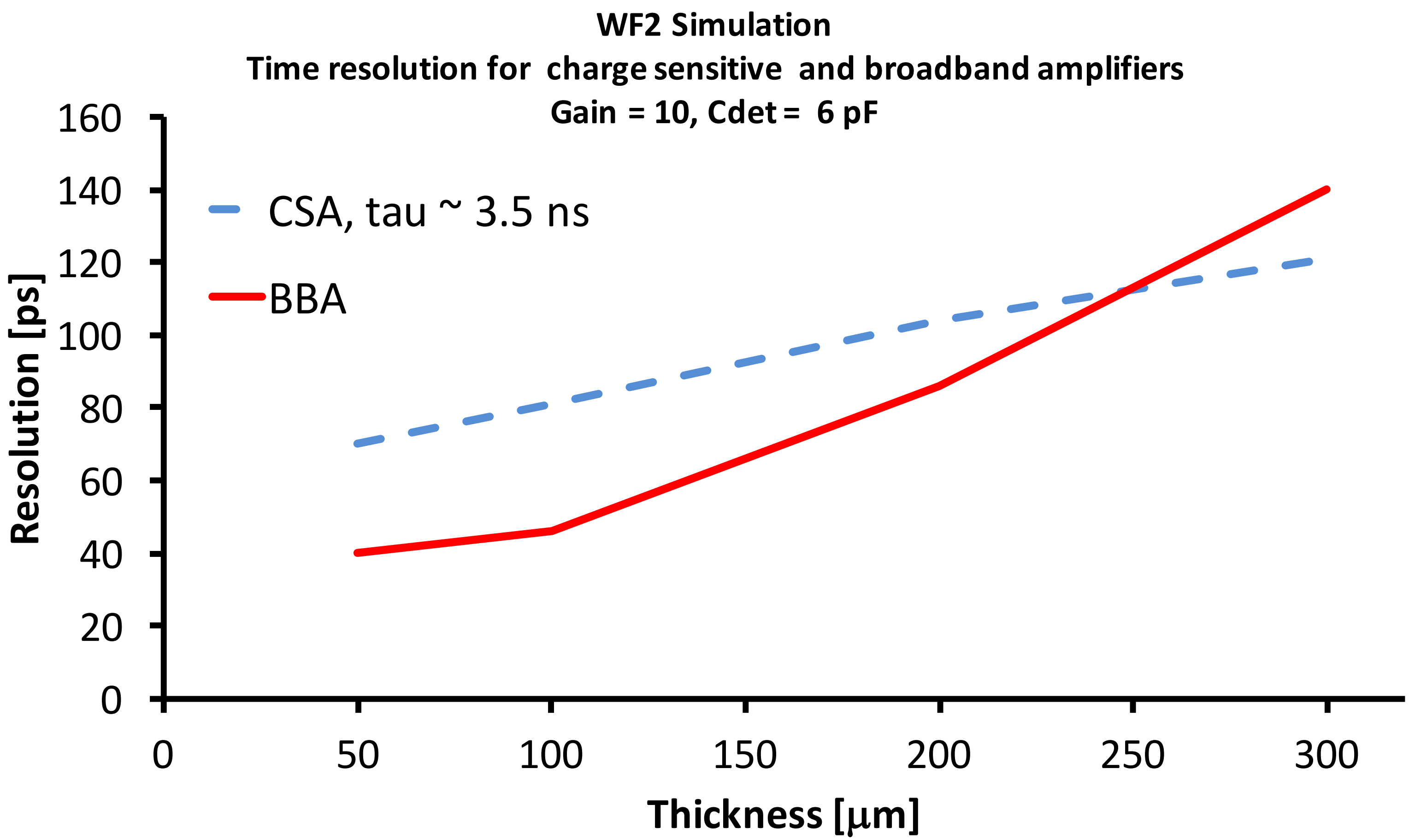


The current rise time (t_{Cur}) | The RC circuit (t_{RC}) | Amplifier rise time (t_{Amp})

There are 3 quantities determining the output rise time after the amplifier:

1. The signal rise time (t_{Cur})
2. The RC circuit formed by the detector capacitance and the amplifier input impedance (t_{RC})
3. The amplifier rise time (t_{Amp})

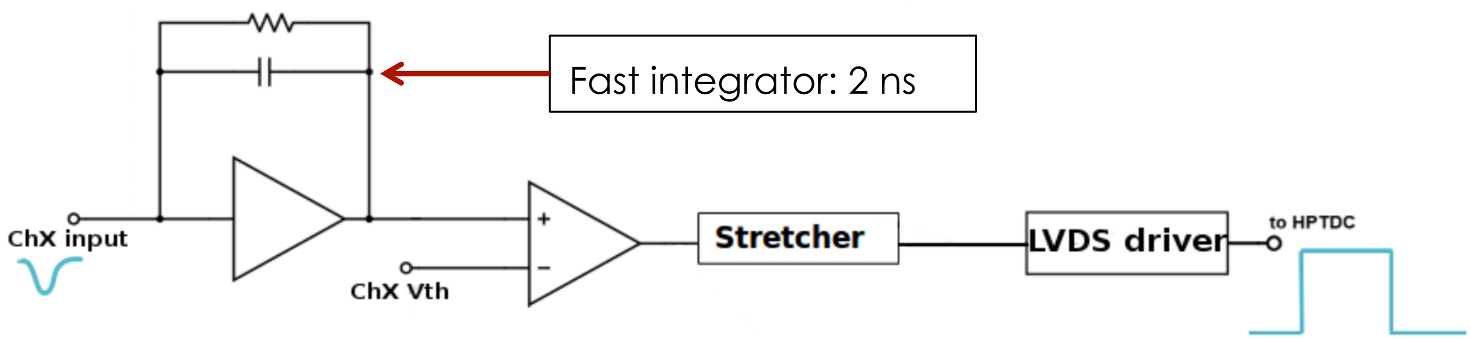
Integrator or current amplifier?



- integrators work best with signals that are longer than their integration time
- Current amplifiers work best with very fast signals

TOFFEE: Time Of Flight Front-End Electronics

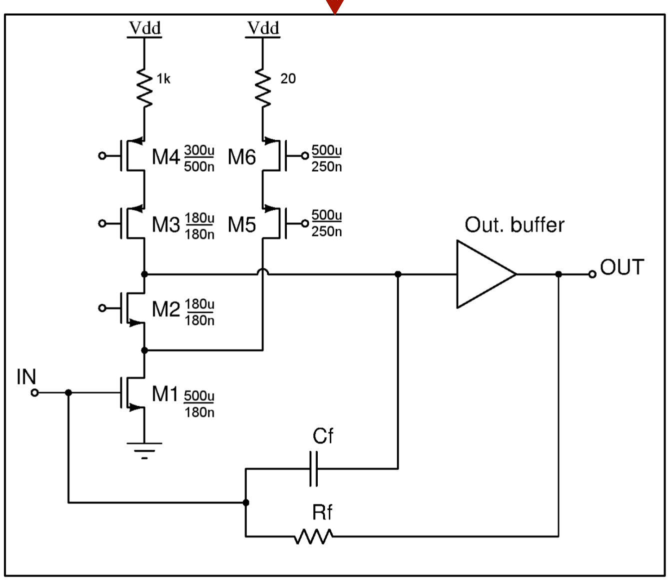
TOFFEE: Fully custom, 8 channel, 110 nm TMC chip to read-out UFSD

