The 4D challenge

erc
UFSD

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 mm

Tracking in 4 Dimensions

INFN Torino, Univ. Trento, FBK, UCSC Santa Cruz

The effect of timing information

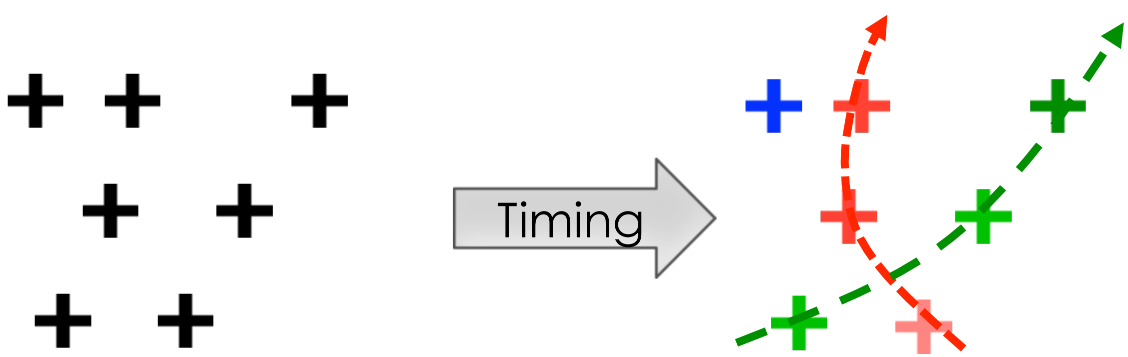
The inclusion of track-timing in the event information has the capability of changing radically how we design experiments.

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

Let me pick 3 situations (colors == time)

1) Timing at each point along the track:

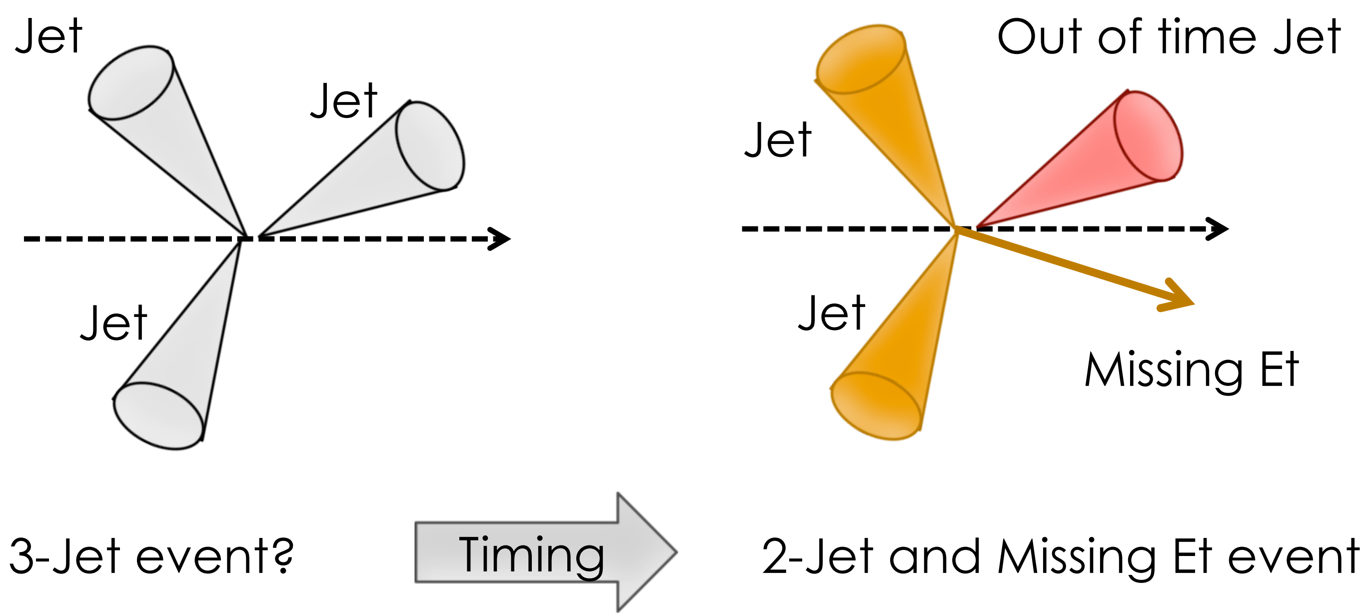
- ➔ Massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments
- ➔ Use only "time compatible points"



