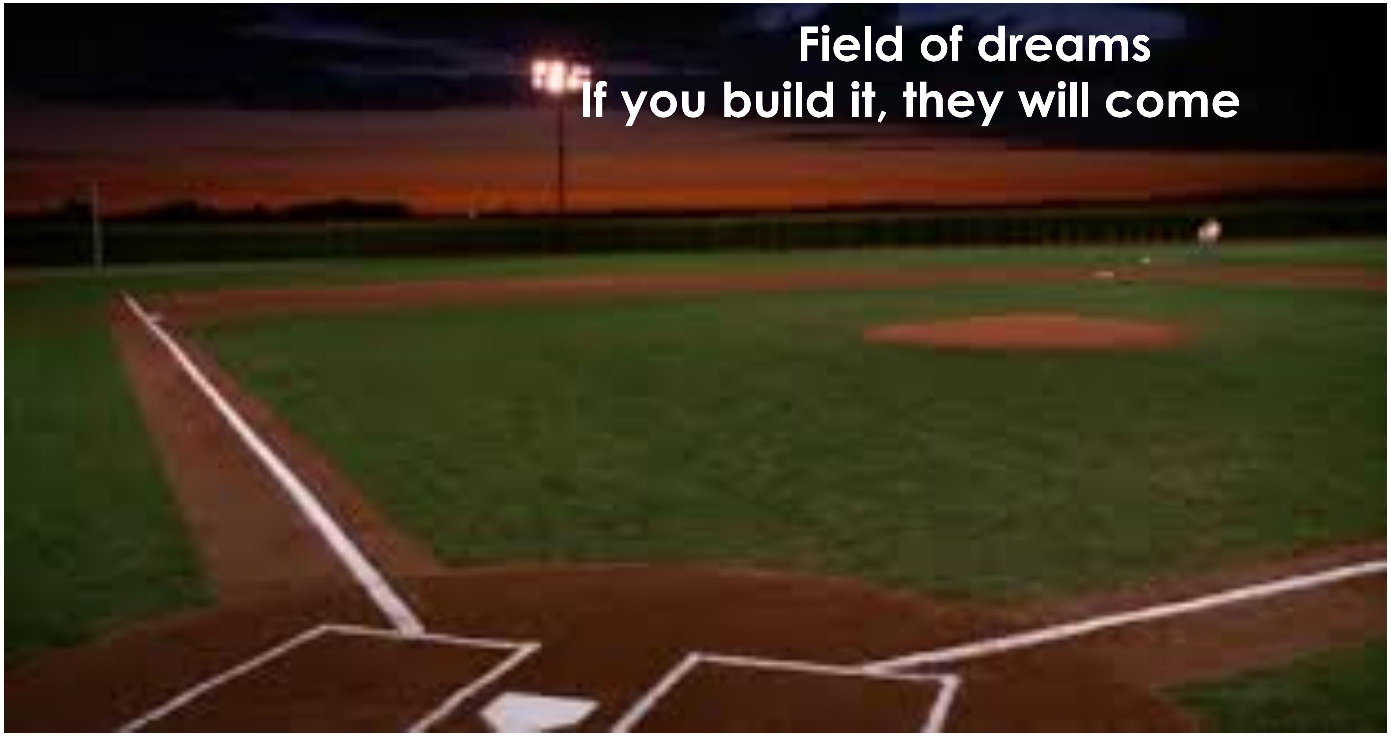
The **4D** challenge

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

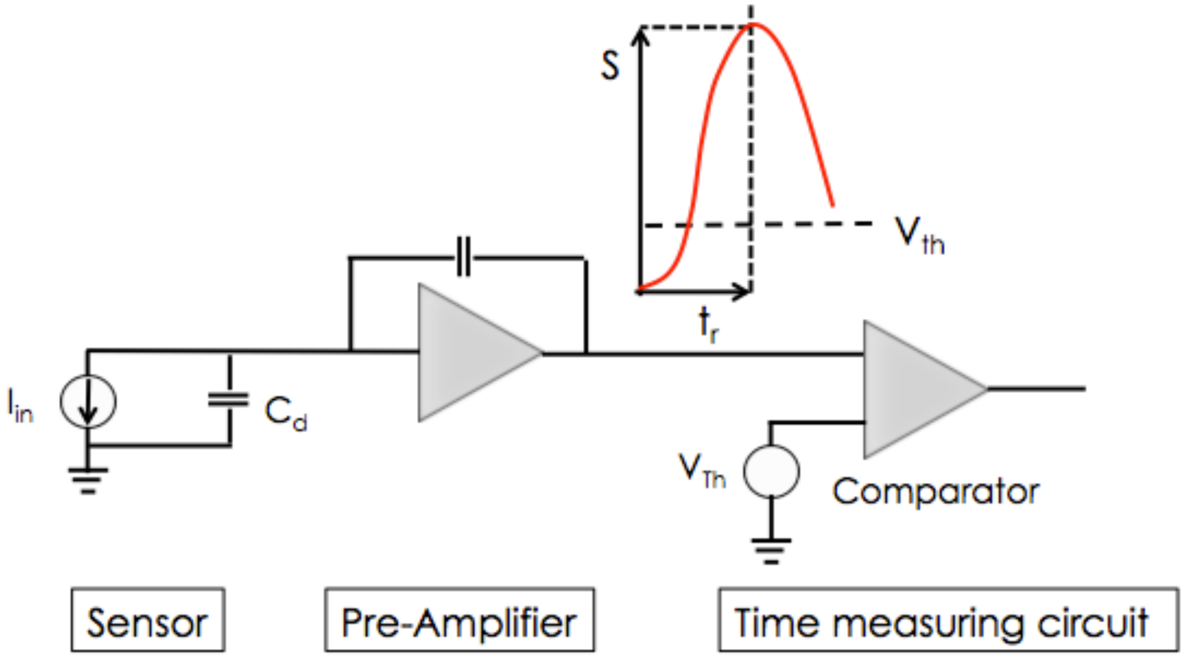
Can we provide from the same detector and readout chain:

Timing resolution ~ 10 ps
Space resolution ~ 10's of μm



A time-tagging detector

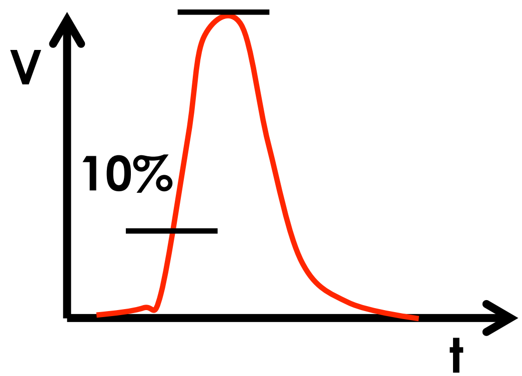
(a simplified view)



Time is set when the signal crosses the comparator threshold

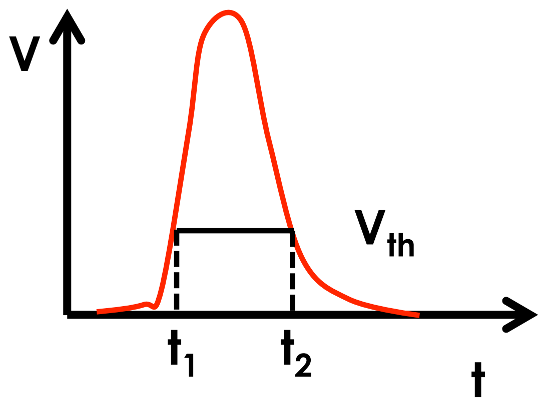
The timing capabilities are determined by the characteristics of the signal at the output of the pre-Amplifier and by the TDC binning.

What is the best "time measuring" circuit?



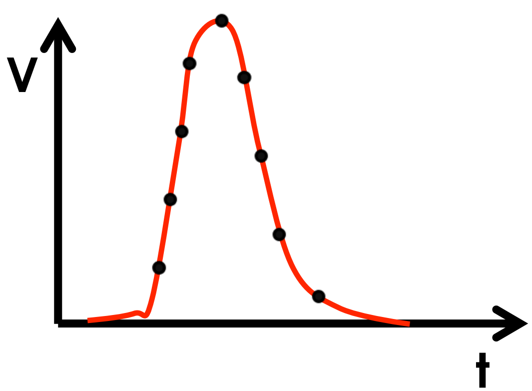
Constant Fraction Discriminator

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

Time resolution

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

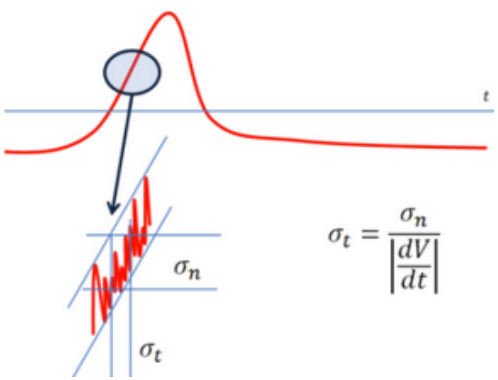
Usual "Jitter" term

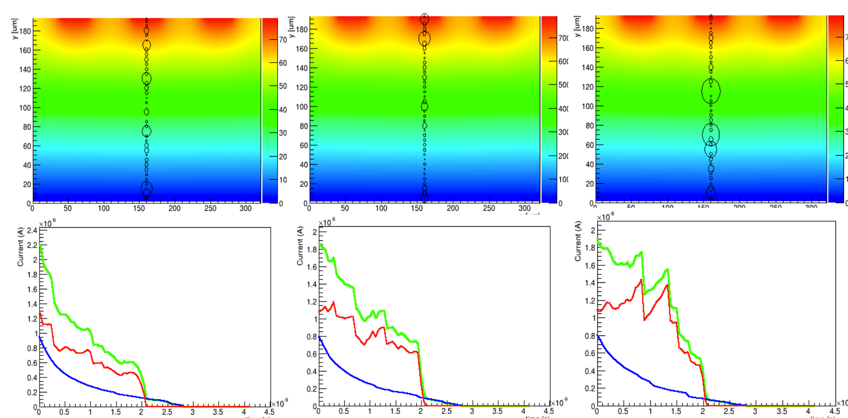
Here enters everything that is "Noise" and the steepness of the signal