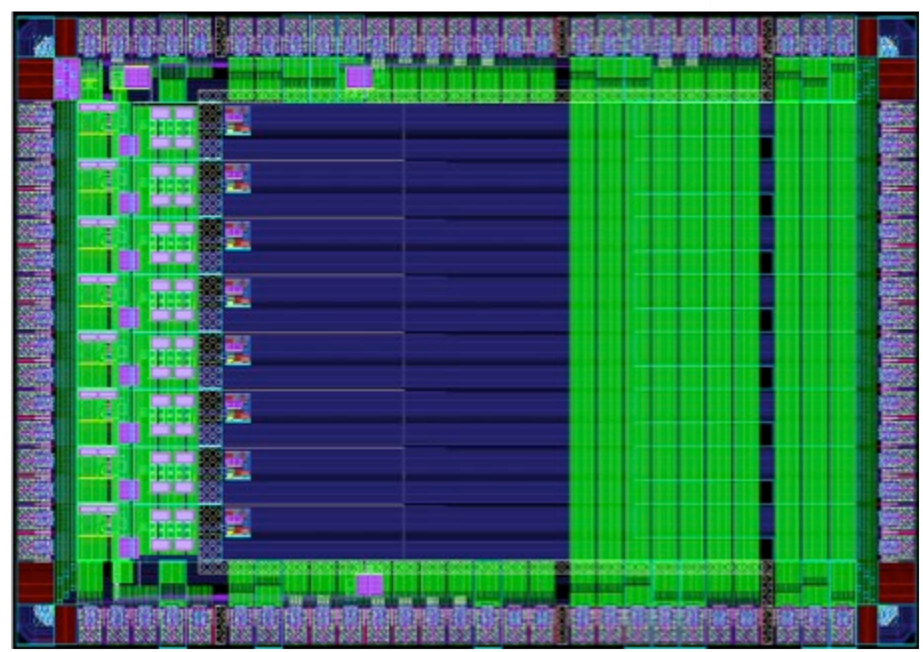


AMPLIFIER

DISCRIMINATOR
first stage +
second stage

STRETCHER =
10x delay blocks

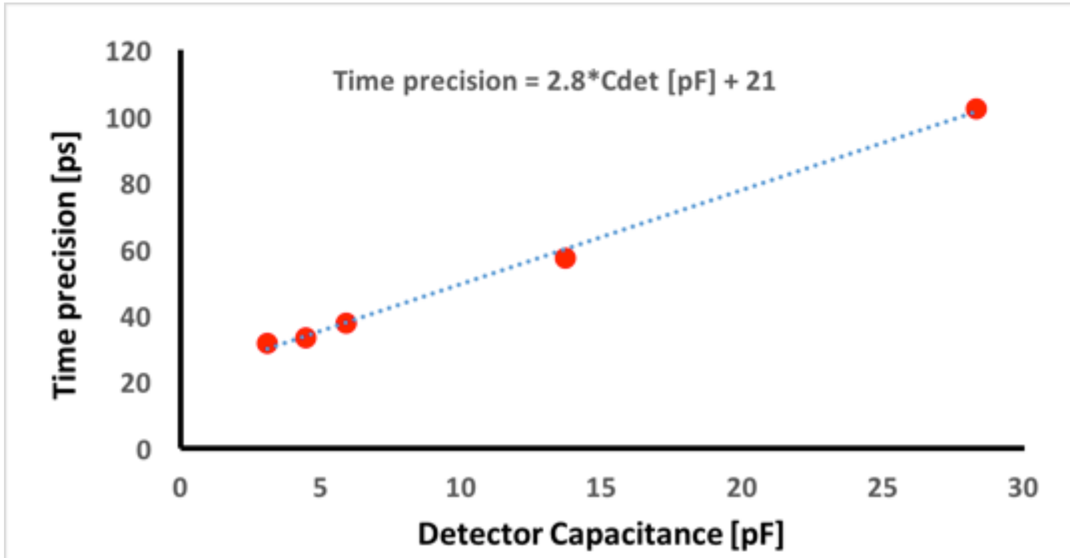




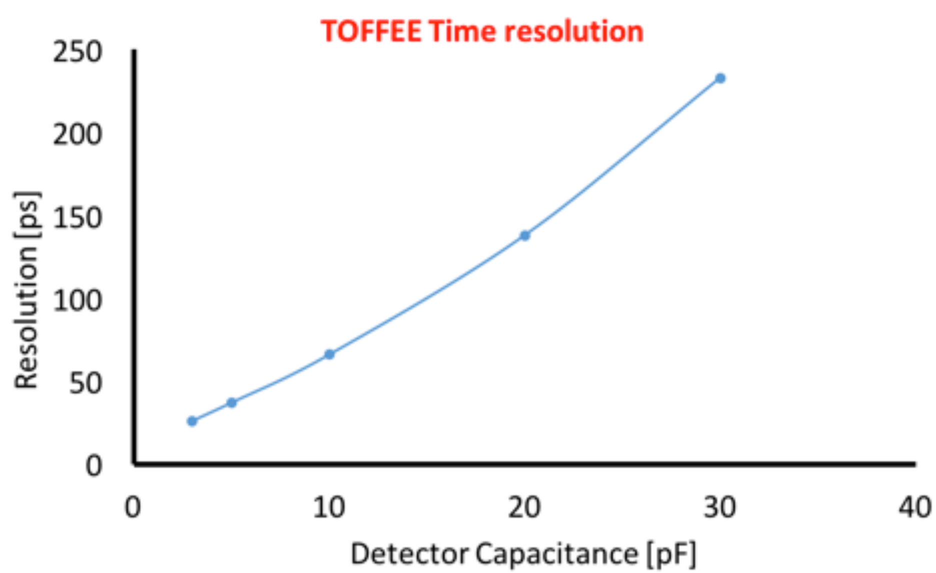
Keep your capacitance low

Two examples of the effect of capacitance on the time resolution

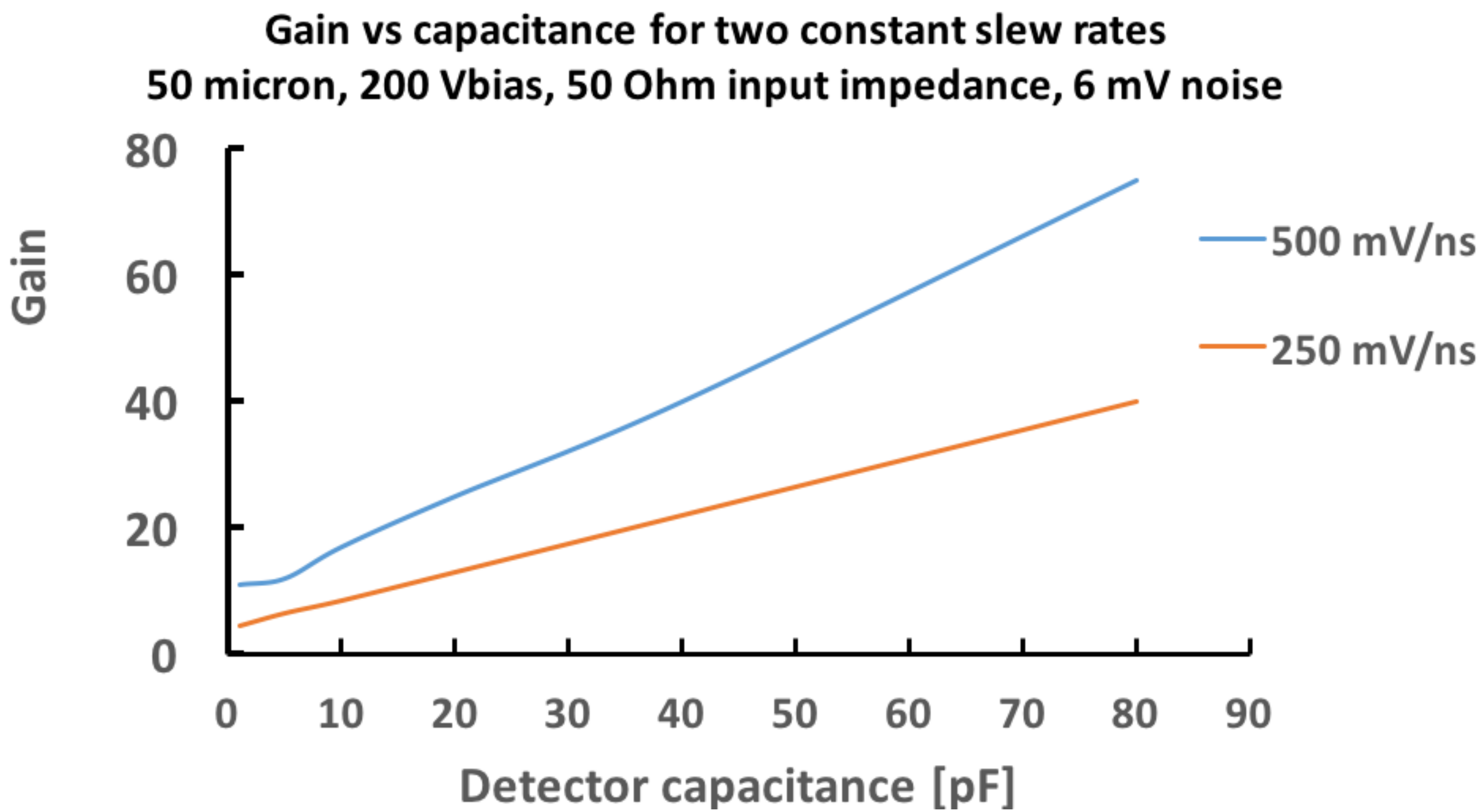
TOTEM current amplifier



TOFFEE fast integrator

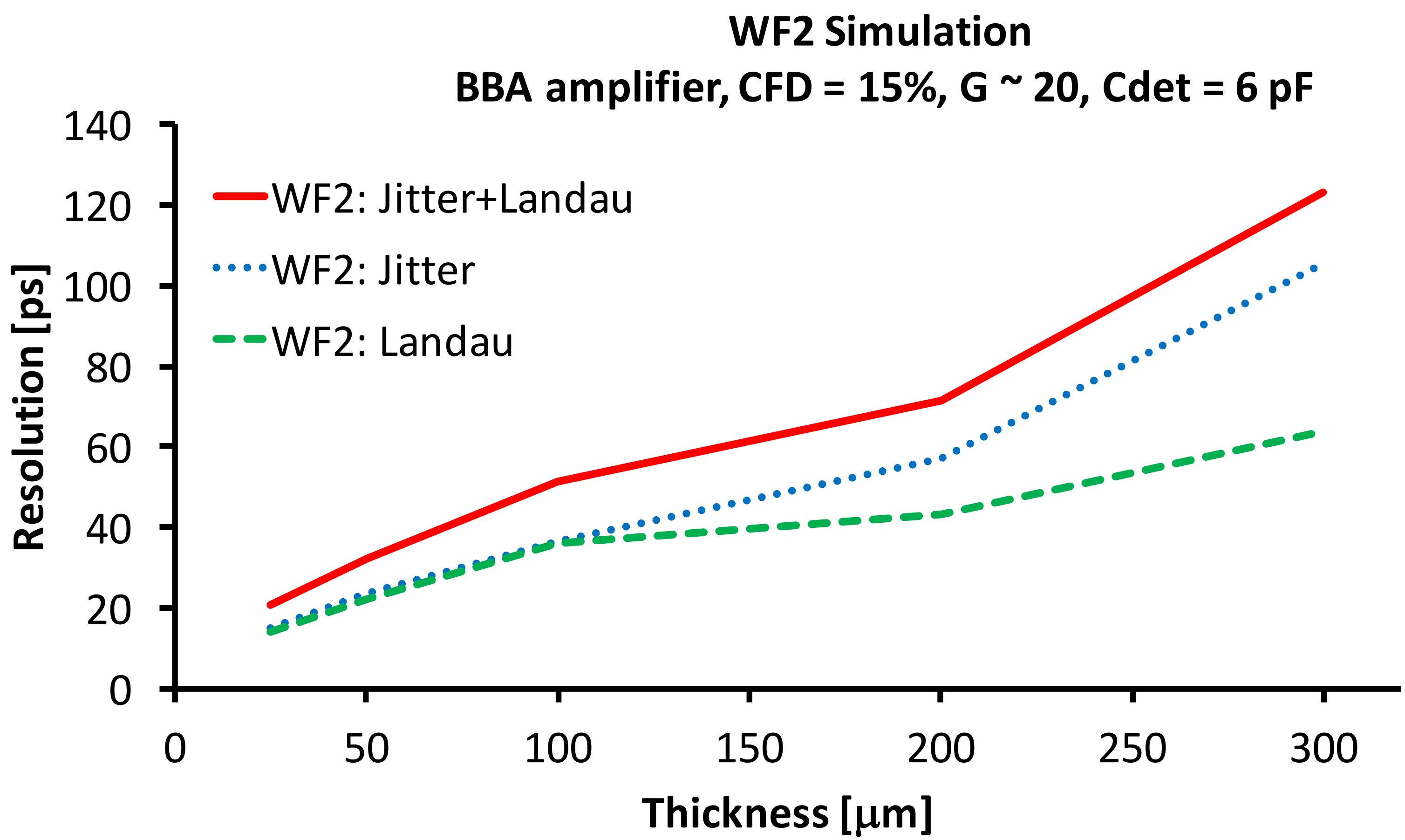


How to read large sensor: more gain



But be aware: more gain is bad for noise, and terrible for radiation damage

How precise can we be?



→ Two main contributions: charge non uniformity and Jitter

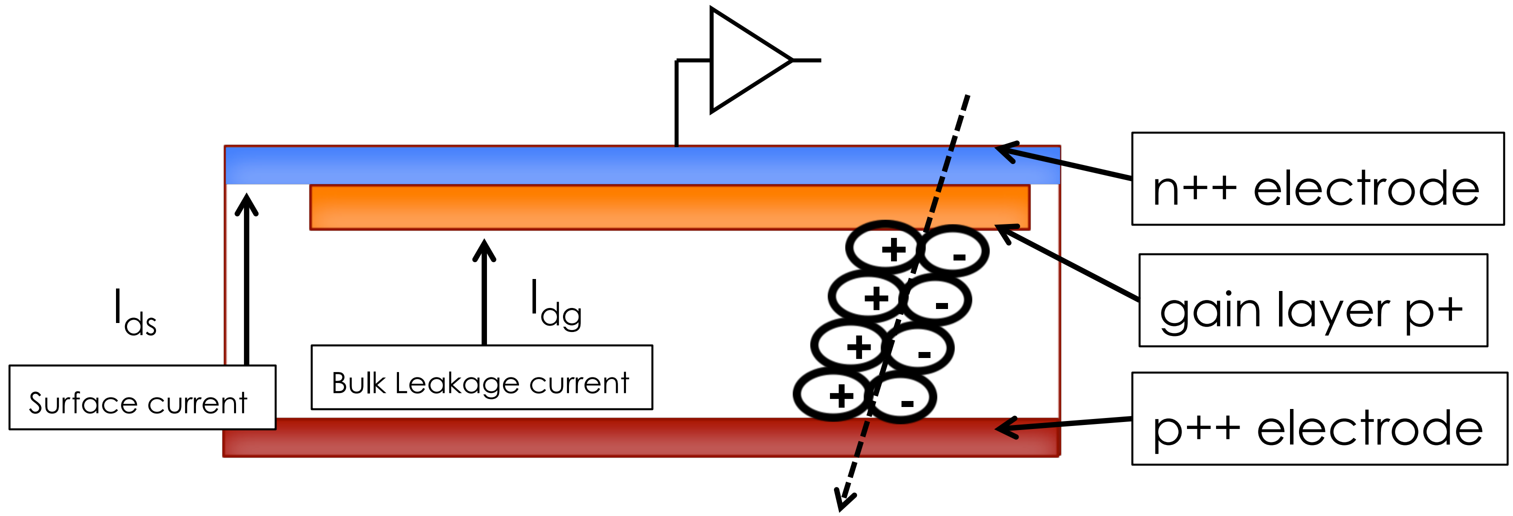
→ The time resolution has a lower limit due to charge non uniformity

Irradiation effects

Irradiation causes 3 main effects:

- Decrease of charge collection efficiency due to trapping
  - ➔ Very small in thin sensor
- Increased leakage current, shot noise ➔ next slides
- Gain layer disappearance ➔ following slides

Shot noise in LGAD - APD



$$i^2_{Shot} = 2eI_{Det} = 2e\left[I_{Surface} + (I_{Bulk})M^2F\right]$$

Current density, nA/sqrt(f)

Correction factor to the standard Shot noise, due to the noise of the multiplication mechanism

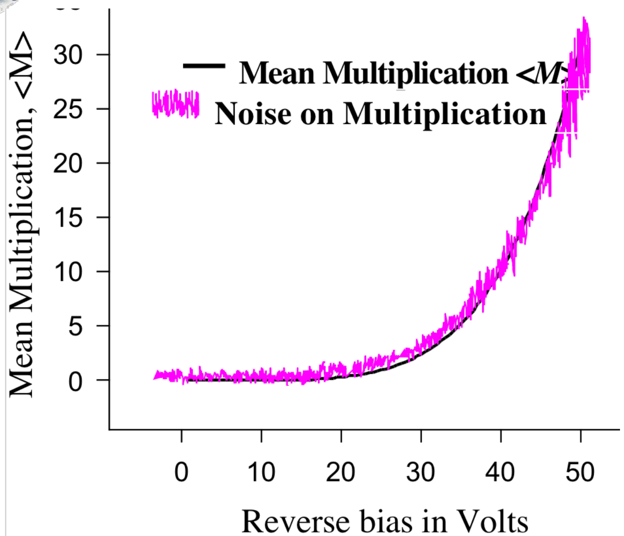
$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

k = e/h ionization rate
x = excess noise index
M = gain

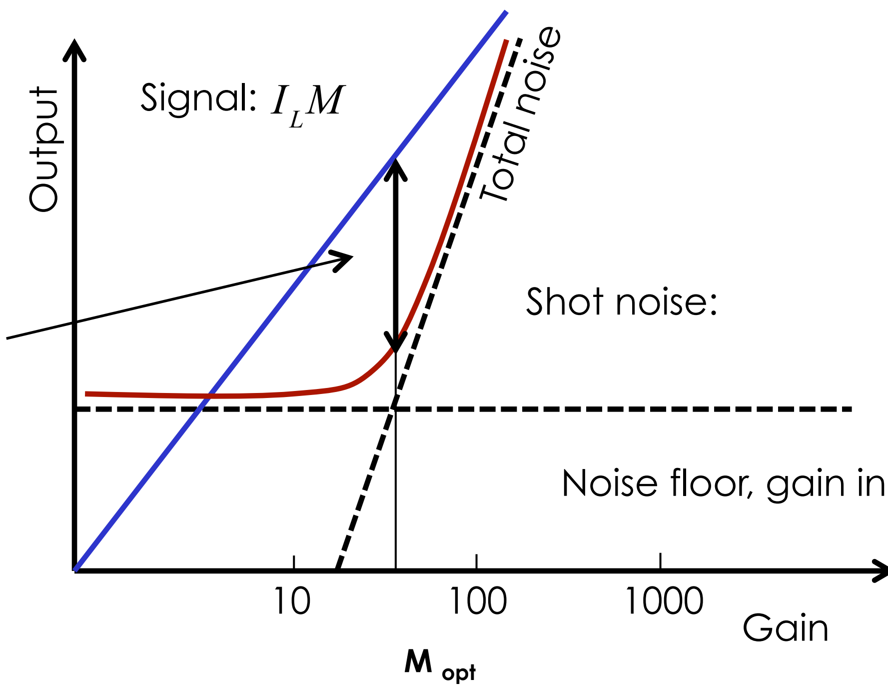
$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \Rightarrow \langle M^2 \rangle = \langle M \rangle^2 F$$

Noise in LGAD & APD – Aide Memoire



Noise increases faster than then signal ➔ the ratio S/N becomes worse at higher gain.

There is an Optimum Gain value: 10-20?