The effect of timing information

2) **Timing at the trigger decision (ATLAS):**

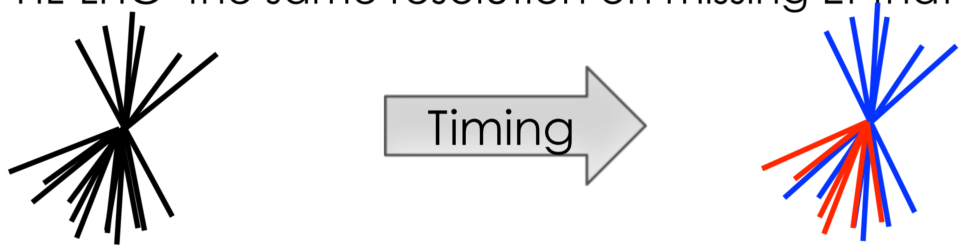
➔ Tracking information might not be available in time for L1 decision, timing can be much faster



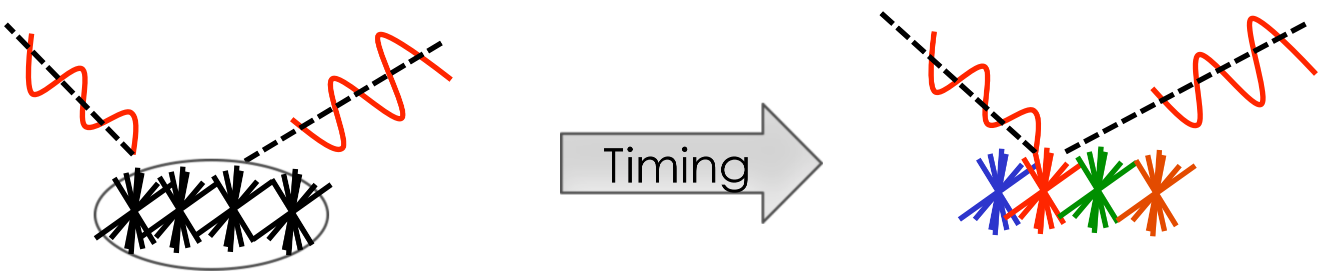
The effect of timing information

3) **Timing for each track/vertex of the event (CMS):**

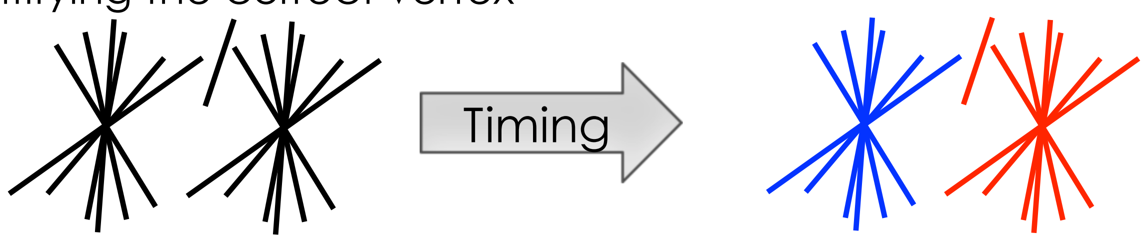
Missing Et: consider overlapping vertexes, one with missing Et: Timing allows obtaining at HL-LHC the same resolution on missing Et that we have now



H ➔ γ γ : The timing of the γγ allows to select an area 1 cm) where the vertex is located. The vertex timing allows to select the correct vertex within this area