Time walk: time correction circuitry

Shape variations: very difficult to simulate

Amplifier non ideal behavior

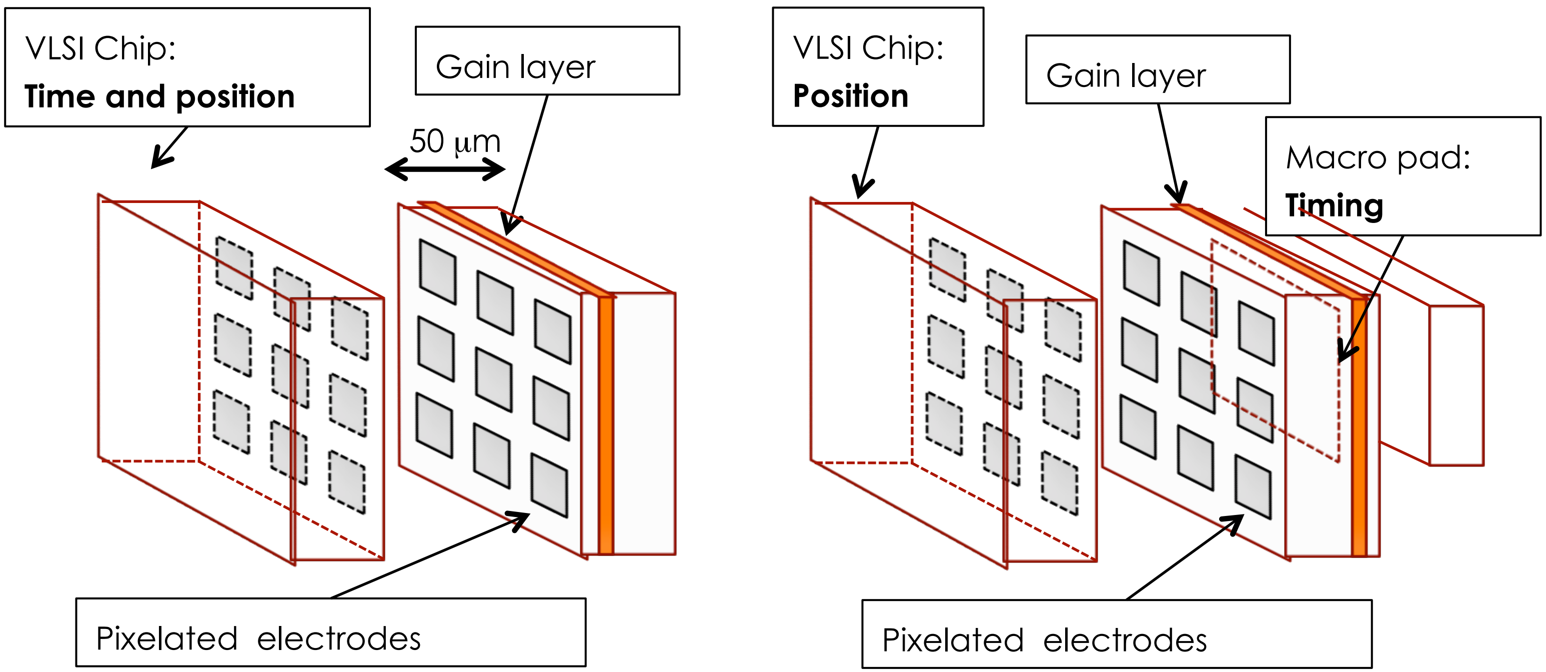




Roadmaps

More of the same: hybrid semiconductor systems

Various idea on segmentation



The real solution: monolithic

> 10 years

This is the correct approach, it goes with Guido's pile-up of 1000

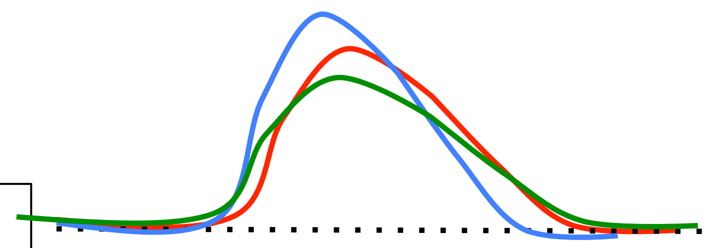
Not all geometries are possible

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity

Weighting field

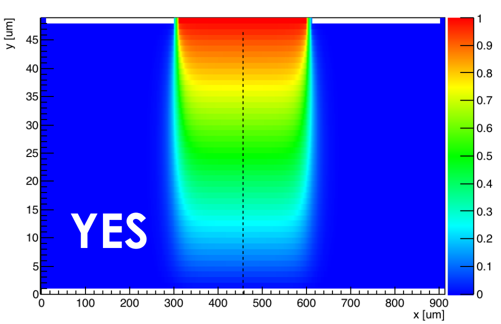


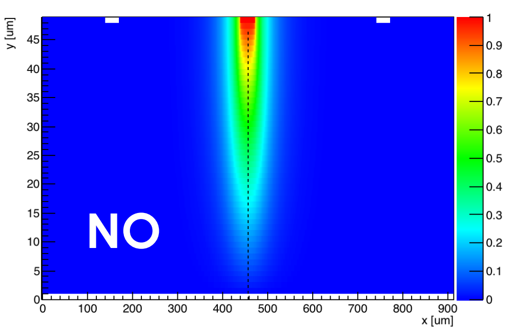
The key to good timing is the uniformity of signals:

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





Possible approaches for hybrid systems

We need to minimize this expression:

$$\sigma_t^2 = \left(\frac{N}{dV/dt}\right)^2$$

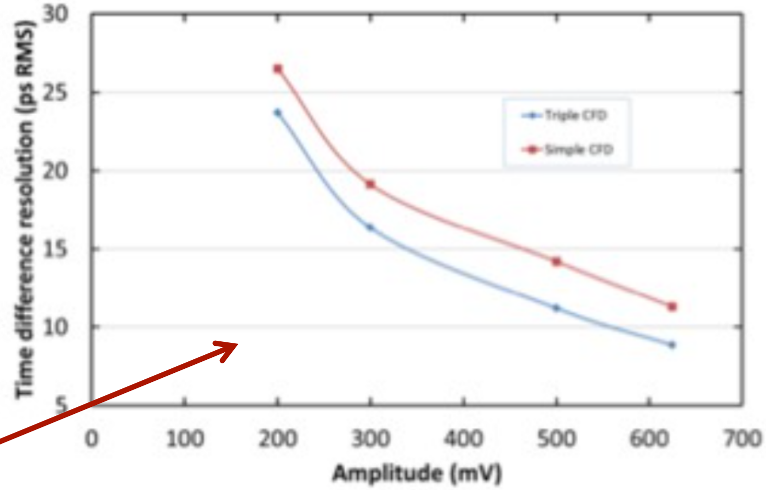
- **APD** (silicon with gain ~ 100): maximize dV/dt
    - Very large signal

- **Diamond:** minimize N, minimize dt
    - Large energy gap, very low noise, low capacitance
    - Very good mobility, short collection time t_r

- **LGAD** (silicon with gain ~ 10): minimize N, moderate dV/dt
    - Low gain to avoid shot noise and excess noise factor

The APD approach

The key to this approach is the large signal: if your signal is large enough, everything becomes easy.