Shot noise

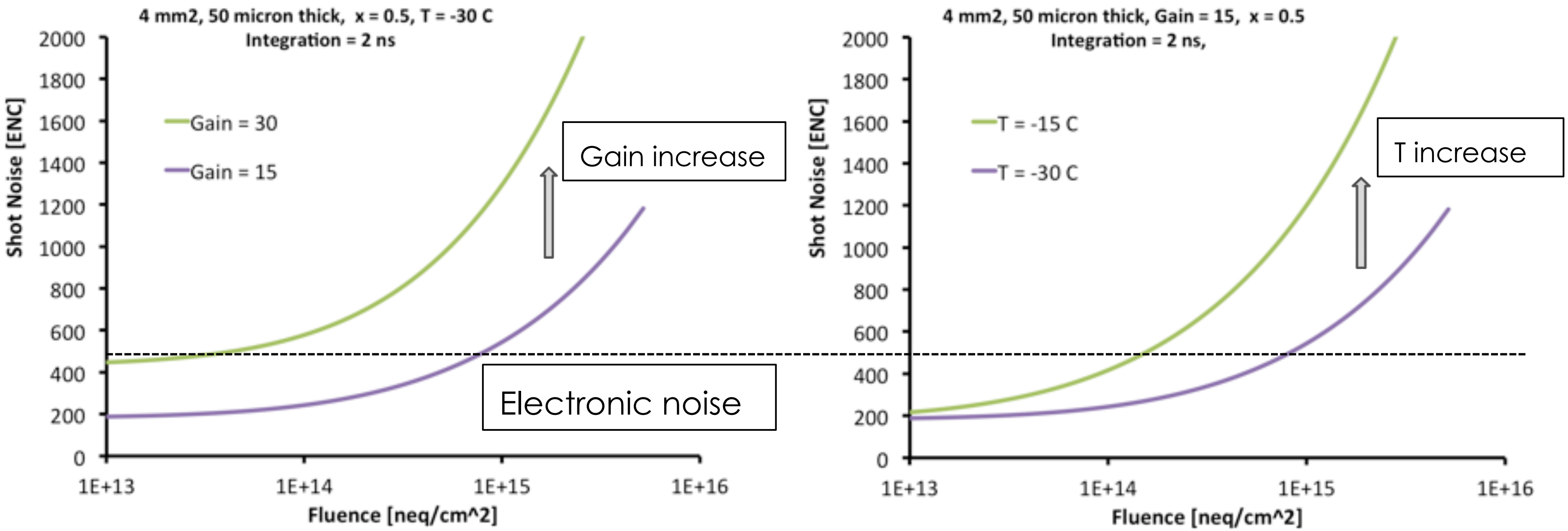
Let's assume a 4 mm^2 pad, 50 micron thick, and a electronic noise of 500 ENC

What is the effect of shot noise as a function of radiation?

Steep dependence on gain

$I = \alpha * \Phi *$ Volume $\alpha = 3\ 10^{-17}$ /cm

Shot noise: $$ENC = \sqrt{\int i^2_{Shot}\, df} = \sqrt{\frac{I * (Gain)^{2+x}}{2e} * \tau_{Int}}$$



To minimize Shot noise:

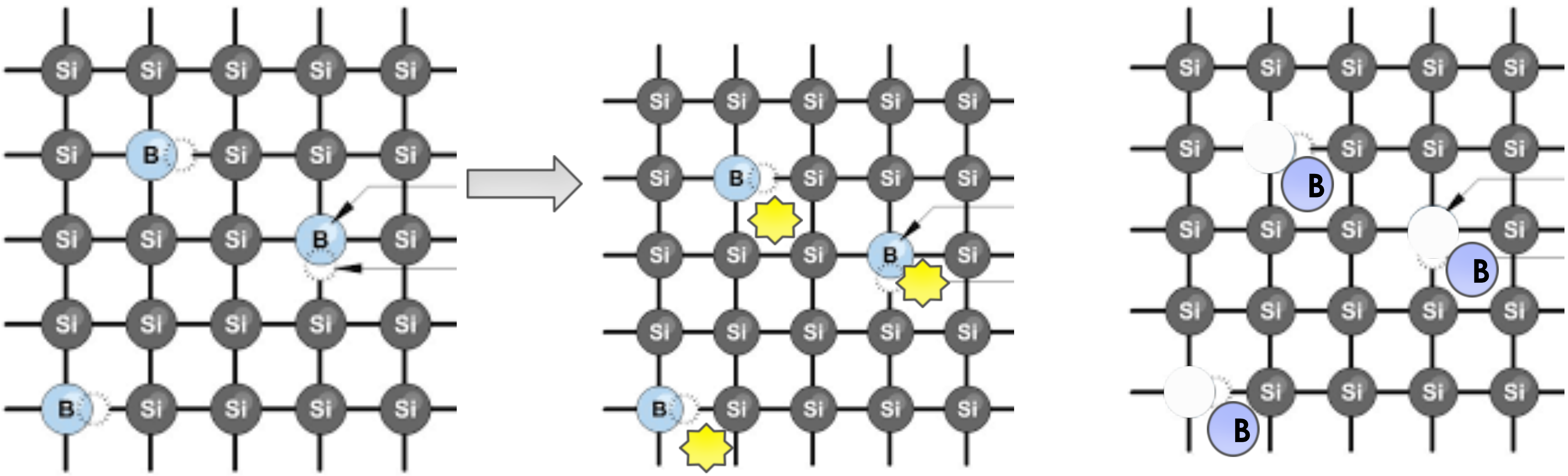
- ➔ Low gain!! Keep the gain below ~ 20
- ➔ Cool the detectors
- ➔ Use small pads to have less leakage current

Radiation issue: Initial acceptor removal

This term indicates the "removal" of the initially present p-doping.

For UFSD this is particularly problematic as it removes the gain layer

Irradiation ➔ Defects ➔ Boron becomes interstitial



The boron doping is still there, only it has been moves into a different position and it does not contribute to the doping profile, it is inactive

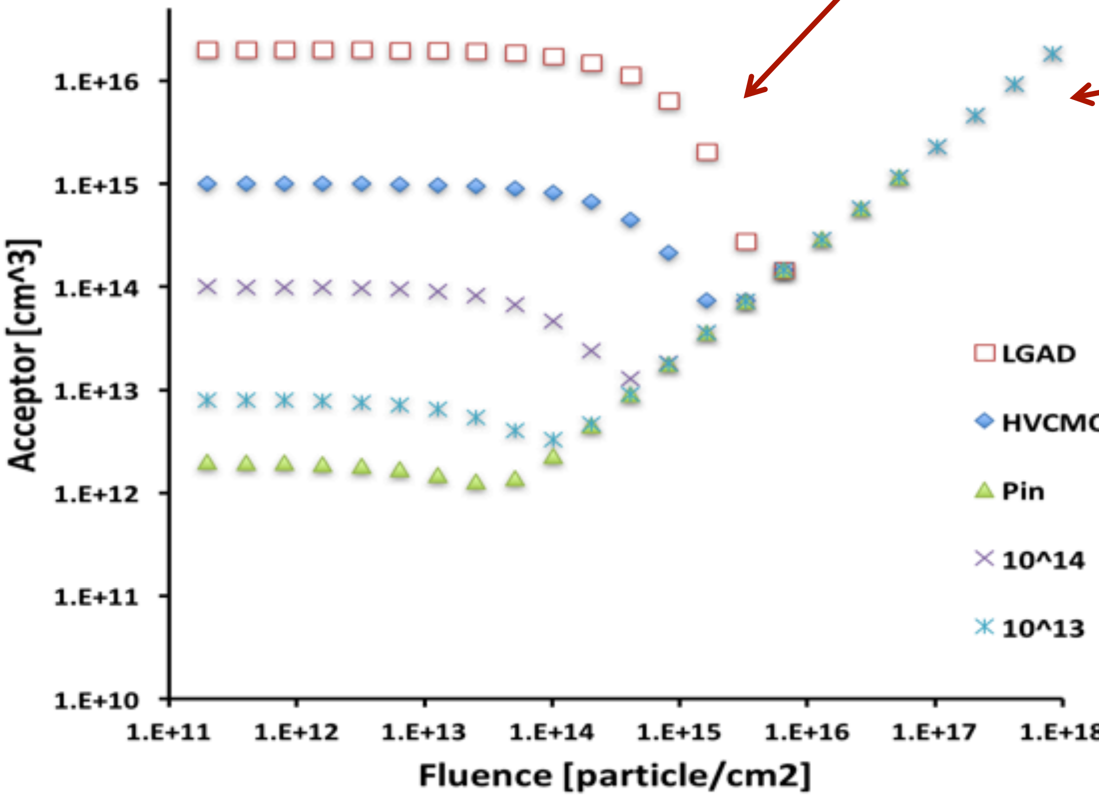
Irradiation main problem: gain layer disappearance

Density of the doping vs irradiation:

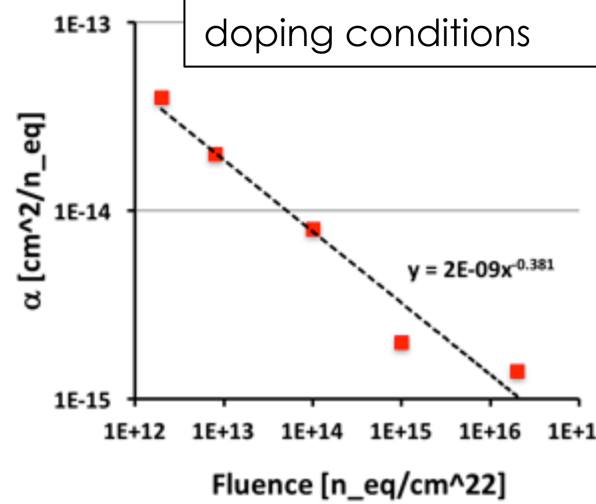
$$N_D = N_0 e^{-\alpha\phi} + \beta\phi$$