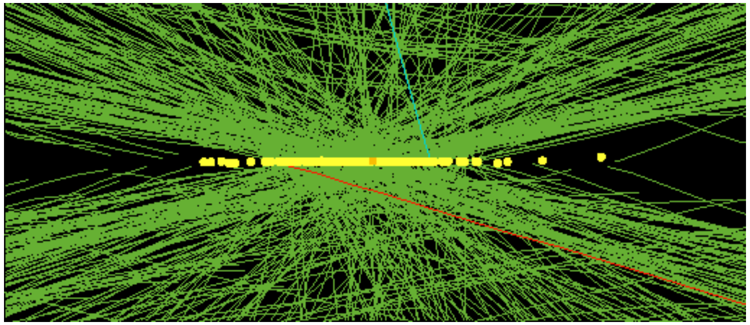
Displaced vertexes: The timing of the displaced track and that of each vertex allow identifying the correct vertex



Is timing really necessary?

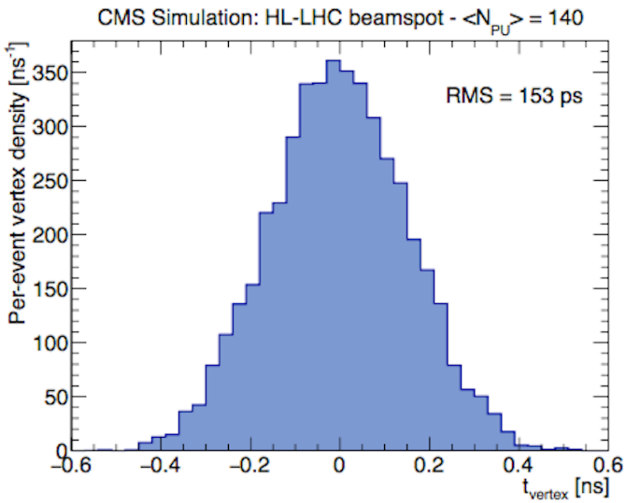
The research into 4D tracking is strongly motivated by the HL-LHC experimental conditions:

150-200 events/bunch crossing



According to CMS simulations:

- **Time RMS between vertexes: 153 ps**
- **Average distance between two vertexes: 500 um**
- **Fraction of overlapping vertexes: 10-20%**
  - Of those events, a large fraction will have significant degradation of the quality of reconstruction



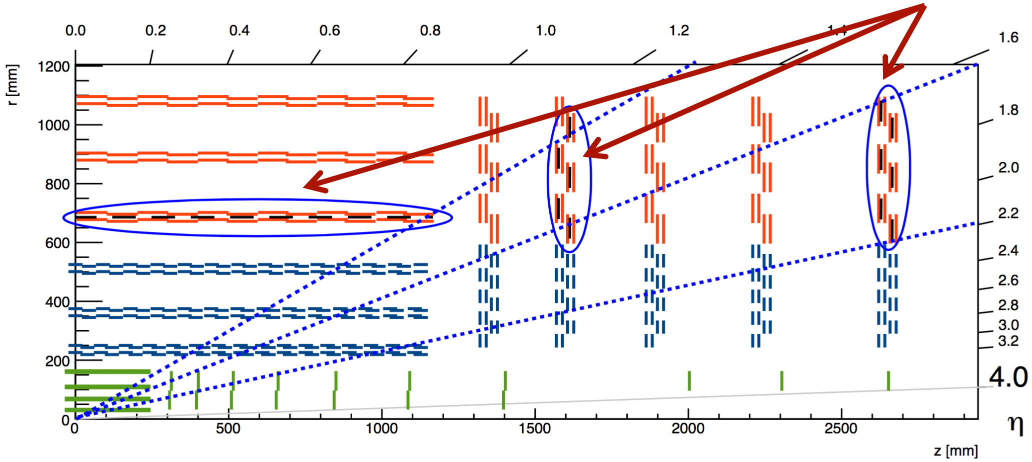
At HL-LHC: Timing is equivalent to additional luminosity