So far they reported:

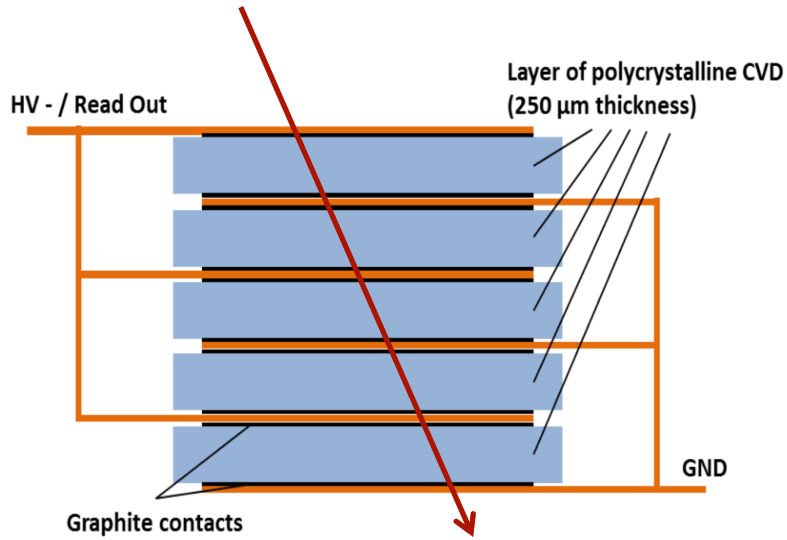
- Excellent time resolution
- Radiation resistance up to < 10^{14} neq/cm^2

The Diamond approach

Diamond detectors have small signal: two ways of fighting this problem

1) Multilayer stack

The signal is increased by the sum of many layers while keeping the rise time short

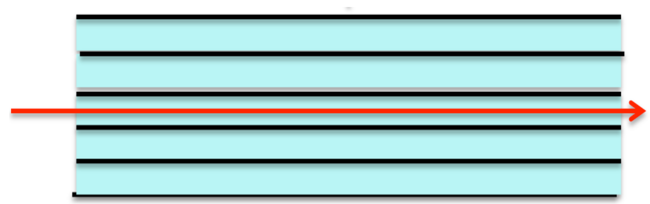


Best resolution:

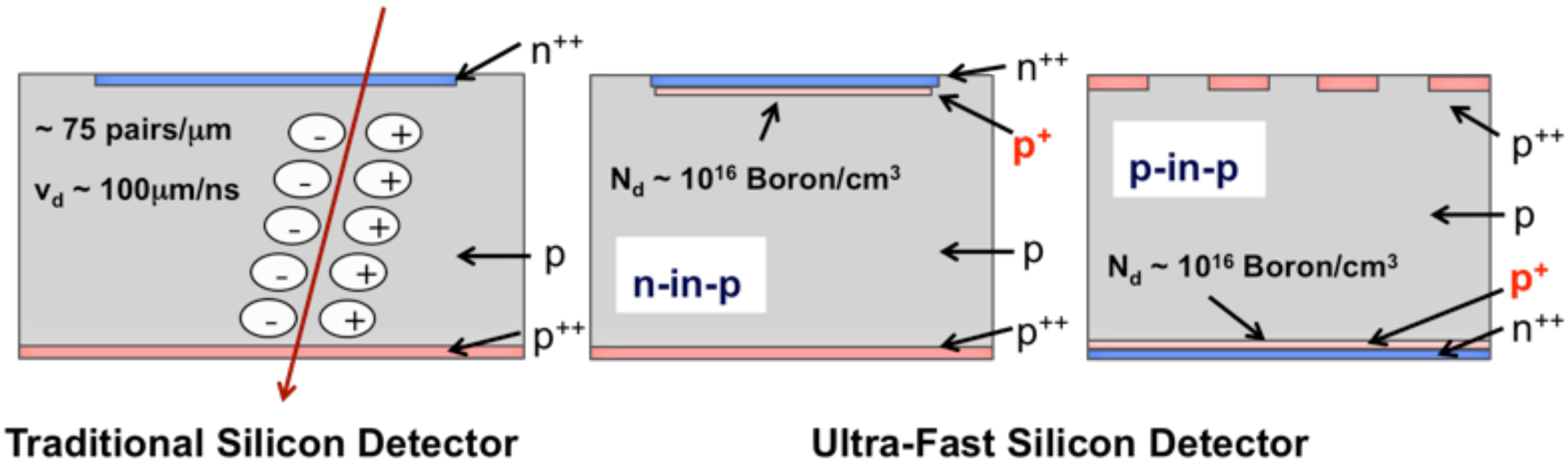
~ 100 ps

2) Grazing

The particle crosses the diamond sensor along the longitudinal direction



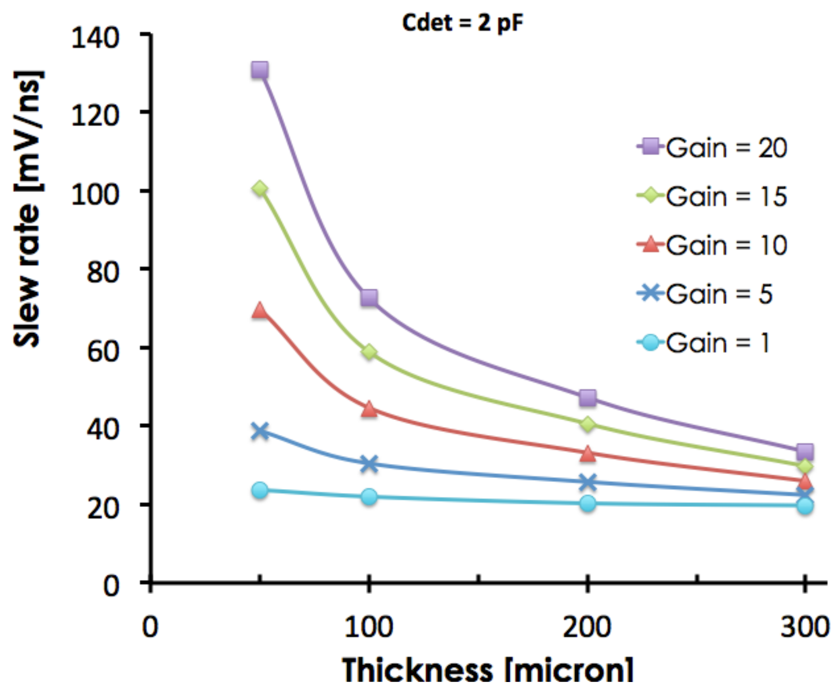
Ultra-Fast Silicon Detector



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.

Large dV/dt, the same noise of traditional sensors

UFSD basic ideas: low gain and thin sensors



300 micron:
~ 50% improvement
with gain = 10

Why **thin** sensors?

Higher signal steepness, more radiation resistance, easier to achieve parallel plate geometry

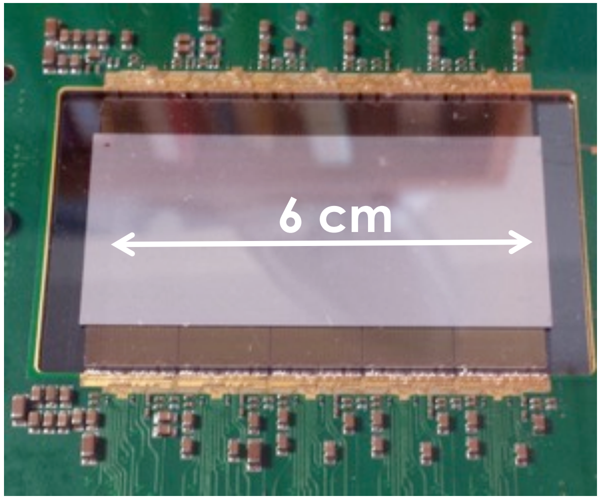
Why **low** gain?

Milder electric fields, possible electrodes segmentation, lower shot noise, no dark count

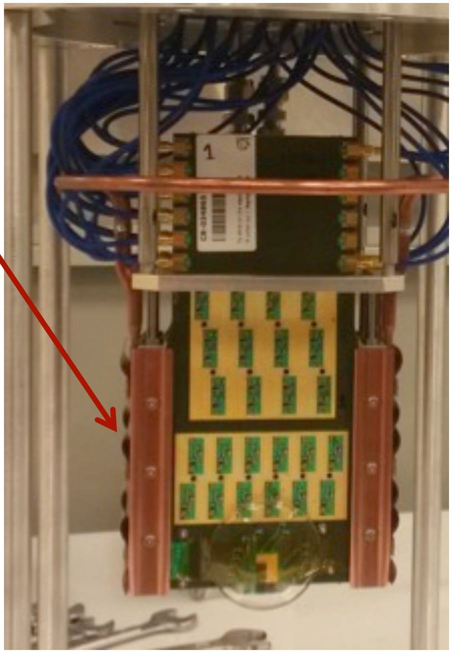
Track-Timing in real experiments

State of the Art:

Silicon pixels: NA62



Diamond: TOTEM



A partisan view of the future: Ultra-Fast Silicon Detectors

- Weightfield: a simulation package for Silicon detectors
- Analysis of the parameters influencing time resolution
- Testbeam results

Simulation

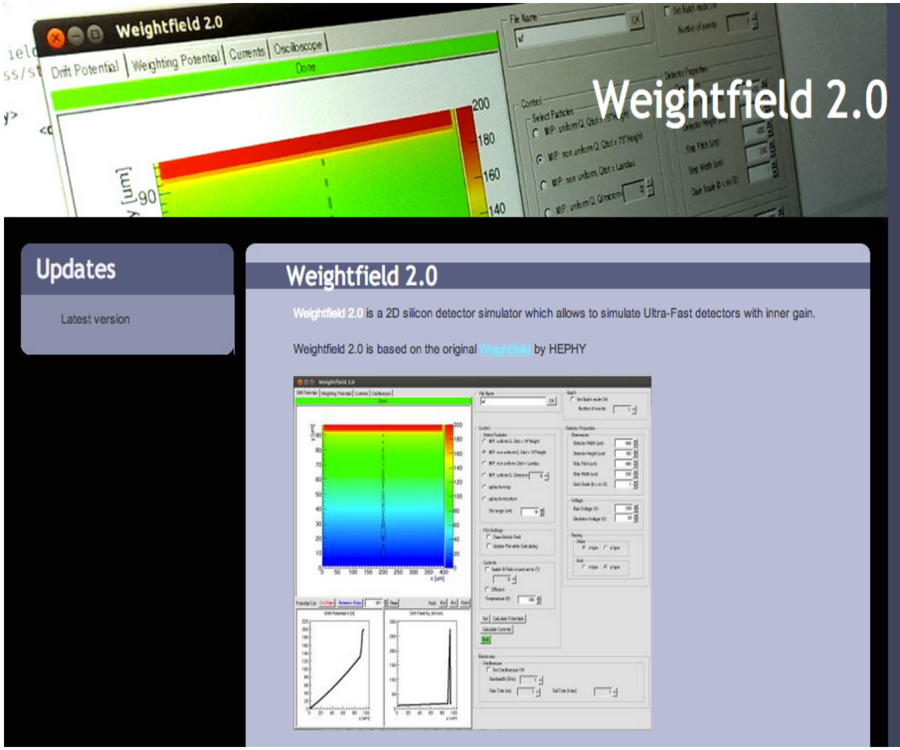
We developed a full sensor simulation to optimize the sensor design