Initial acceptor removal

Deep level creation
p-doping lookalike

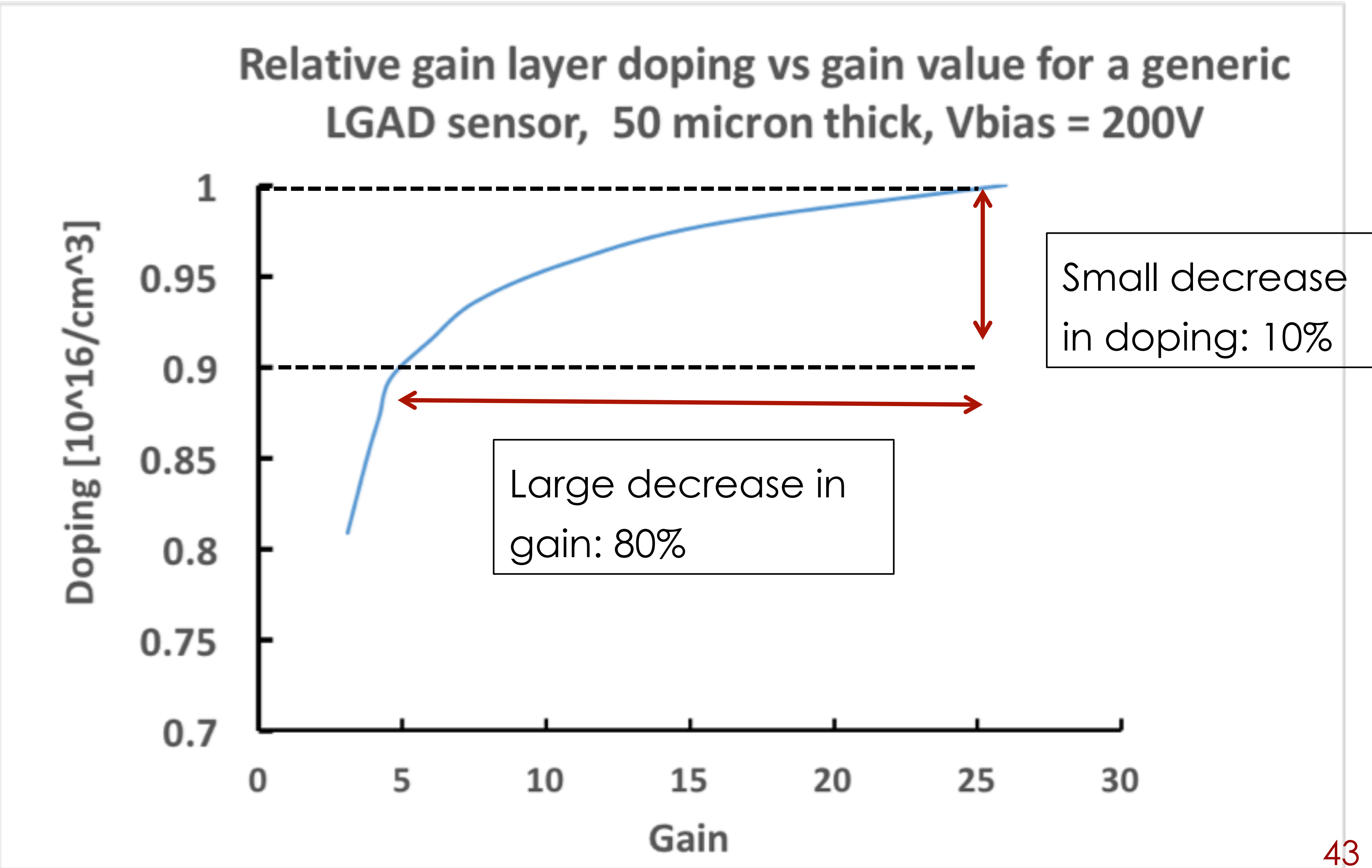


α is a function of initial doping conditions



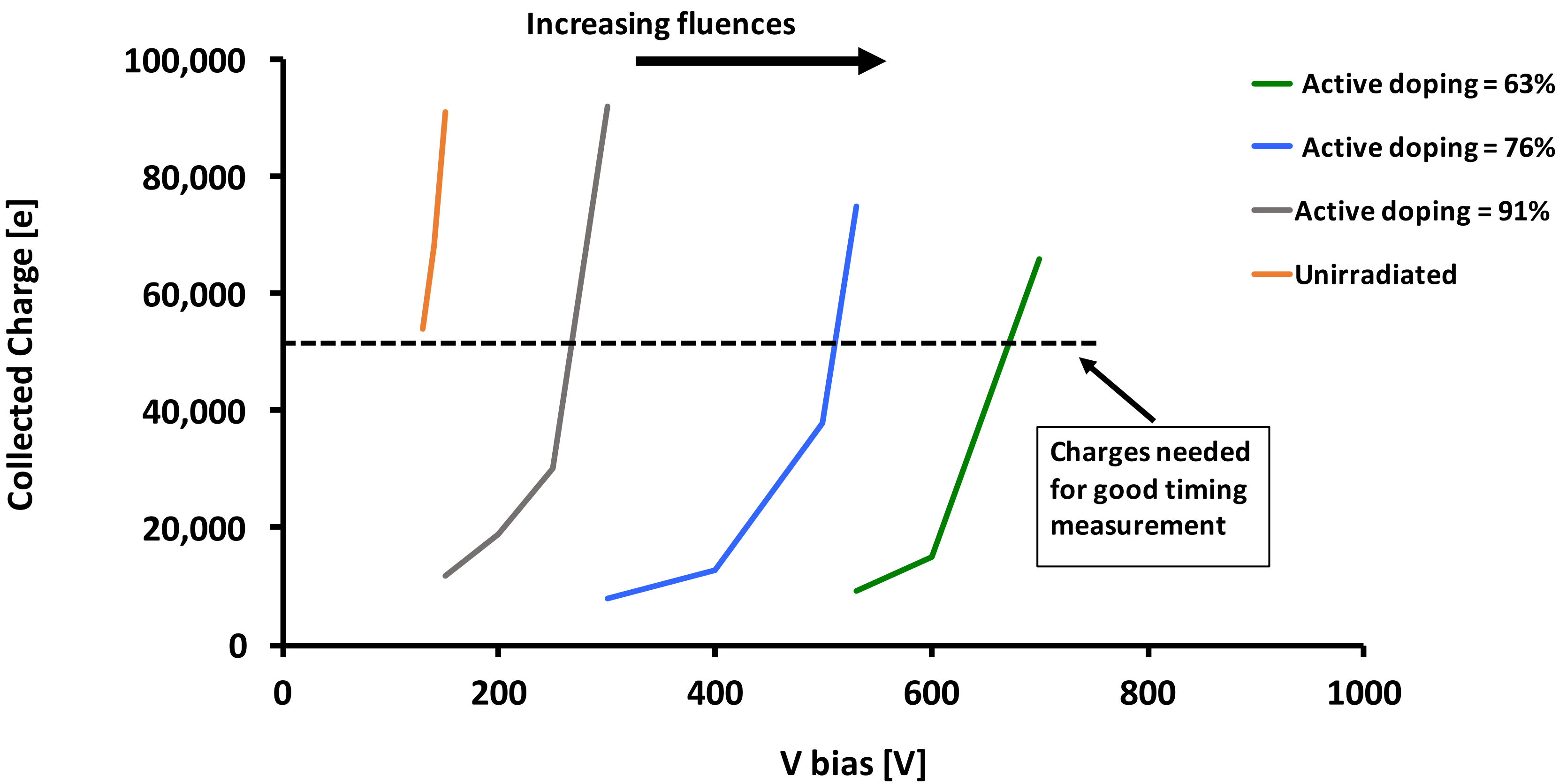
Gain vs gain layer doping

Unfortunately, the gain is very sensitive to the doping level



Compensation with Vbias

The necessary field can be recovered by increasing the external Vbias: proven to work up to 5 10^{14} n^{eq}/cm^2



How can we sustain more radiation?

There is the understanding that Boron is not "gone", but it is simply inactive, it has gone from being sub-stitutional to being interstitial.

➔ The Boron presence has been measured after irradiation

What can we do?

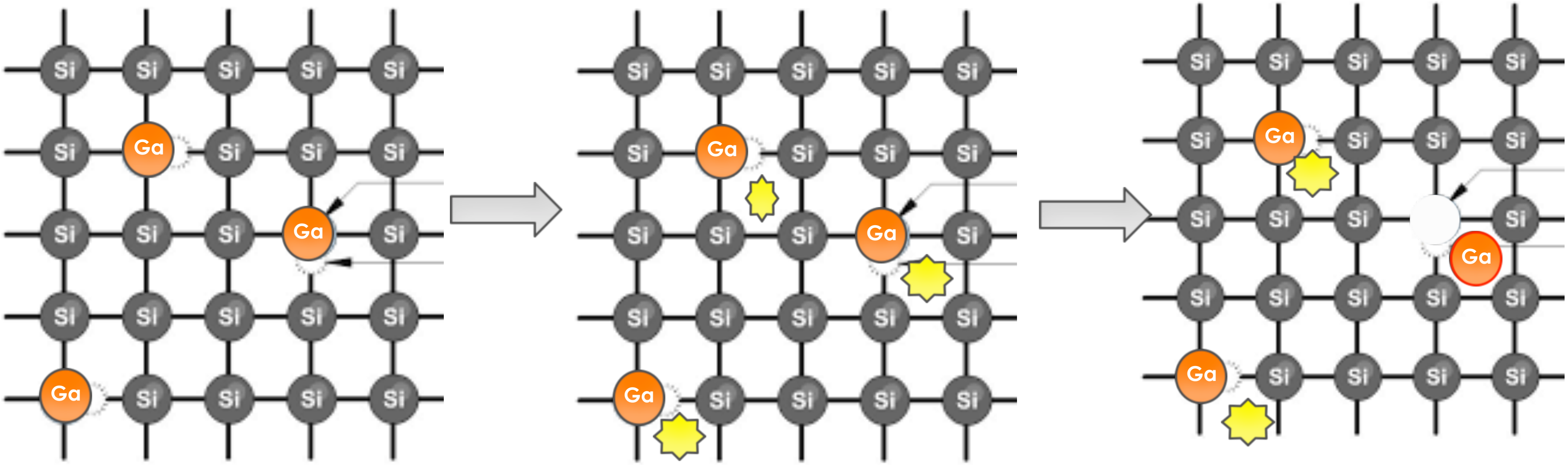
➔ Try different manufactures
- CNM has been tested
- FBK and HPK are being tested as we speak, results at TREDI 2017, end of February

➔ Try different dopant: use Gallium instead of Boron
- Being manufactured right now

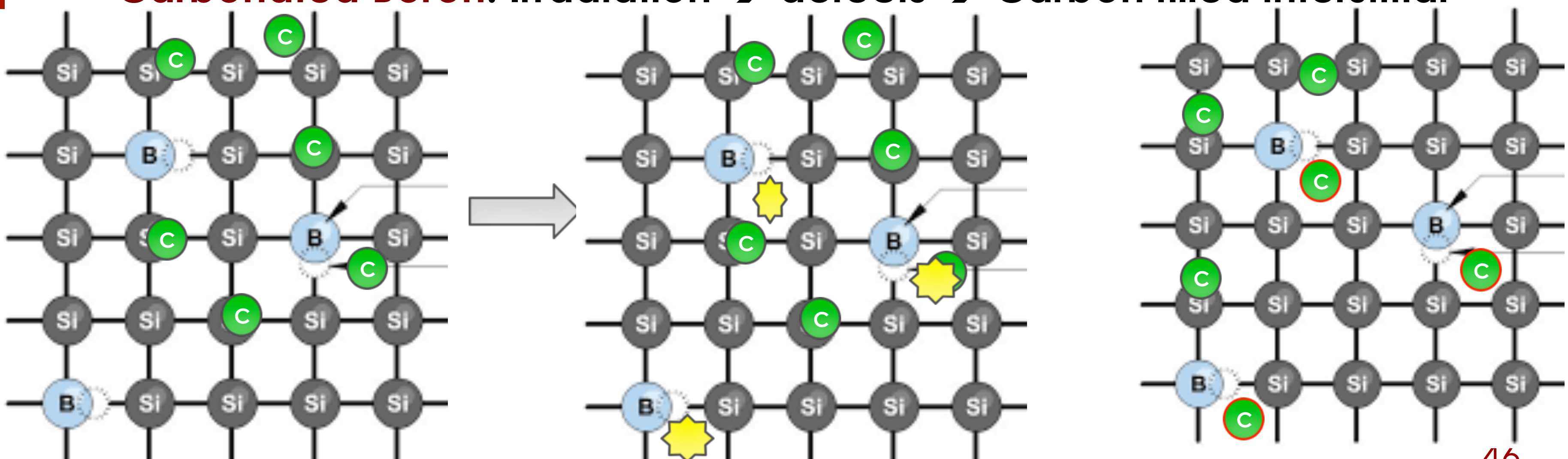
➔Add carbon to the gain layer
- It might protect the Boron…

Initial acceptor removal: mitigation

Gallium doping: Irradiation ➔ defects ➔ Lower diffusivity

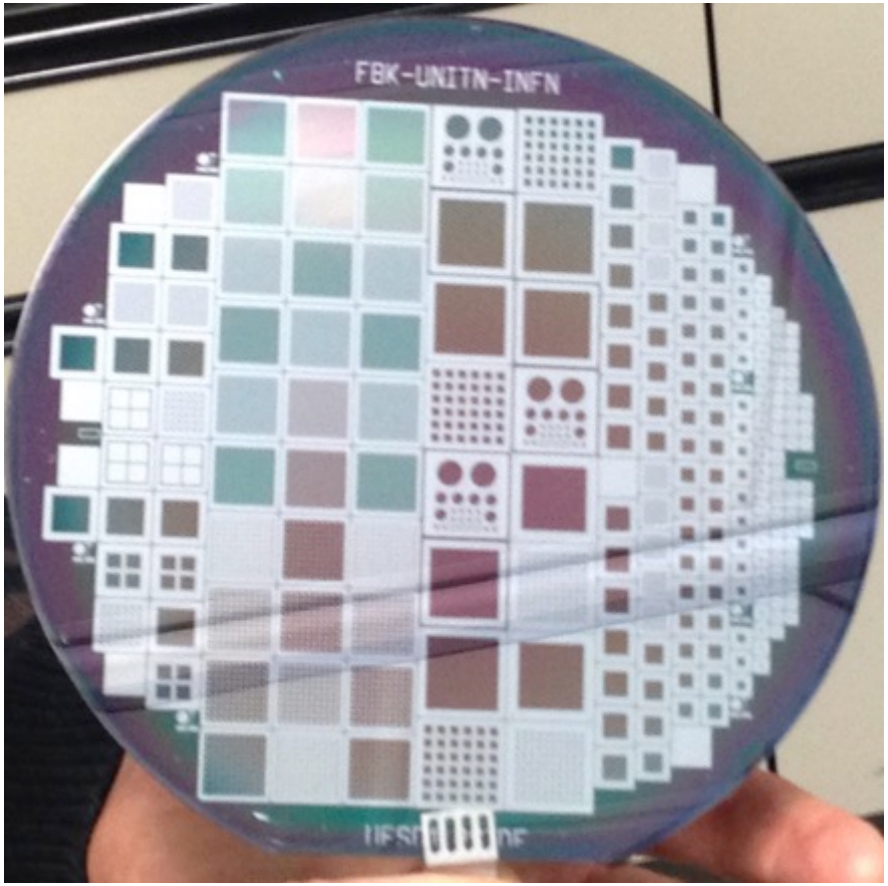


Carbonated Boron: Irradiation ➔ defects ➔ Carbon filled interstitial

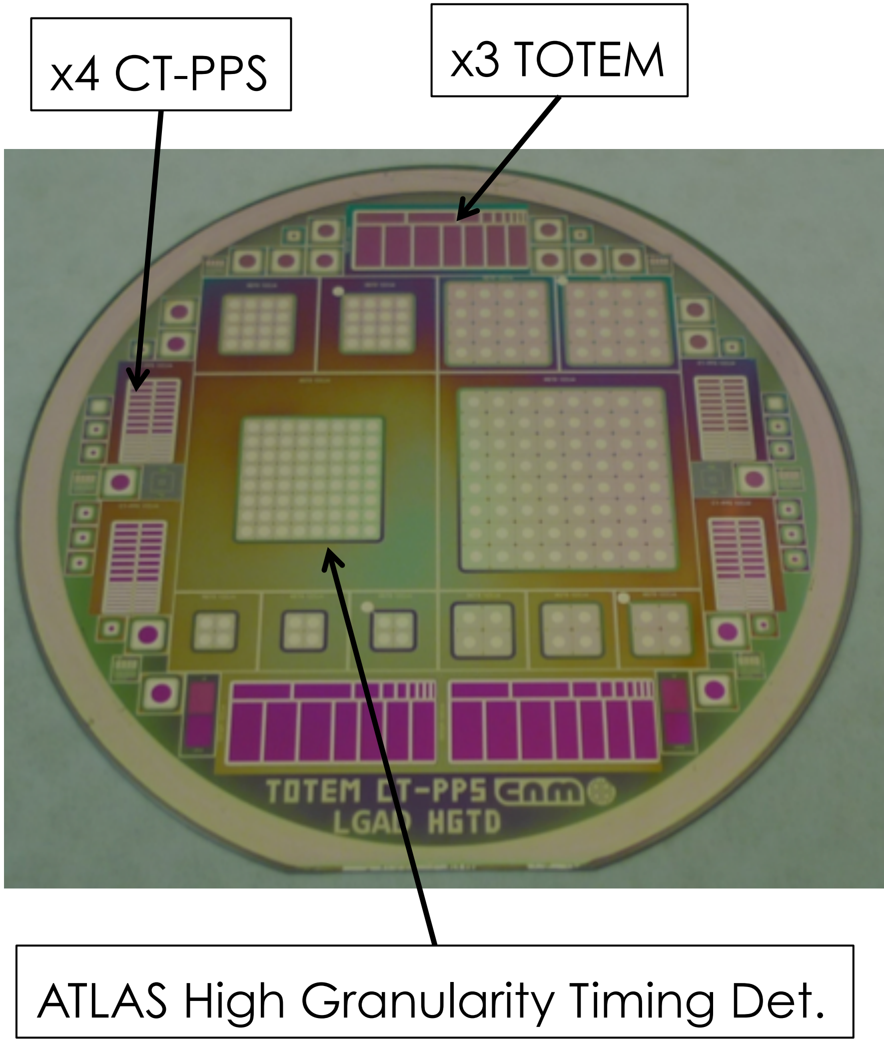


Sensors: FBK & CNM

FBK 300-micron production
Very successful, good gain and overall behavior
➔ We have now a second producer



CNM 75-micron
CNM 50-micron production



Sensors for the CMS CT-PPS detectors

New production of 50 micron thick, segmented UFSD sensors.