In other experiments (NA62, PADME…):

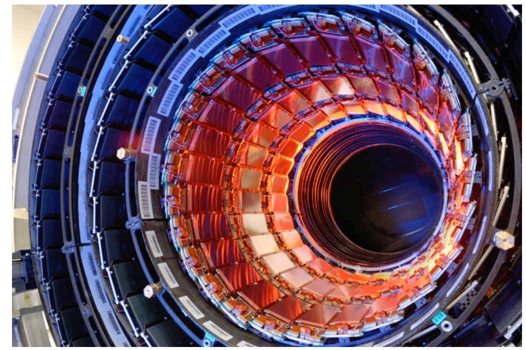
Timing is key to background rejection

Where do we place a track-timing detector?

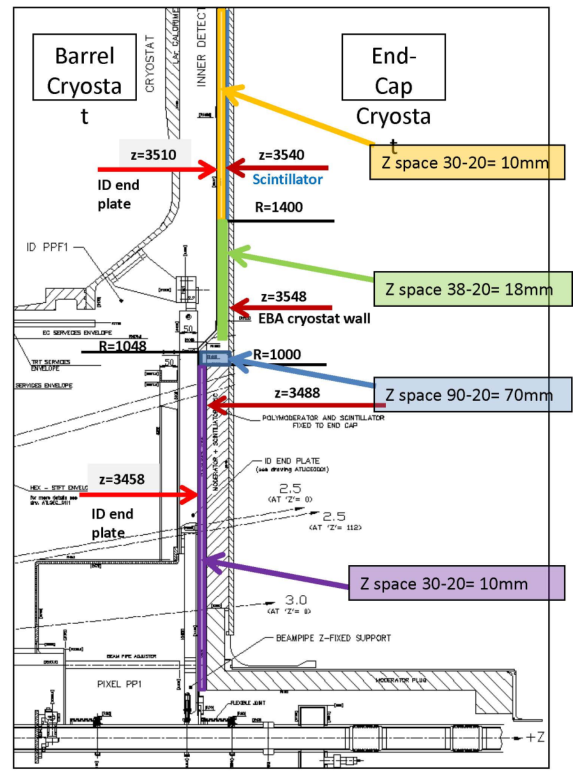
Some (all?) layers in a silicon tracker can provide timing information



Lindsey Gray, FNAL



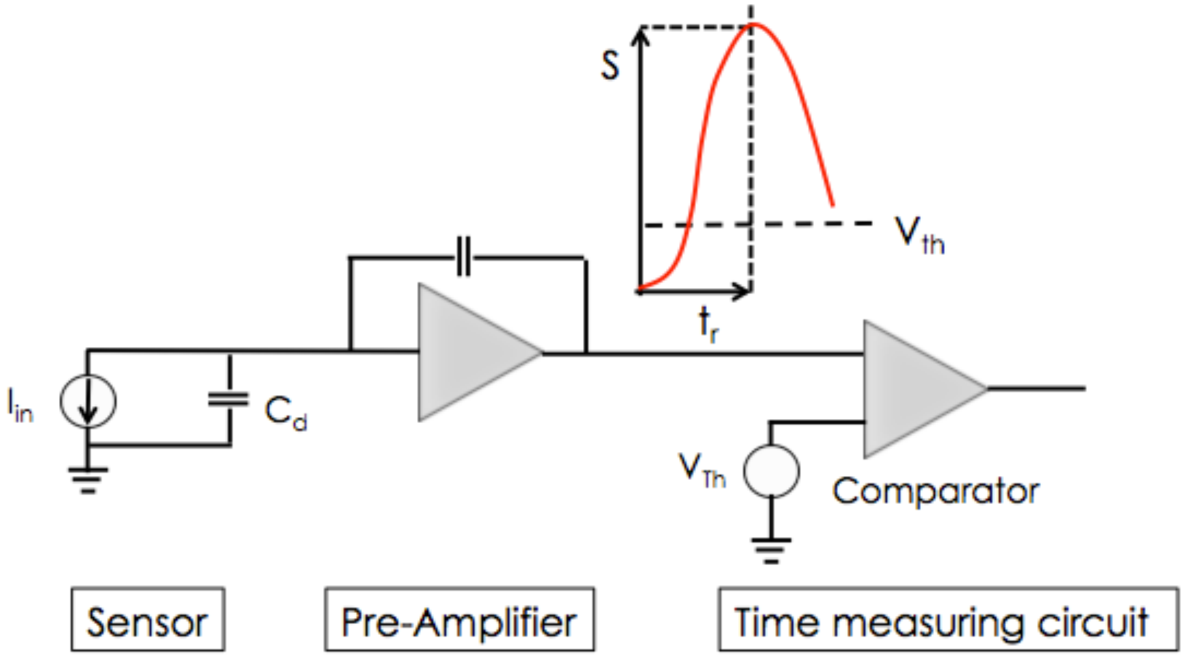
An additional detector can provide timing information, separated from the tracker