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

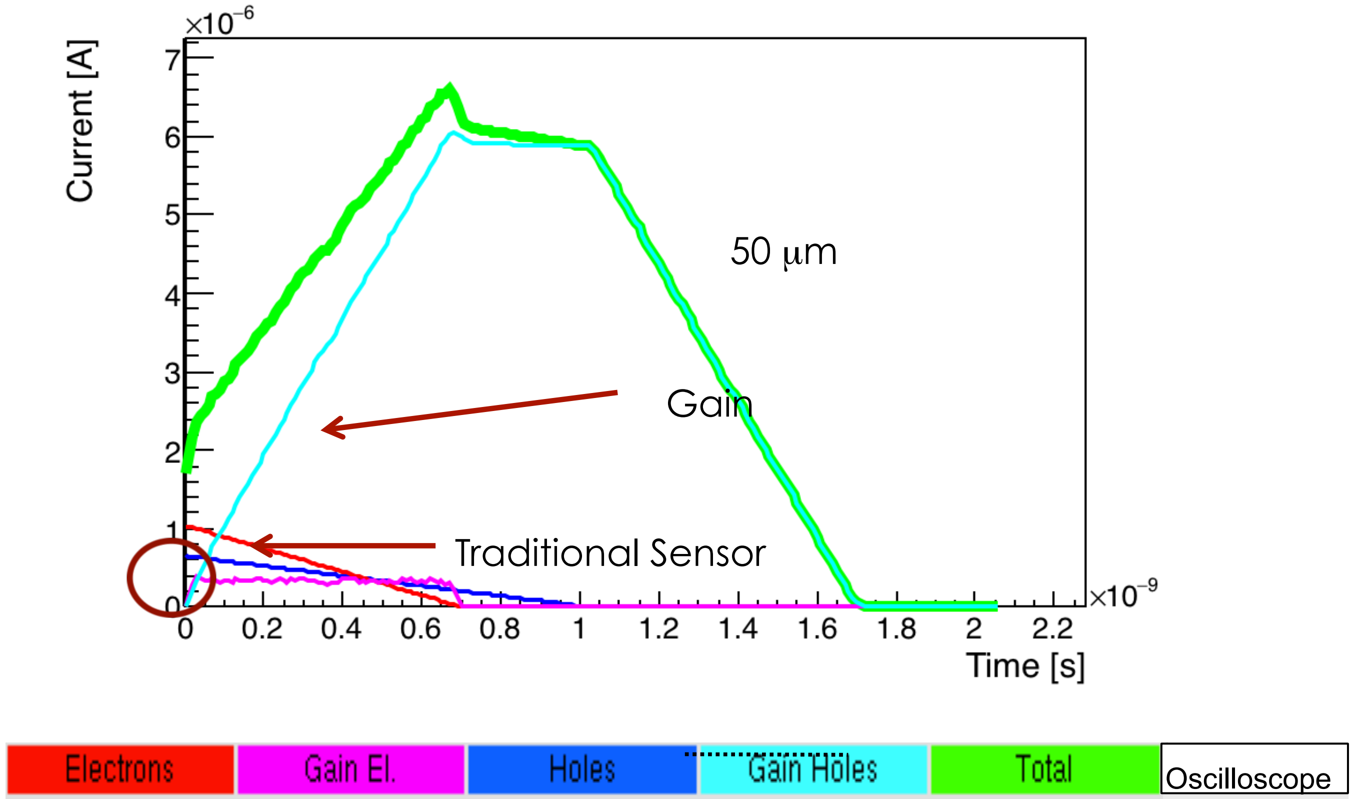


For each event, it produces a file with the current output that can be used as input in the simulation of the electronic response.

UFSD Signal characteristics

The signal from UFSDs is different from that of traditional sensors:

➔to fully exploit UFSDs, dedicated electronics needs to be designed.



Simulated Weightfield2

Traditional sensors

Charges generated uniquely by the incident particle

Ultra-Fast Silicon Detectors

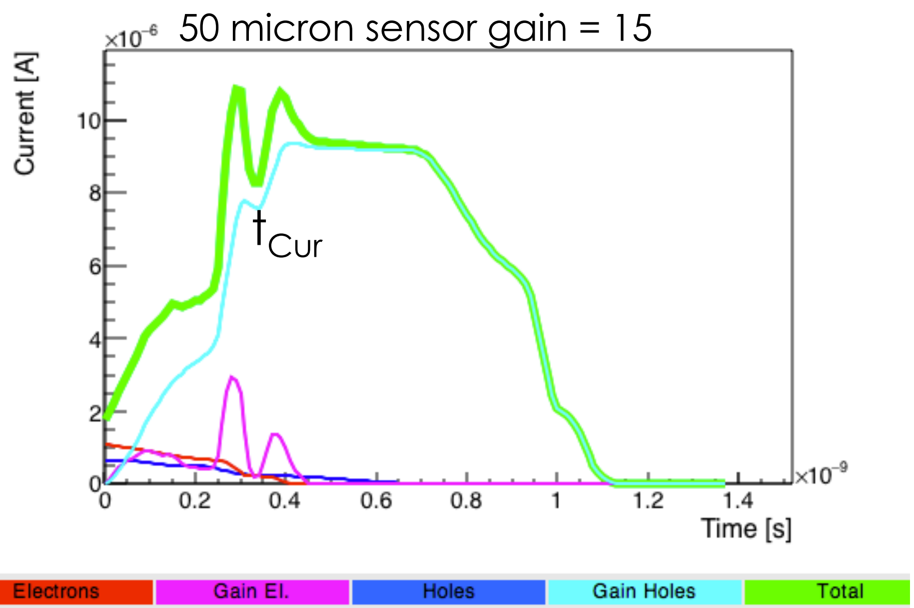
Current due to gain holes creates a longer and higher signal

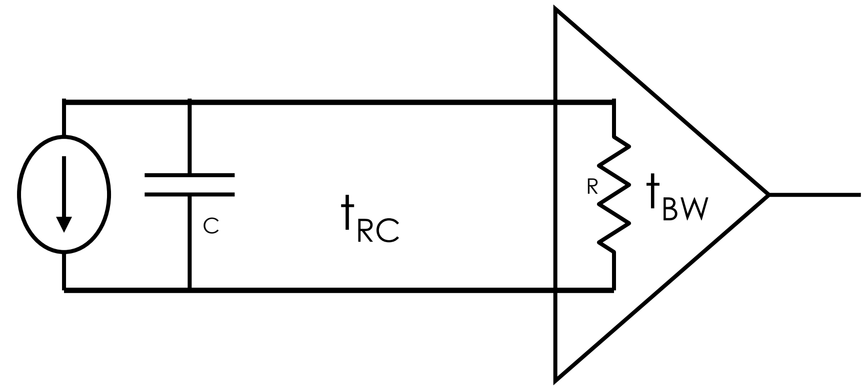
The players: noise and slopes

Landau Noise

Shot Noise

Electronic Noise





The current rise time (t_{Cur})

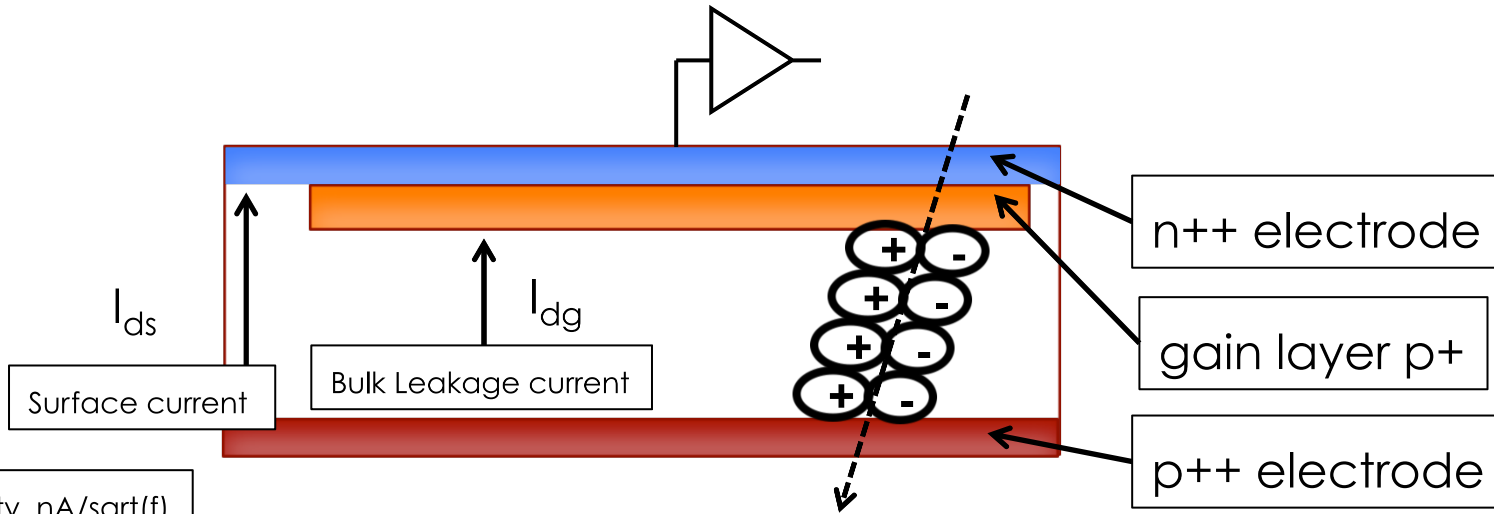
The RC circuit (t_{RC})