Gain ~ 15

32 fat strip array for CT-PPS

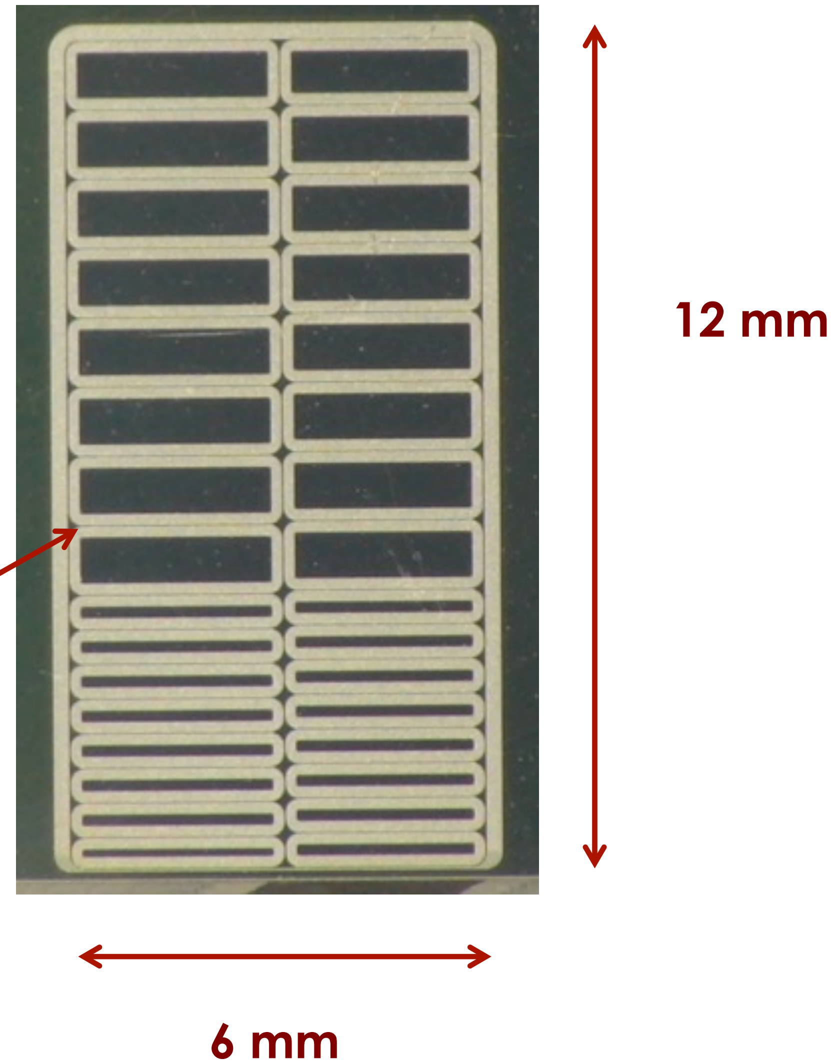
Strips:

3 mm x 0.5 mm

3 mmx x 1 mm

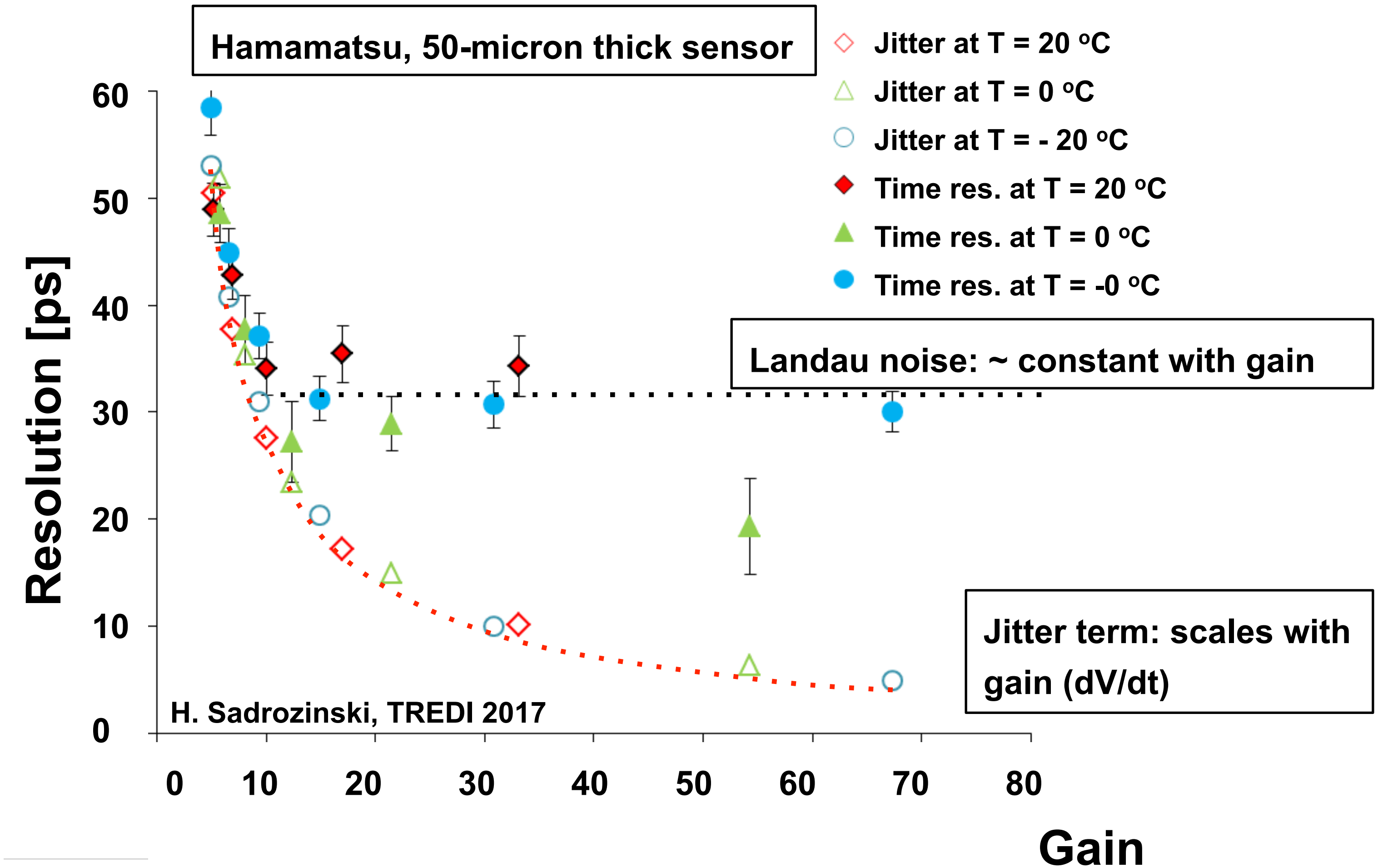
Distance between pads: 50 micron

➔ Able to produce segmented UFSD



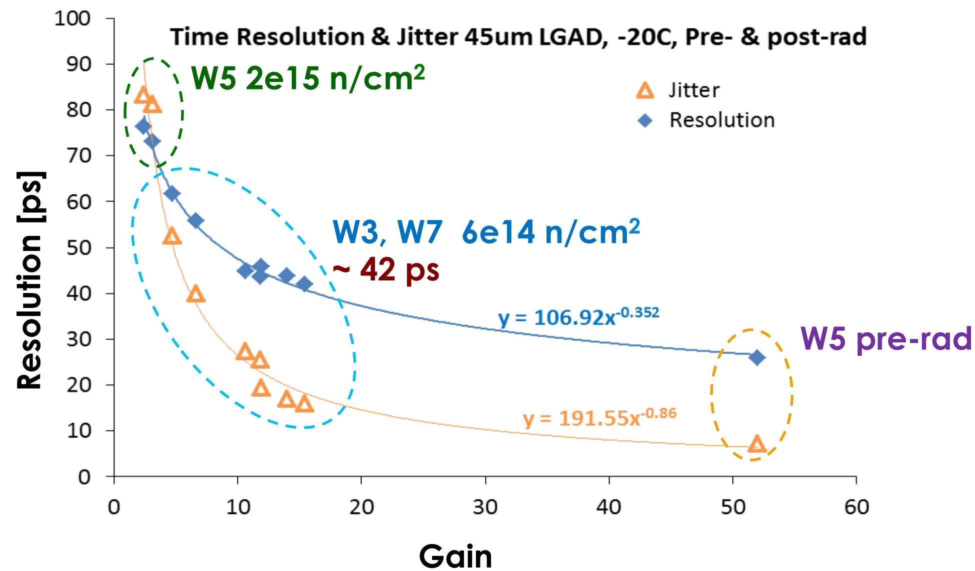
Latest results on UFSD time resolution

UFSD from Hamamatsu confirm our simulation: 30 ps time resolution,
Value of gain ~ 20

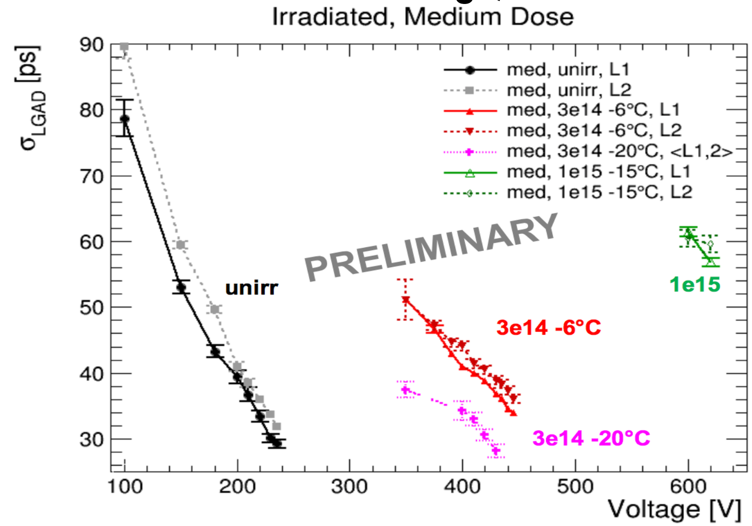


Time resolution for irradiated sensors

H. Sadrozinski, TREDI 2017

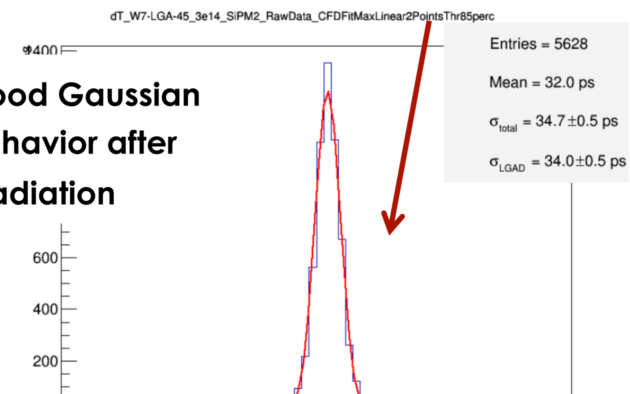


J. Lange, TREDI 2017



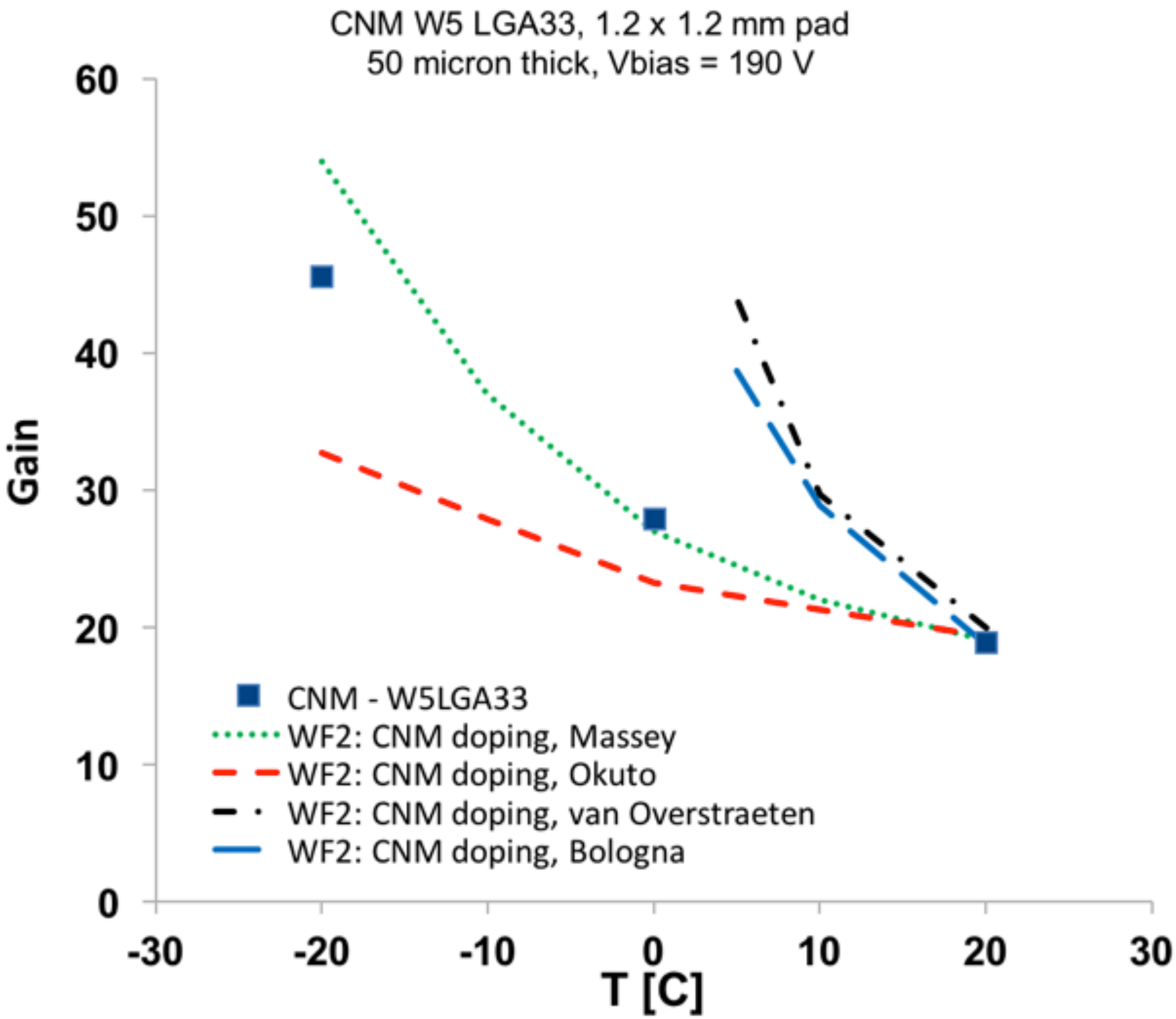
No unexpected features, the signals are still large and the leakage current does not prevent to reach good time resolution.