How do we build a 4D tracking system?

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

Time resolution

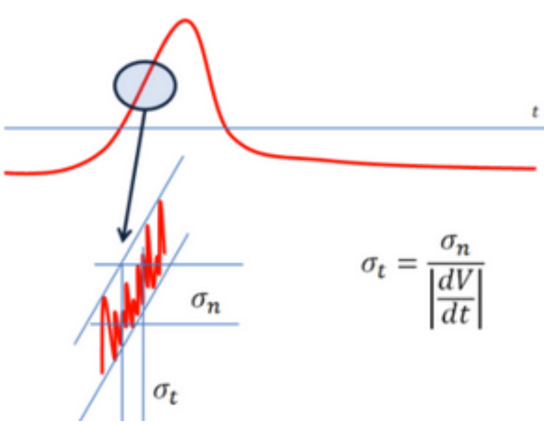
$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

Usual "Jitter" term

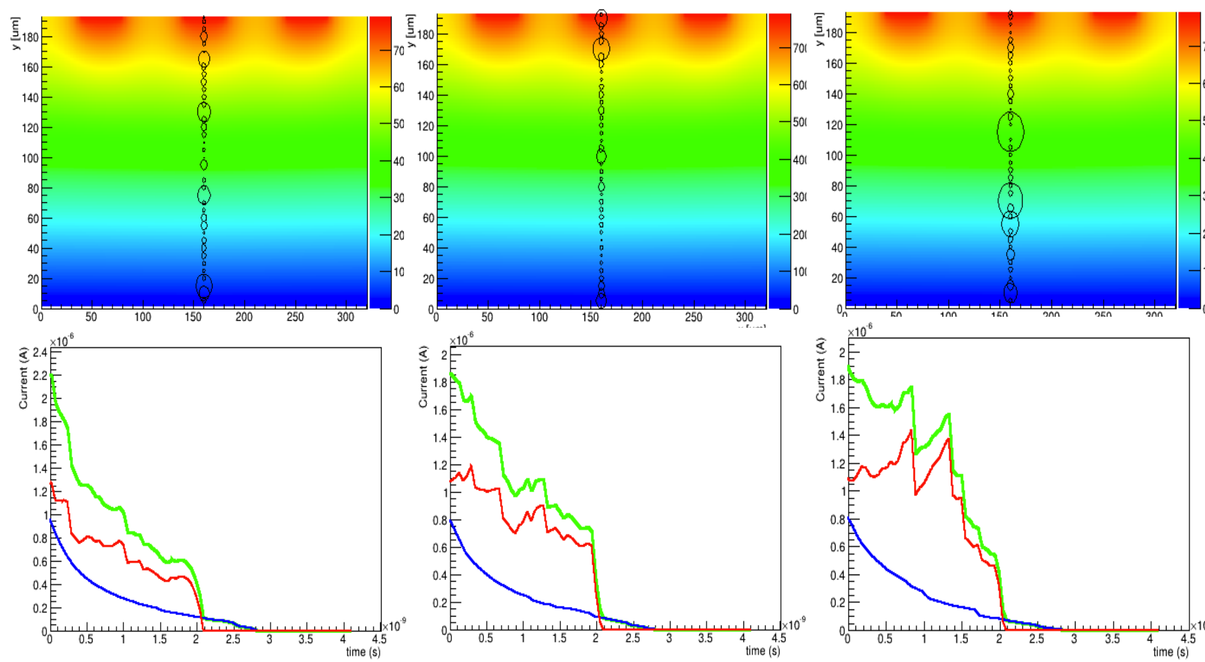
Here enters everything that is "Noise" and the steepness of the signal