Amplifier BW f (t_{BW} ~0.35/f)

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

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

Shot noise in LGAD - APD



Current density, nA/sqrt(f)

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

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

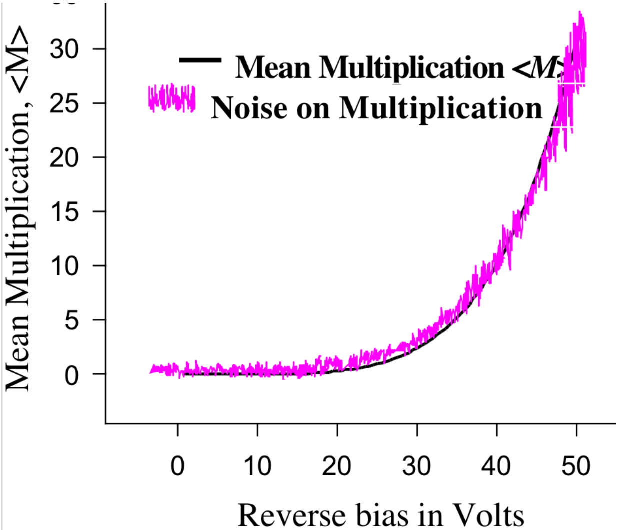
$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

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

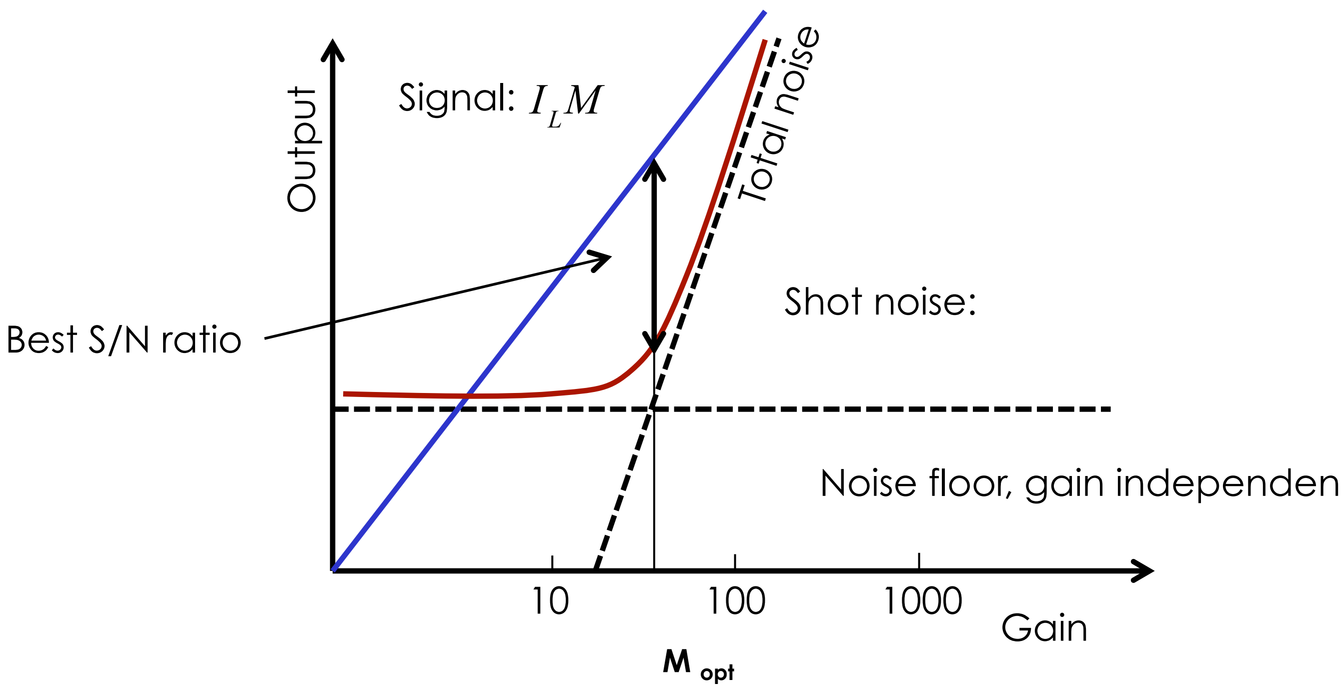
$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \Rightarrow \langle M^2 \rangle = \langle M \rangle^2 F$$

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?



The Shot noise voltage term

Let's assume a 4 mm² pad, 50 micron thick.