Good Gaussian behavior after irradiation



No difference in behavior before and after irradiation: the time resolution scales with gain. ➔ Keep the gain high

Running cold

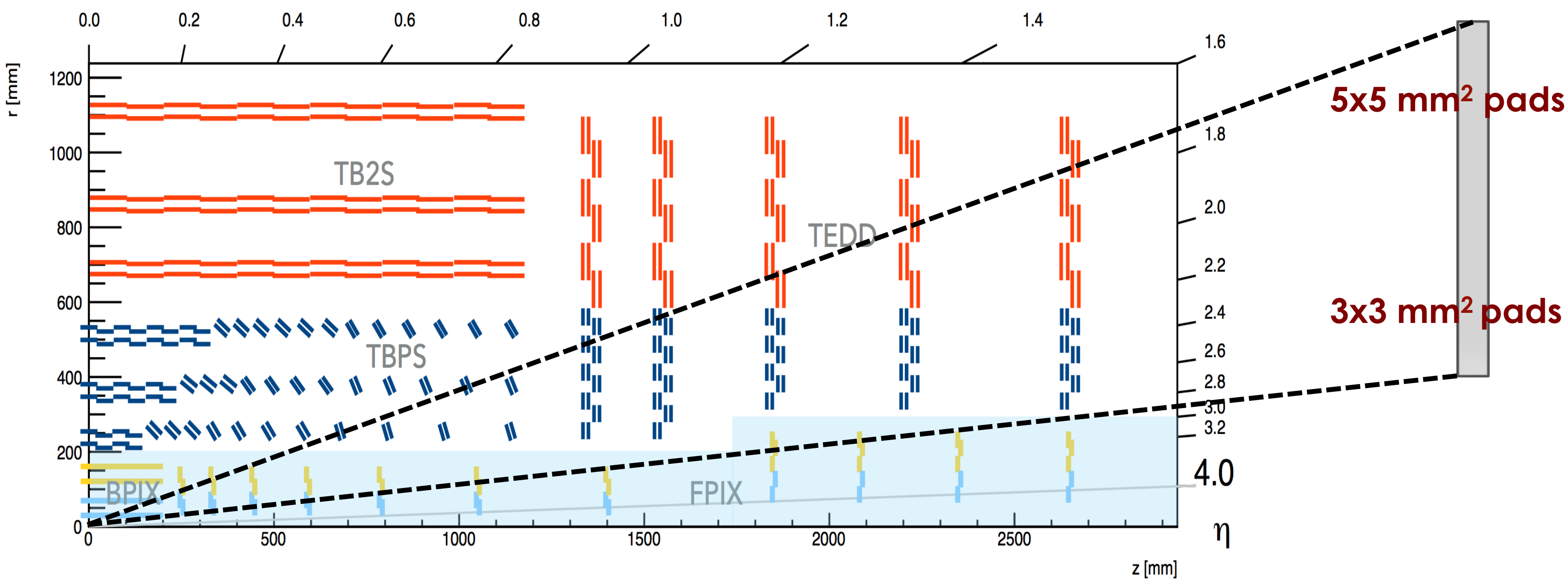


And now we need to build the detector..

Position? We don't quite know, but we assume outside the tracker

Granularity? If we want to keep 1% occupancy, the sensor should be about 3 x 3 mm^2 in the inner part and 5 x5 mm^2 in the out

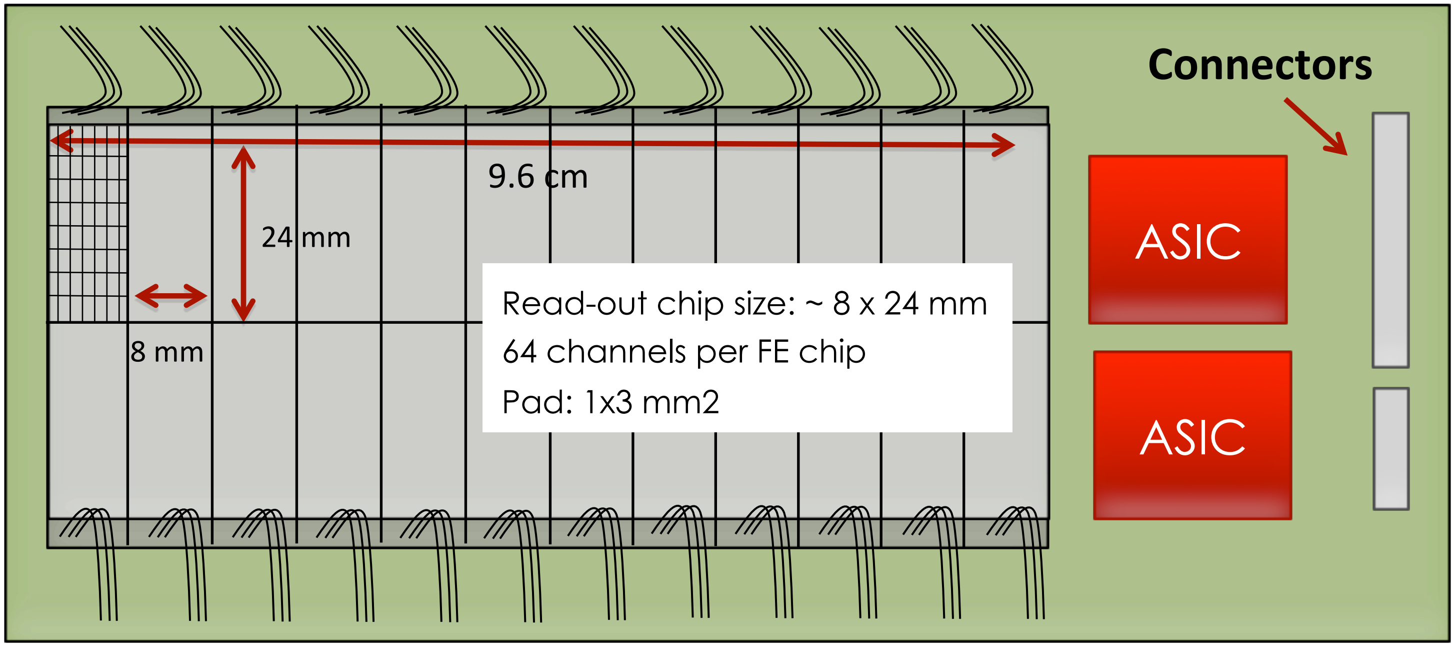
Not in the trigger



And: mechanics, cooling, HV & LV distribution, High precision clock, data transmission

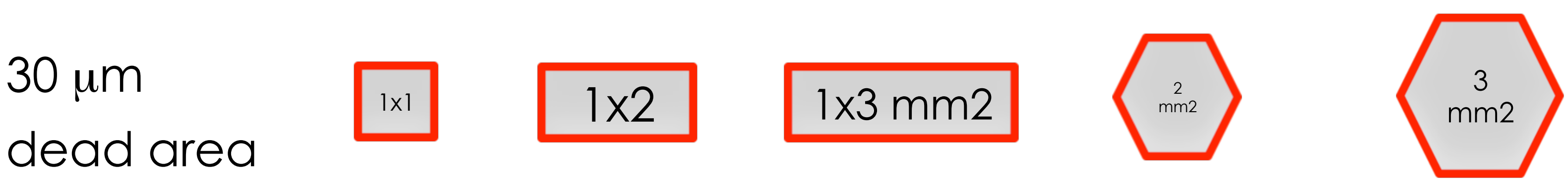
CMS Timing Module for the endcap

Use the geometry 5x10 cm2 as baseline



From physics: what is the granularity? 1x1 mm2, 1x2 mm2, 1x3 mm2.

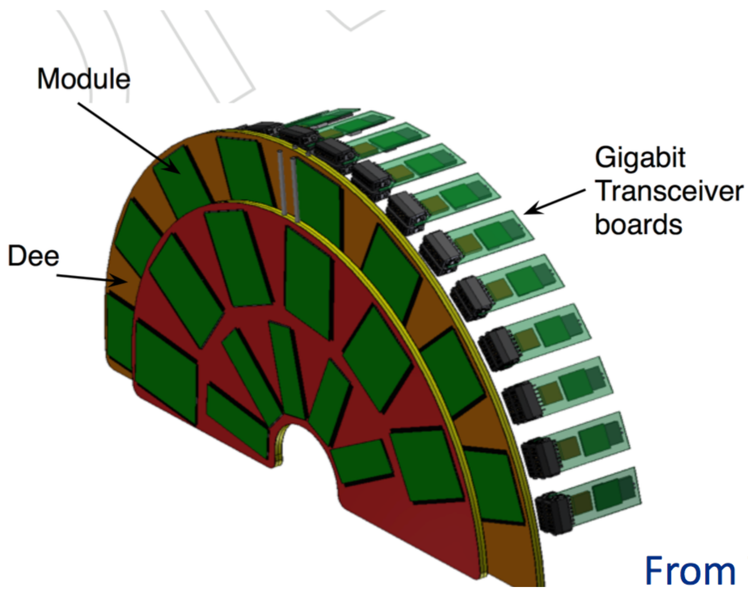
Shall we use hexagon to minimize the perimeter?

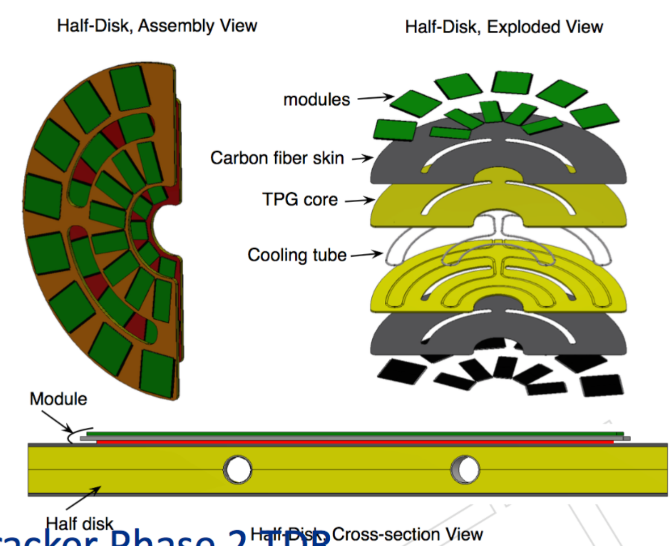


Dead area:	**12%**	**9%**	**8%**	**9%**	**6%**

Endcap disks

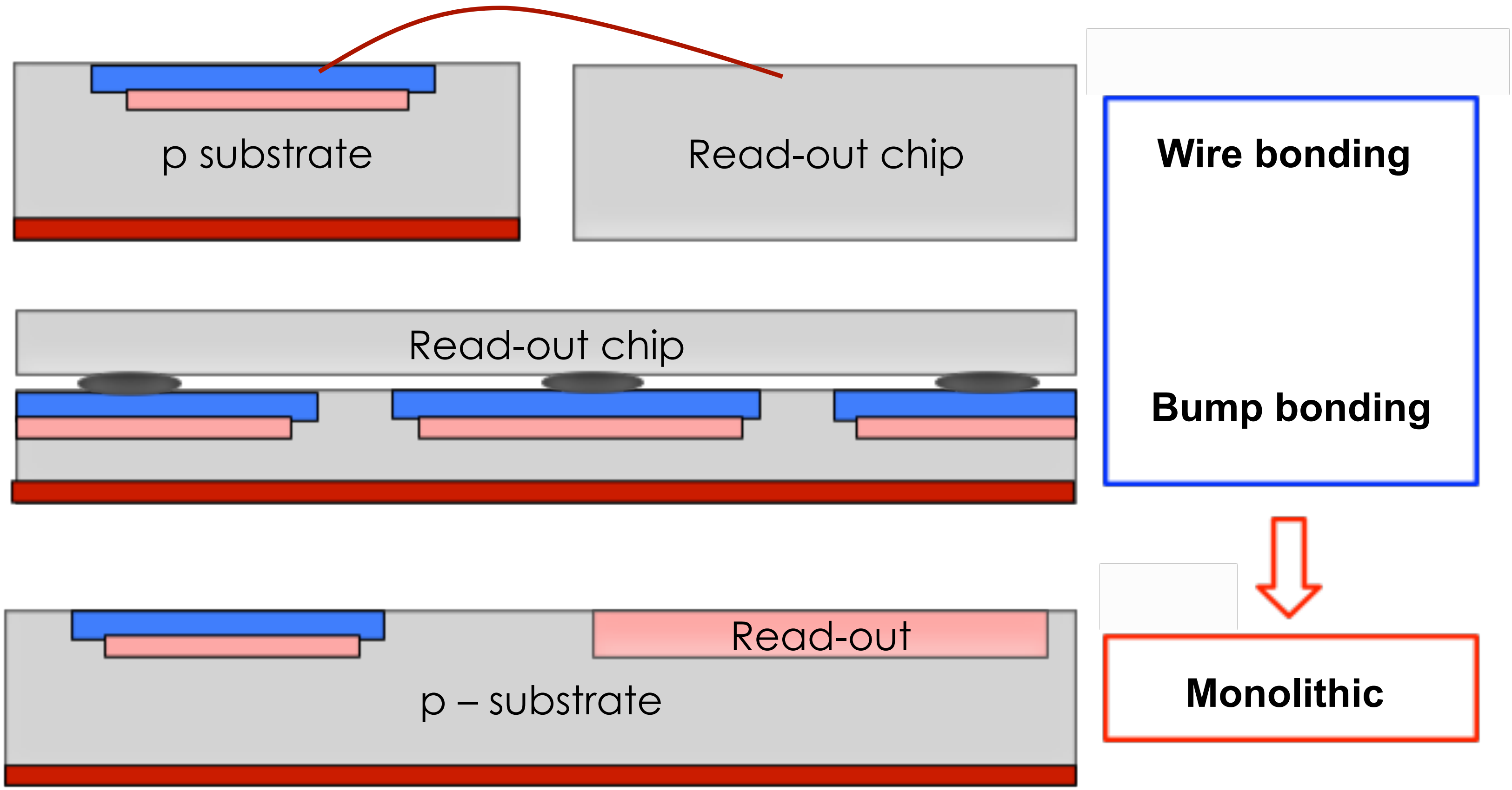
- ETL support structure similar to pixel upgrade
  - Modules are mounted on planar half-disc structures
  - Modules placed on both sides of the dees to provide hermetic coverage
- CO_2 flows in embedded tubes under the ROCs
  - Sensors and ROC running at -25°C
- Many common aspects with the tracker: a lot of expertise and experience to borrow
  - Manual jig-based assembly technique, will consider robotic assembly as well
- The routing of services, cooling, and support designed by FNAL engineer





From Tracker Phase 2 TDR

Can we use Monolithic technology?



Summary

4Dimensional timing can be achieved using special silicon sensors with internal gain

In the proposed Timing Detector, CMS foresees to use crystals in the barrel and UFSD sensors in the endcap

UFSD sensors are currently the only technology available able to maintain good gain up to $\sim 10^{15}\ n_{eq}/cm^2$

CMS timing layer will be discussed **TODAY** at the CMS management board, and then, eventually, by the full collaboration during the first week of April.

References

1. R. Mulargia et al, “Temperature dependence of the response of Ultra Fast Silicon Detectors” Pixel 2016, to be published in JINST 11 (2016) C12016
2. N. Cartiglia et al, “The 4D pixel challenge”, JINST 11 (2016) C12016
3. N. Cartiglia et al, “Beam test results of a 16 ps timing system based on ultra-fast silicon detectors”, NIMA 850 (2017) 83 – 88
4. B. Baldassarri et al, Signal formation in irradiated silicon detectors, NIMA 845 (2017) 20 – 23
5. N. Cartiglia et al, Tracking in 4 Dimensions, NIMA 845 (2017) 47 – 51
6. N. Cartiglia et al, Design Optimization of Ultra-Fast Silicon Detector, NIMA 796 (2015) 141-148, doi:10.1016/j. nima.2015.04.025i
7. F. Cenna et al, Weightfield2: A fast simulator for silicon and diamond solid state detector, NIMA 796 (2015) 149-153, doi:10.1016/j.nima.2015.04.015
8. G-F Dalla Betta et al, Design and TCAD simulation of double-sided pixelated low gain avalanche detectors, NIMA 796 (2015) 54-157, doi:10.1016/j.nima.2015.03.039
9. N. Cartiglia et al., Timing Capabilities of Ultra-Fast Silicon Detectors, doi:10.5506/APhysPolBSupp.7.657
10. N. Cartiglia, et al., Performance of Ultra-Fast Silicon Detectors, JINST 9 (2014) C02001
11. H.-W. Sadrozinski et al., Sensors for ultra-fast silicon detectors, NIMA 765 (2014) 7
12. H.-W. Sadrozinski, et al., Ultra-fast silicon detectors, NIMA 730 (2013) 226-231

Acknowledgement

This research was carried out with the contribution of the Ministero degli Affari Esteri, "Direzione Generale per la Promozione del Sistema Paese" of Italy.

Ministero degli Affari Esteri e della Cooperazione Internazionale

DIREZIONE GENERALE
PER LA PROMOZIONE DEL SISTEMA PAESE
Unità per la cooperazione scientifica e tecnologica bilaterale e multilaterale

This work is currently supported by INFN Gruppo V, UFSD project (Torino, Trento Univ.,FBK).

This work was developed in the framework of the CERN RD50
The work is supported by HORIZON2020 Grants and UFSD ERC grant UFSD669529

Backup

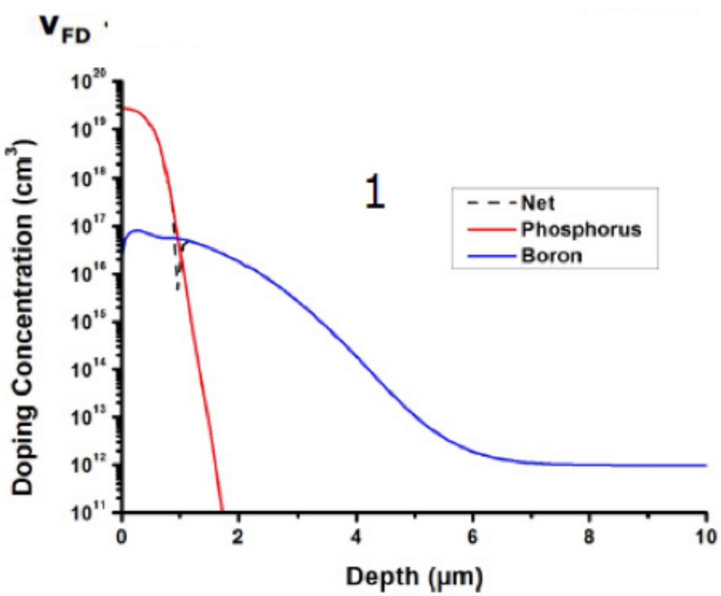
Low Gain Avalanche Detectors (LGADs)

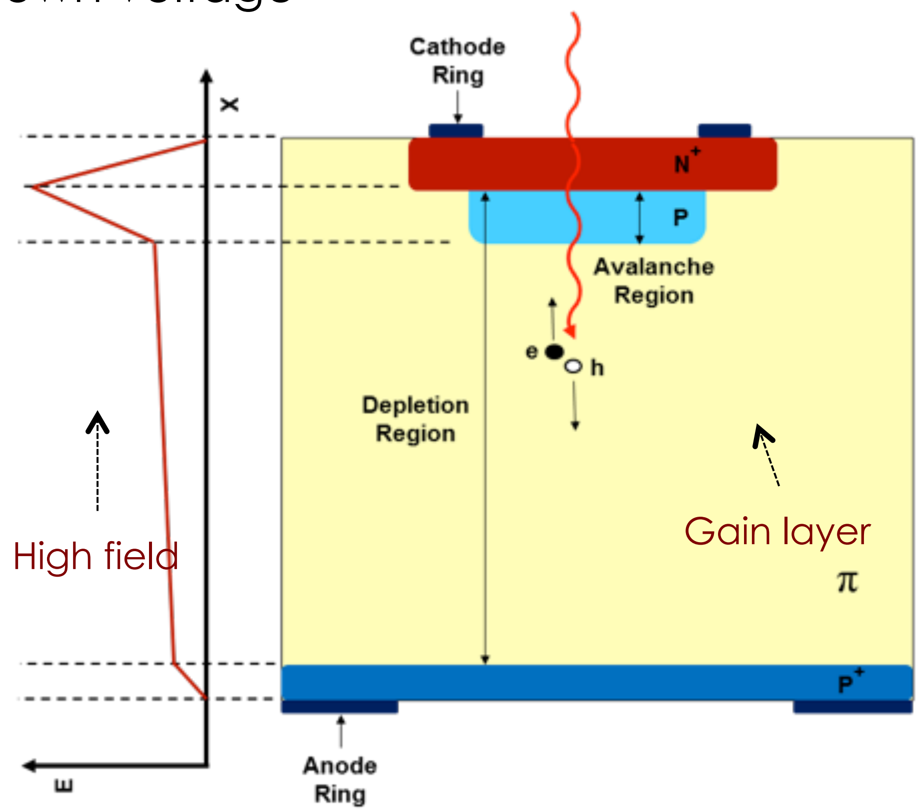
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

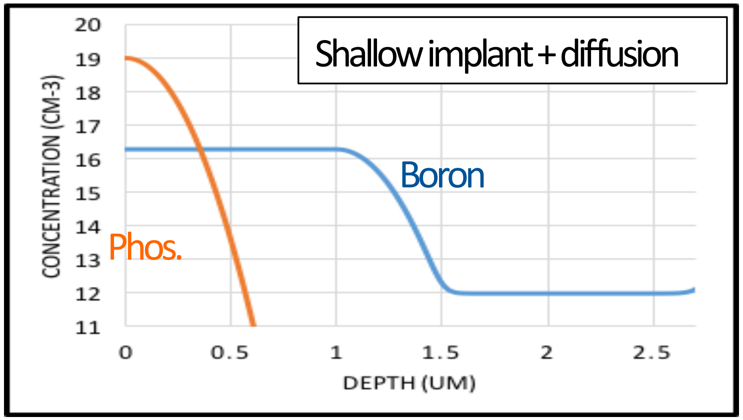


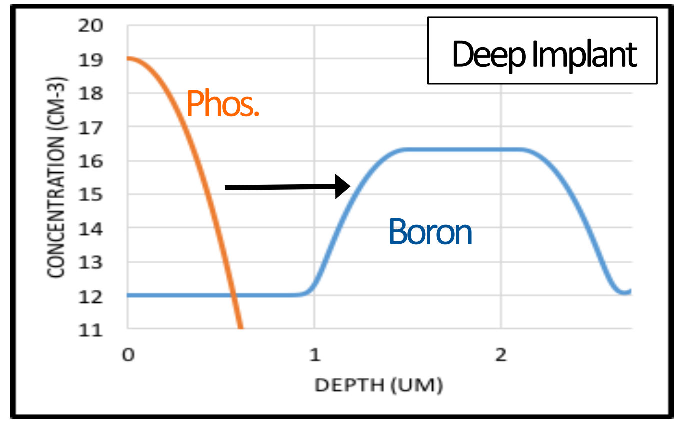


Gain layer design

The doping profile of the Gain layer controls the shape of the Electric Field

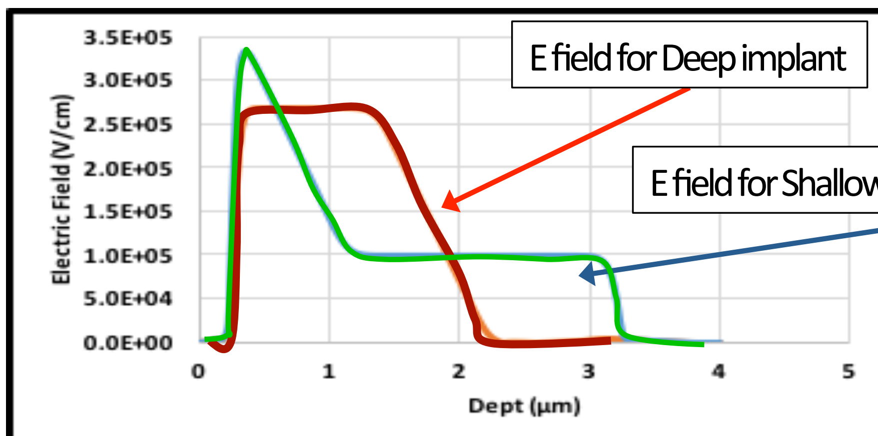
2 technological approaches are possible:





The deep implant approach has several advantages:

- Avoid peaked Electric Field -> less noise
- Is more reliable (independent of thermal diffusion and of doping compensation effect)



CMM
CENTRE FOR MATERIALS AND MICROSYSTEMS

When do we decide?

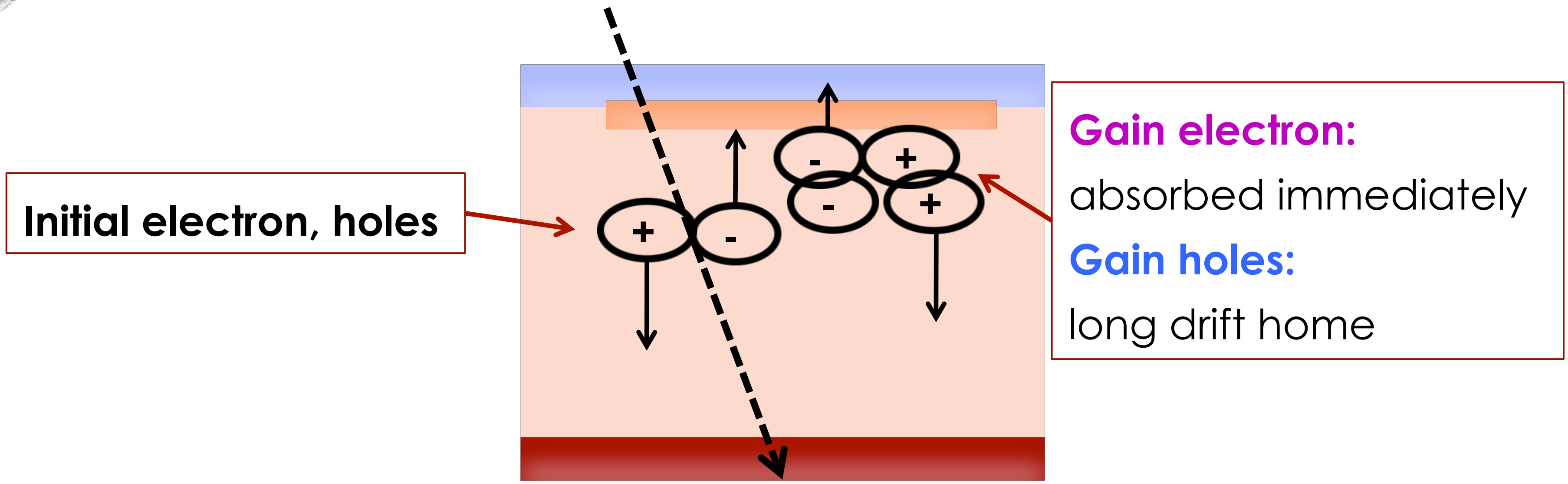
CMS plans to reach a decision on whether or not to proceed with the R&D phase by LHCC in May