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

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

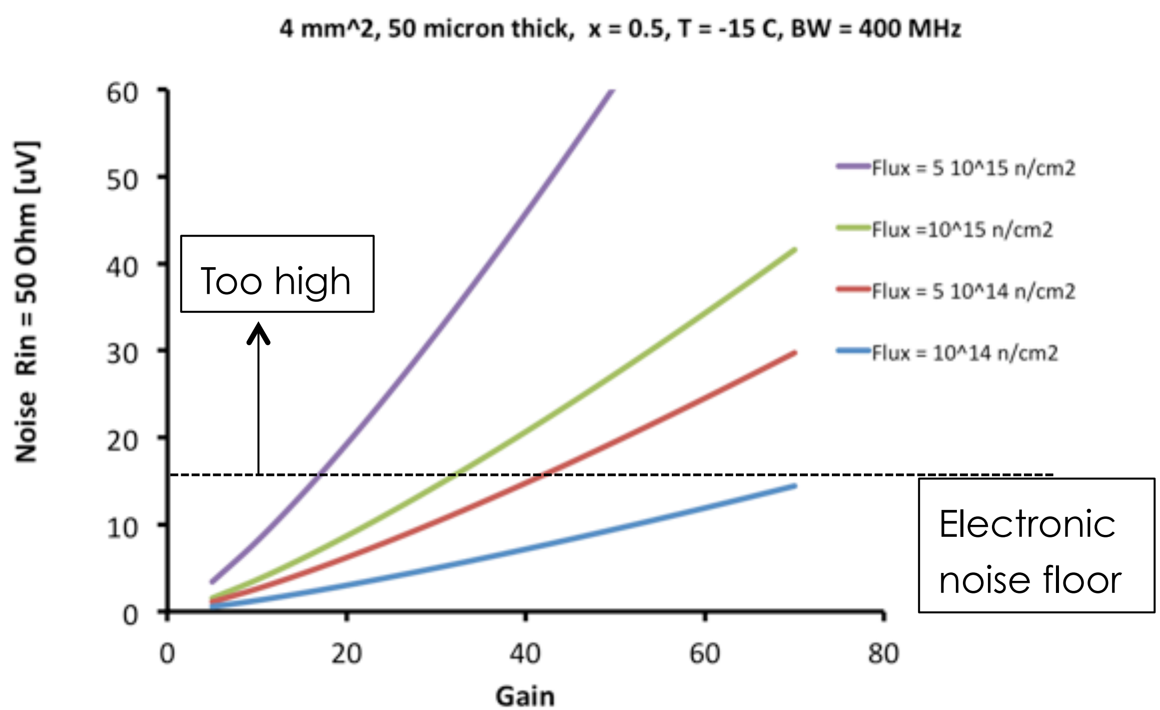
Steep dependence on gain

Shot noise: $$i = \sqrt{\int i^2_{Shot}\, df} = \sqrt{2eI * (Gain)^{2+x} * BW}$$

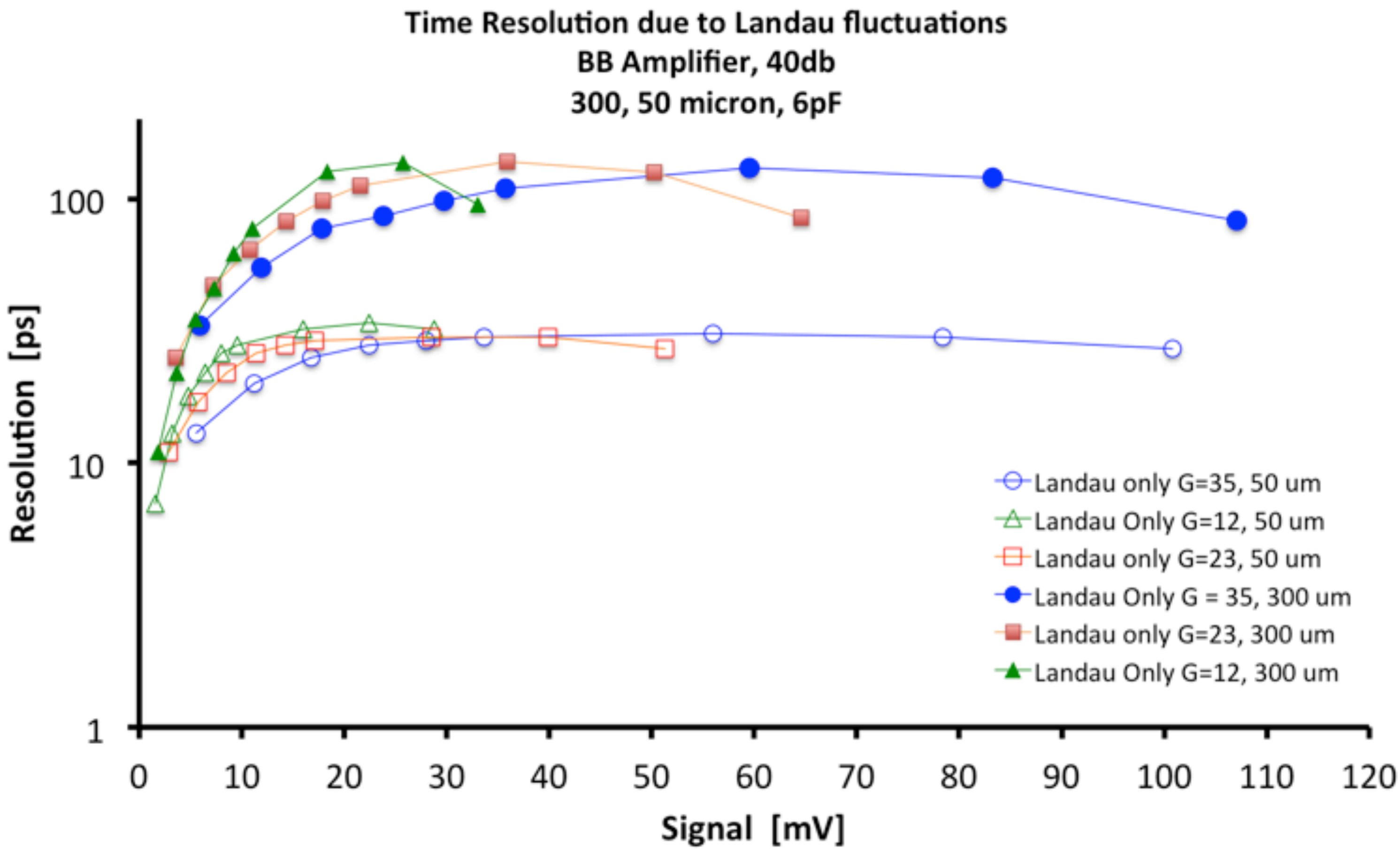
Voltage Shot noise: $$v_{Shot} = i_{Shot} * R_{input}$$

Voltage Shot noise:

- ➔ **Cool the detectors**
- ➔ **Low gain!! Keep the gain below ~ 20**



50 -300 micron Sensors: Landau noise



To minimize Landau noise:

→ Set the comparator threshold as low as you can

→ Use thin sensors

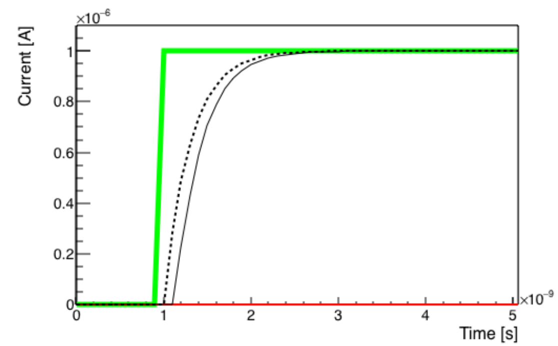
The slope term: dV/dt

The rise time of the output signal is due to the sum of the current rise time, the RC system and the amplifier BW:

$$\tau_{\text{rise}} = \sqrt{\tau_{Cur}^2 + \tau_{\text{RC}}^2 + \tau_{\text{BW}}^2}$$

For a BB amplifier, the general output is:

$$V(t) = V_0 * \text{Gain} * (1. - e^{-t/\tau_{\text{rise}}})$$



And the derivative is:

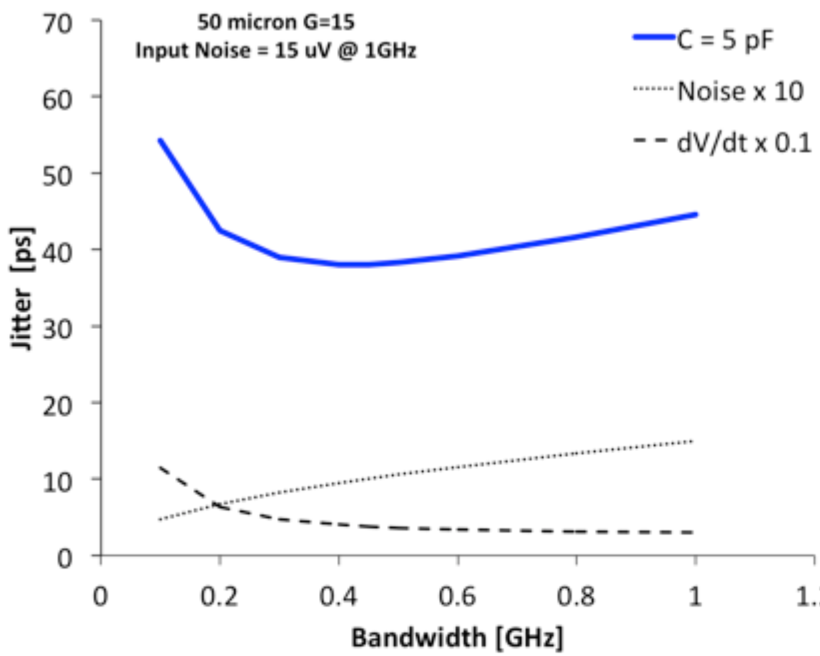
$$\frac{dV}{dt} = V_0 * \text{Gain} * \frac{1}{\tau_{\text{rise}}} e^{-t/\tau_{\text{rise}}}$$

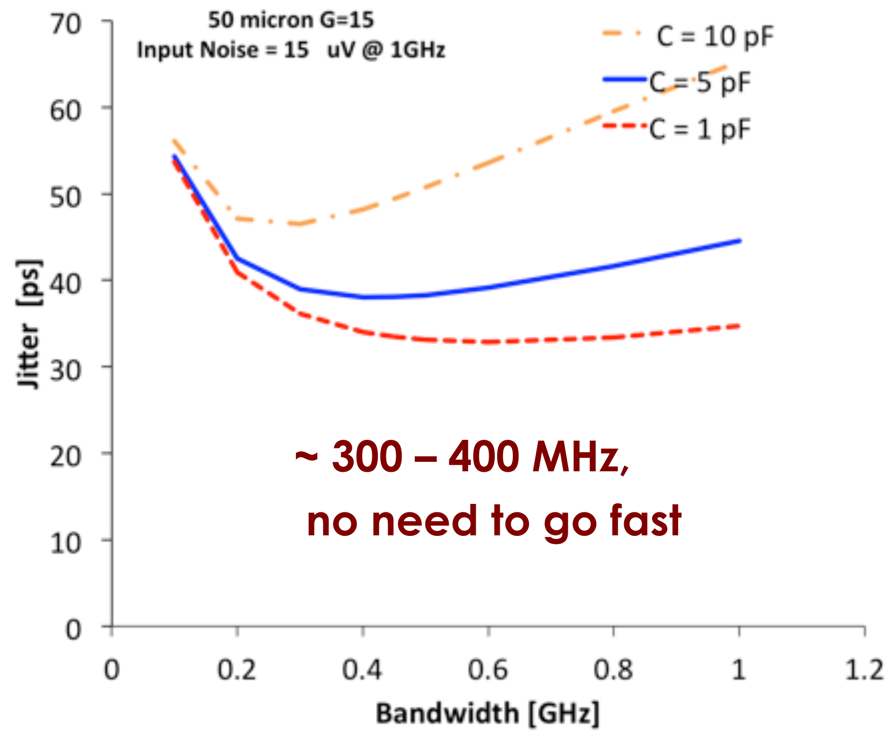
Determination of the best BW

$$\text{Jitter} = \text{N}\frac{1}{dV/dt|_{t_0=100\,ps}} = \frac{k}{\sqrt{t_{\text{BW}}}}\frac{1}{V_0\text{Gain}\frac{1}{\tau_{\text{rise}}}e^{-t_0/\tau_{\text{rise}}}} = \frac{k}{V_0\text{Gain}}\frac{\tau_{\text{rise}}}{\sqrt{t_{\text{BW}}}}e^{t_0/\tau_{\text{rise}}}$$

Normalization: N = 15 uV @ 1GHz

$$\tau_{\text{Rise}} = \sqrt{\tau^2_{\text{Cur}} + \tau^2_{\text{RC}} + \tau^2_{\text{BW}}}$$





~ 300 – 400 MHz, no need to go fast

Broad minimum at BW: $\tau_{BW} = \sqrt{\tau^2_{\text{Cur}} + \tau^2_{\text{RC}}}$

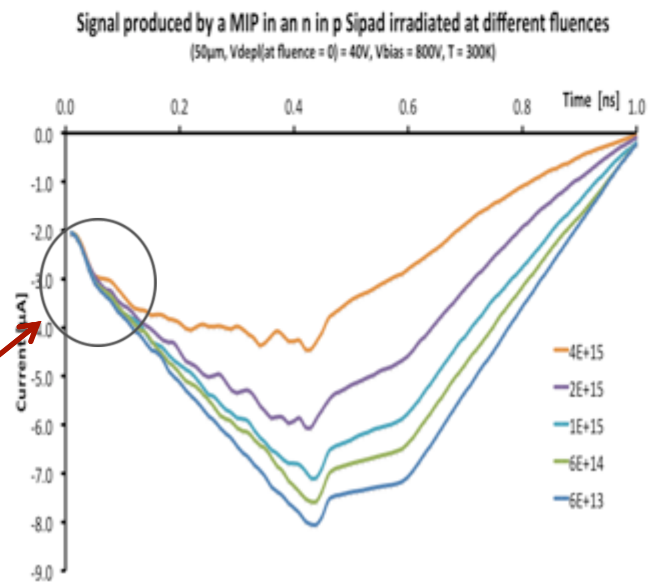
Irradiation - I

Irradiation causes 3 main effects:

1. Decrease of charge collection efficiency due to trapping
2. Changes in doping concentration
3. Increased leakage current

1) Decrease of charge collection efficiency due to trapping

We ran a full simulation of CCE effect.
In 50 micron thick sensors the effect is rather small
Up to 10^{15} neq/cm^2 the effect is negligible in the fast initial edge used for timing



Irradiation - II

2) Changes in doping concentration

Irradiation normally creates p-doping, n-silicon becomes p-silicon.

➔ This additional p-doping is due to defects creation.

However: there is evidence **that irradiation causes "initial acceptor removal" at fluences above a few 10^{14} n_{eq}/cm^2**

➔ the "real" p-doping of the LGAD gain layer is deactivated.

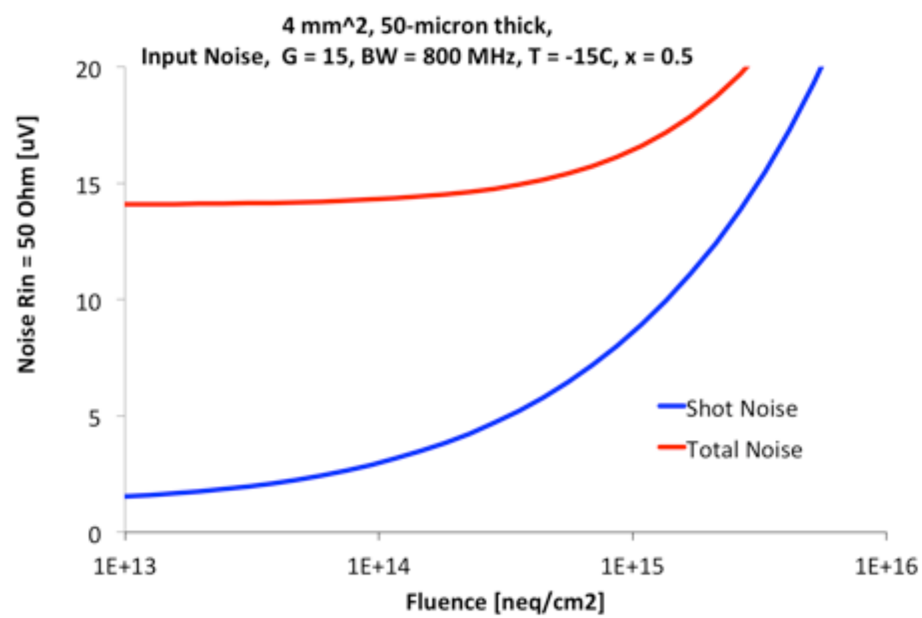
Two paths:

- Short term: use Vbias to compensate for the loss on gain
- Long term: Gallium doping

3) Increased leakage current

Assuming Gain ~ 15, T = -15C,

Shot noise starts to be important above a fluence ~ 10^{15} n^{eq}/cm^2



UFSD Italian Contribution

The project started as an INFN Gruppo V initiative.

Sensors are being fabricated at FBK (as an alternative to CNM, Barcelona)

Electronics: very good expertise in Italy, Torino (CMOS), Tor Vergata (SIGE)

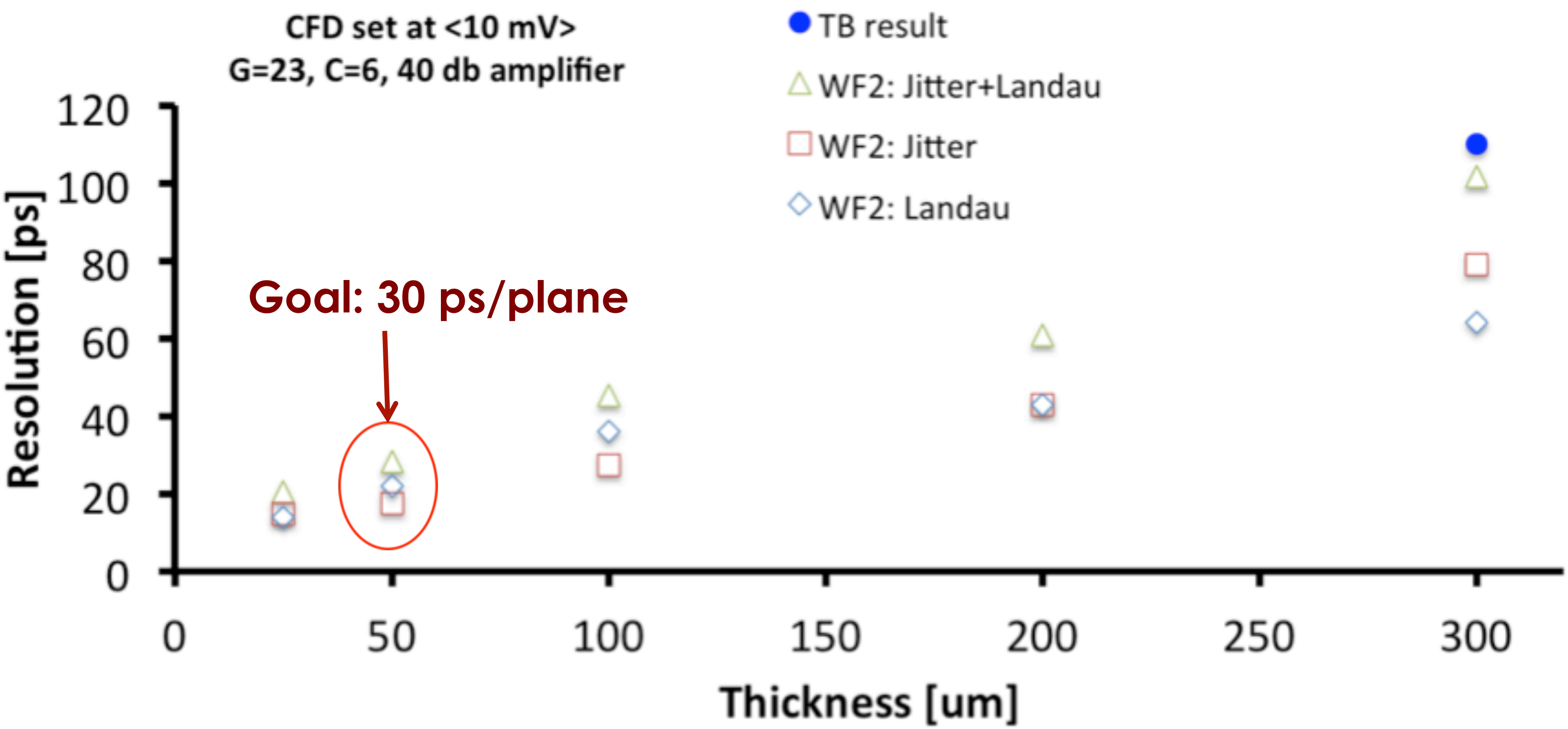
Large area sensors: not yet ready, maybe via LFoundry.

Competition: Hamamatsu will deliver prototype Low gain device by the summer

Contributions from Horizon 2020

Testbeam results and extrapolation

2014 Frascati: 2 LGAD 7x7mm^2 300μm (C = 12pF, Gain =10)
2014 CERN: 2 LGAD 7x7mm^2 300 μm (C = 12pF, Gain =10)
2015 CERN: 2 LGAD 3x3mm^2 300 μm (C = 4pF, Gain =10 - 20)



WF2 = Weightfield2, simulation program.
Contribution of the Jitter and Landau parts to the total time resolution as a function of the sensor thickness.

What Else?

Sensors are only the first step..