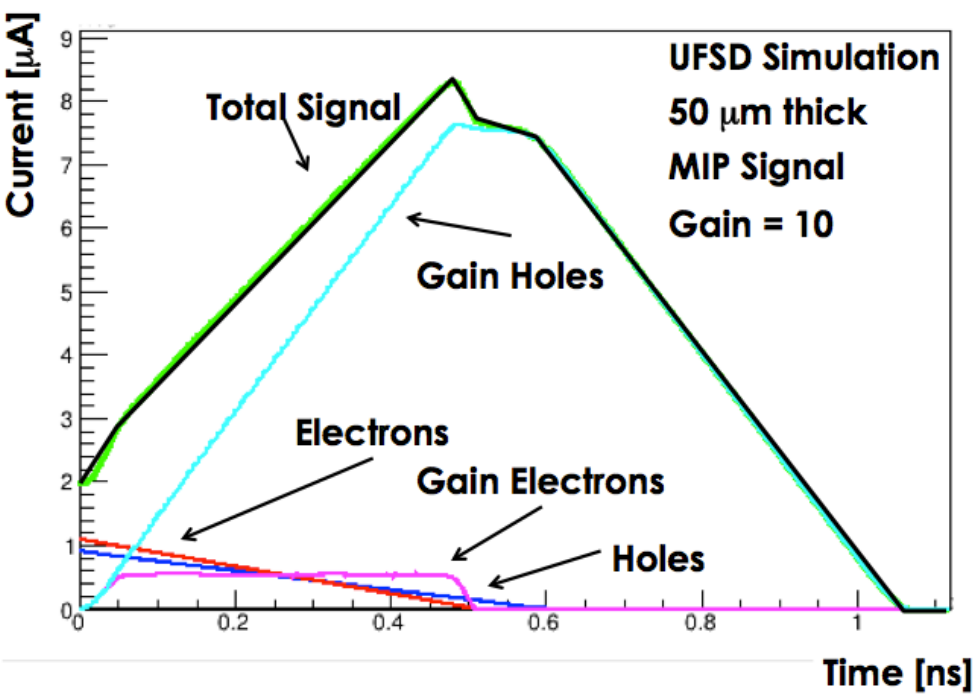
JAN FEB MAR APR MAY

2. **Present an updated document at the CMS Week** — **Jan 30th**
   - From Jan 30th to LHCC to finalize content → can report at WGM meetings
3. **Give an information talk to the LHCC** — **Feb 21st**
4. **Review report at WGM** — **Mar 16th**

   → End of the review process
5. **CMS decision at CMS week** — **Apr 3rd**
6. **Formally present CMS position to LHCC** — **May 9th**

How gain shapes the signal



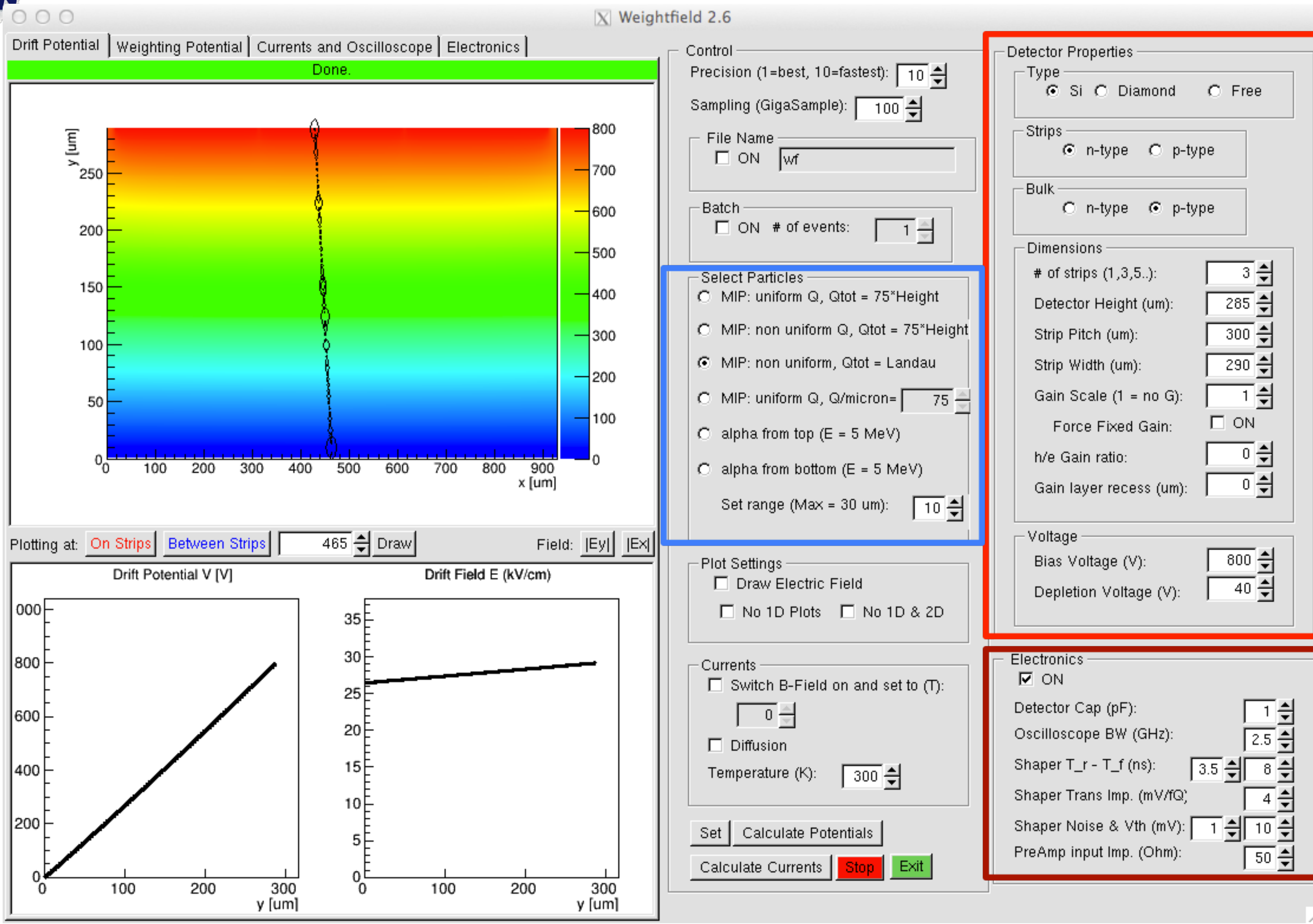


Electrons multiply and produce additional electrons and holes.

- **Gain electrons have almost no effect**
- **Gain holes dominate the signal**

➔ **No holes multiplications**

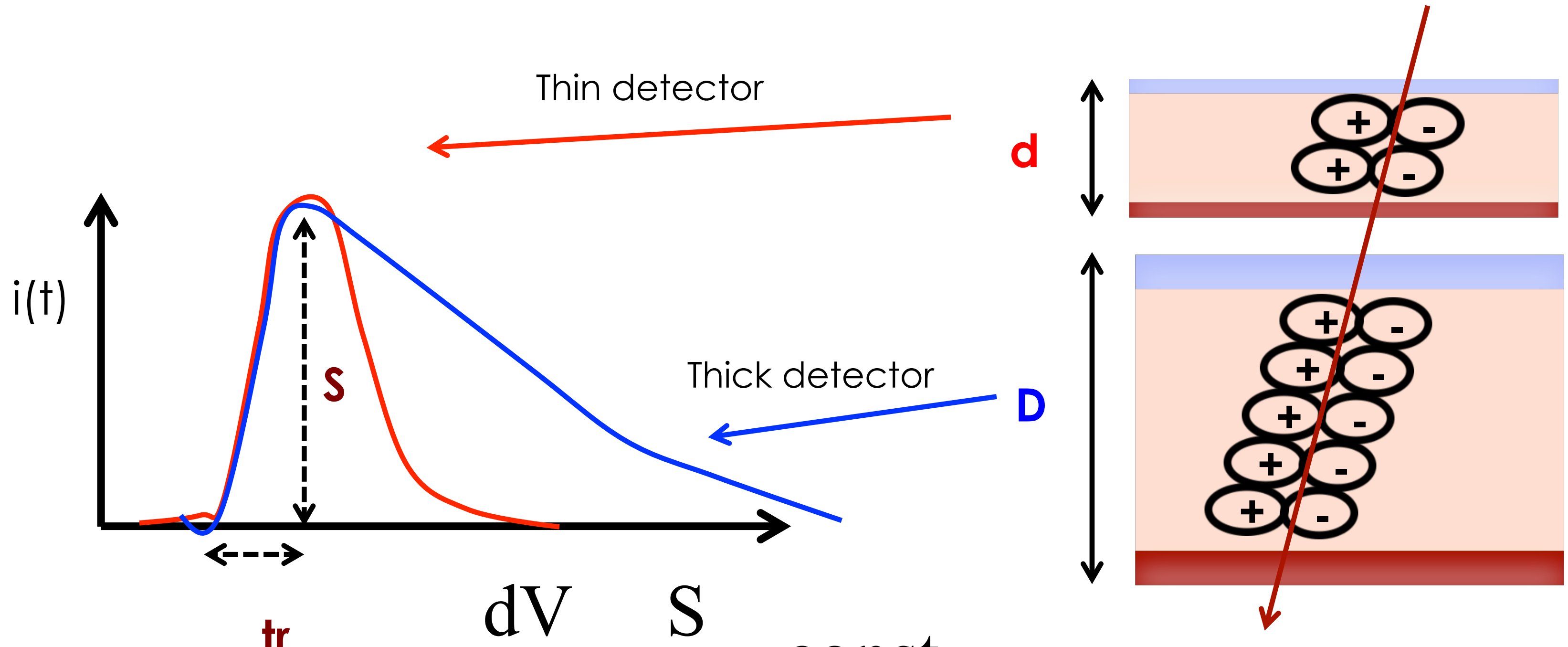
WeightField2: a program to simulate silicon detectors



N. Cartiglia, INFN, Torino - Saclay 27/03/17

Thin vs Thick detectors

(Simplified model for pad detectors)



$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

Thick detectors have longer signals, not higher signals

Best result : NA62, 150 ps on a 300 x 300 micron pixels

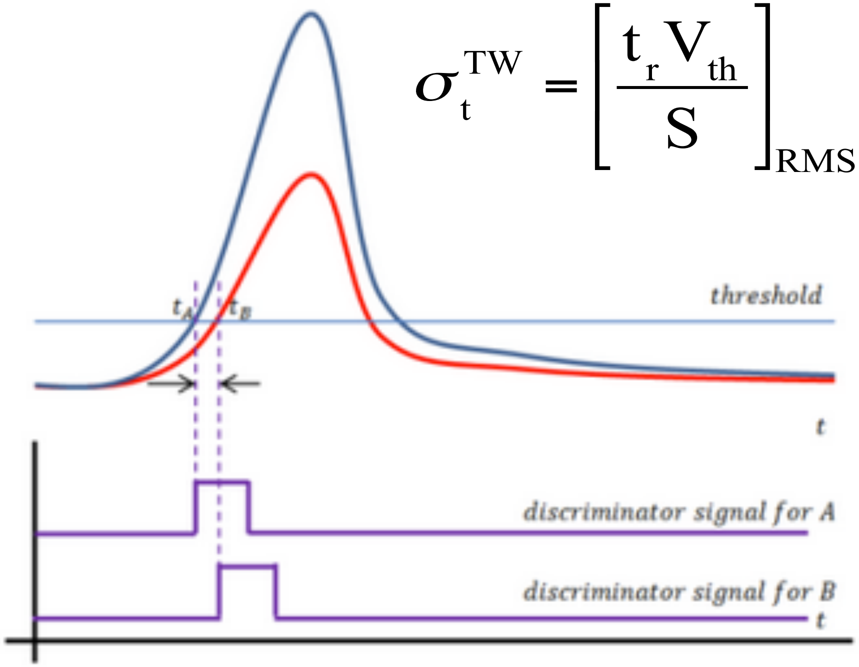
How can we do better?

2 important effects: Time walk and Time jitter

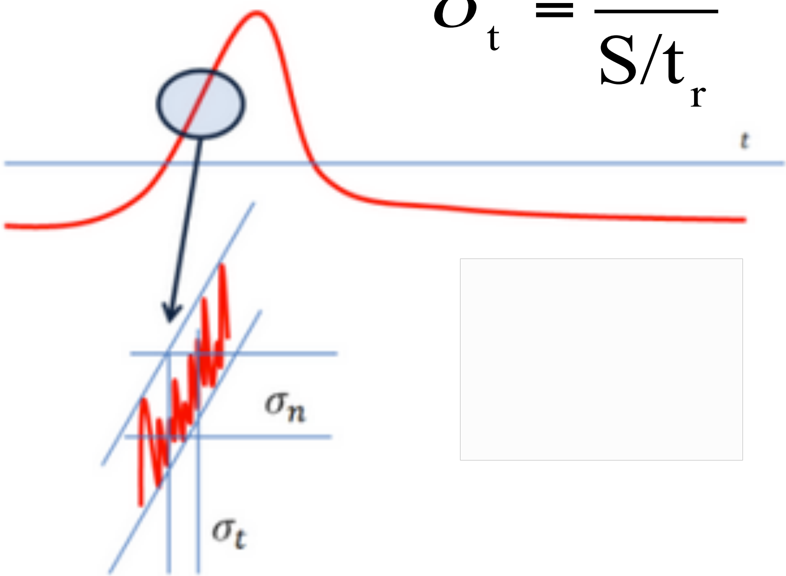
Time walk: the voltage value V_{th} is reached at different times by signals of different amplitude

Jitter: the noise is summed to the signal, causing amplitude variations

$$\sigma_t^{TW} = \left[\frac{t_r V_{th}}{S}\right]_{RMS}$$



$$\sigma_t^{J} = \frac{N}{S/t_r}$$



Due to the physics of signal formation

Mostly due to electronic noise

Time walk and jitter ~ $N/(S/t_r)$ = $N/(dV/dt)$