Electronics: timing requires a lot of excellent design [A. Rivetti]

Cooling: precision timing requires a lot of current

➔ large timing systems need an extremely advance cooling removal

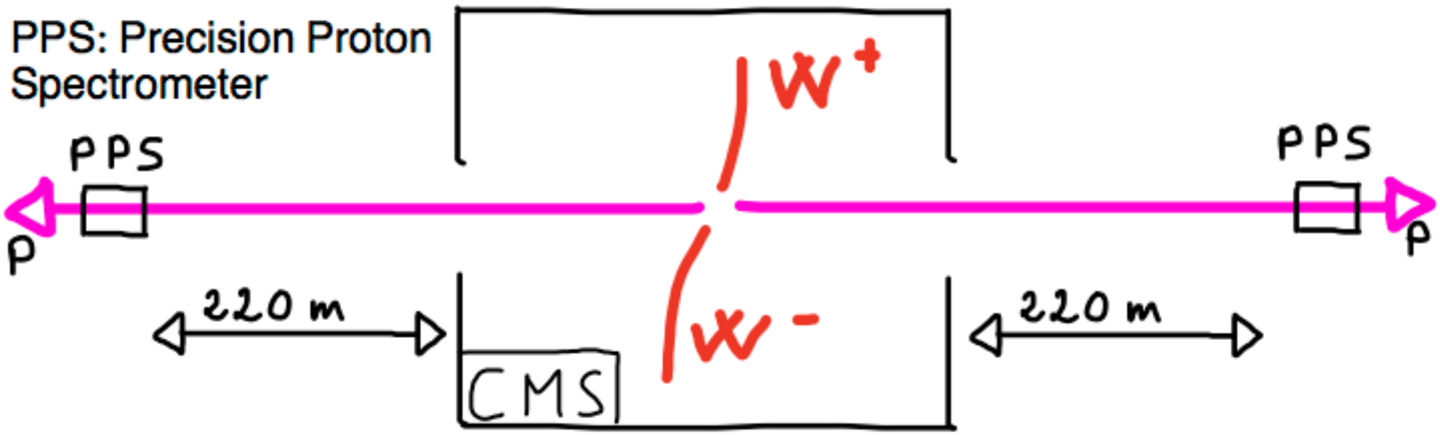
High Precision Clocks: need a very good timing reference system, otherwise you don't know your precision….

Reconstruction: new algorithms, L1 and offline [G. Punzi]

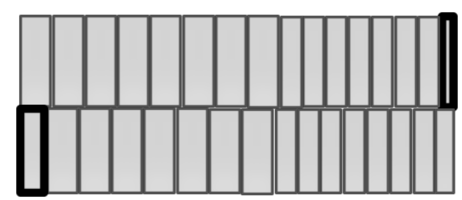
CT-PPS: a UFSD - Diamond demonstrator

There is a class of events that have two protons in the final state

We need to know **the position** and **the time** of the two protons



Fat strips UFSD



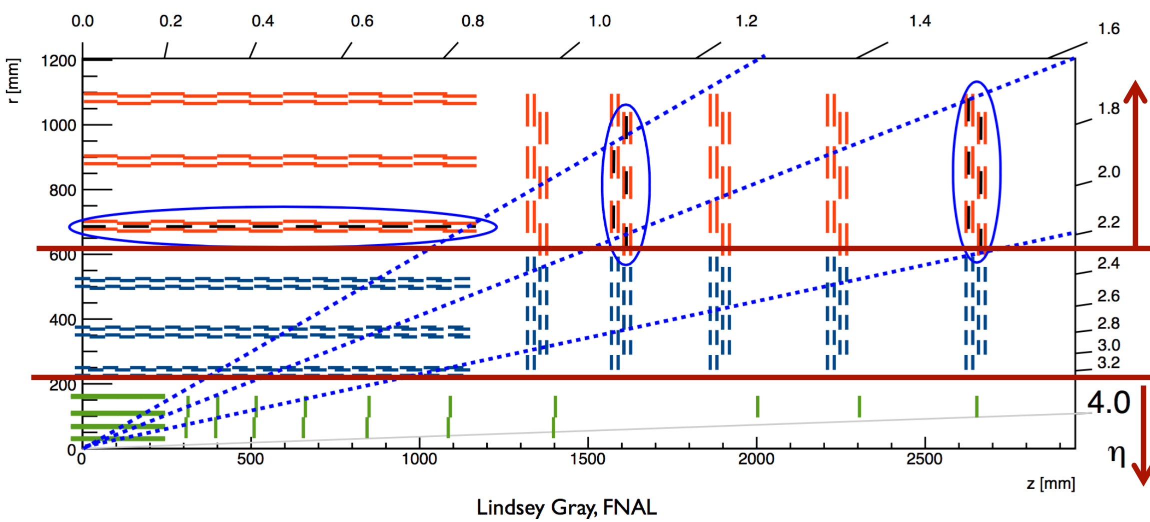
Electronics: custom ASIC designed in Torino

Diamond: multilayer sensors are under development.

Goal: ~ 30 ps per plane ➔ 15 ps for the whole system.

CMS Timing working group

Goal: assign time information to each vertex and each track



Current version:
Ready below a few10^{14} n/cm^2

R&D for 10^{14-15} n/cm^2

Above10^{16} n/cm^2 **never?**

Physics case ➔ If "yes": Is it possible to build it?

➔ if "yes": is CMS-Italia interested?

ATLAS High-Granularity Timing Detector HGTD

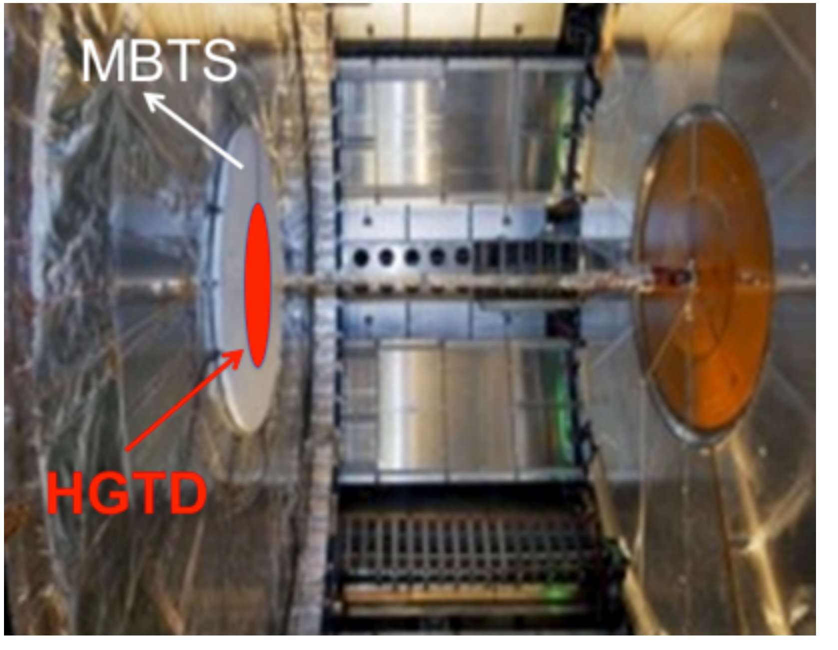
Hartmut Sadrozinski, UCSC

Suppression of pile-up (Run 2)

4 active layers per side (~10 m^2 in total) in front of FCAL
HGTD baseline dimensions:
- Z =[3475, 3545] mm ; **ΔZ=70mm**
- Rmin ~ -90 mm (η max≈4.3)
- Rmax ~ 600 mm (η min≈2.4)
- Possible to extend η =5.0 (Rmin ~ 50mm)

Required timing resolution: 50 – 100 ps

There are several technologies being considered.



Physics case ➔ If "yes", Is it possible?

➔ if "yes" is ATLAS-Italia interested?

What resolution can we expect?

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

Electronic Noise: ~ 500 ENC

Silicon:
Shot Noise ($5*10^{14}\ n_{eq}/cm^2$): ~ 1-200 ENC
dV/dt (Sensor+Electronics): : ~ 15 mV/ns

Diamond:
Shot Noise ($5*10^{14}\ n_{eq}/cm^2$): ~ 0 ENC
dV/dt(Sensor+Electronics): : ~ 15 mV/ns

UFSD (50-micron thick, Gain =15):
Shot Noise ($5*10^{14}\ n_{eq}/cm^2$): ~ 500 ENC
dV/dt (Sensor+Electronics): ~ 50 mV/ns

Multilayer Diamond
Shot Noise ($5*10^{14}\ n_{eq}/cm^2$): ~ 0 ENC
dV/dt (Sensor+Electronics): ~ 50 mV/ns

Time walk: ~ 5-10 ps
Shape variations: ~ 15 - 20 ps

Summary:
UFSD (thick) ~ 120 ps
Silicon ~ 100 ps
Diamond ~ 100 ps

Measured

UFSD (thin) ~ 30 ps
Diamond Multilayer ~ 30 ps

~ 1 year

UFSD: The next few years

2016:

- **Thin sensor prototypes**. By the end of 2016 I expect a much better understanding of the gain mechanism, and how thin sensors work.
- **Irradiation program**. Damage, trapping, gain changes in thin sensors, use of Gallium instead of Boron?
- **Sensor demonstrator for ATLAS, CMS**
- **Discrete component read-out**, on the PPS geometry
- **First custom chip**, 4-8 channel, analog-comparator
- **Installation of system demonstrator in PPS**
- **Lot's of testbeam**

2017:

- **Additional sensor production**, exploring large production capability
- **R&D on full custom read-out chip**