Time walk: time correction circuitry

Shape variations: non homogeneous energy deposition



$$\sigma_t = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|}$$



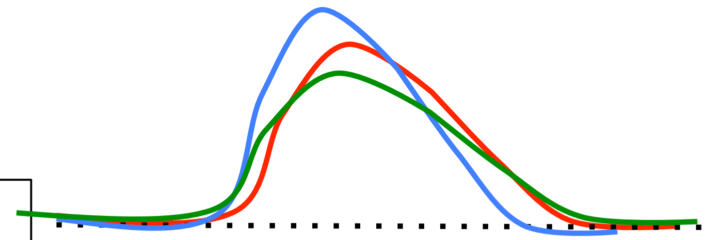
Not all geometries are possible

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity

Weighting field

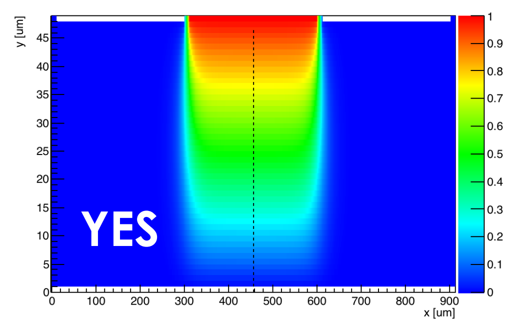


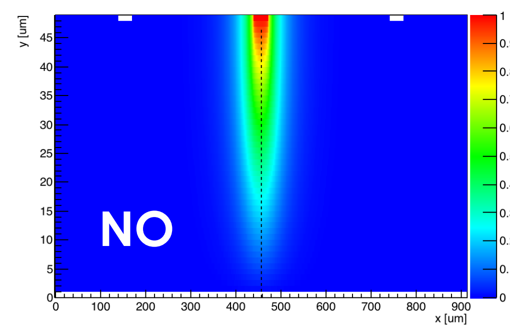
The key to good timing is the uniformity of signals:

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 timing systems

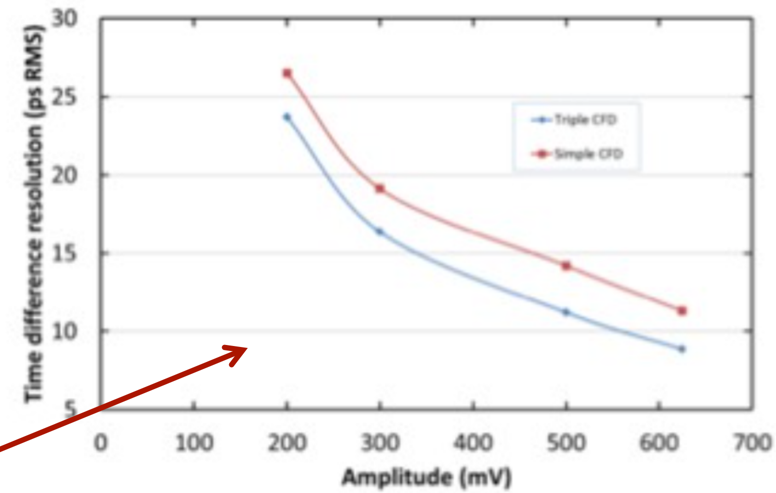
We need to minimize this expression:

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

- **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 on a single channel.

To be done:

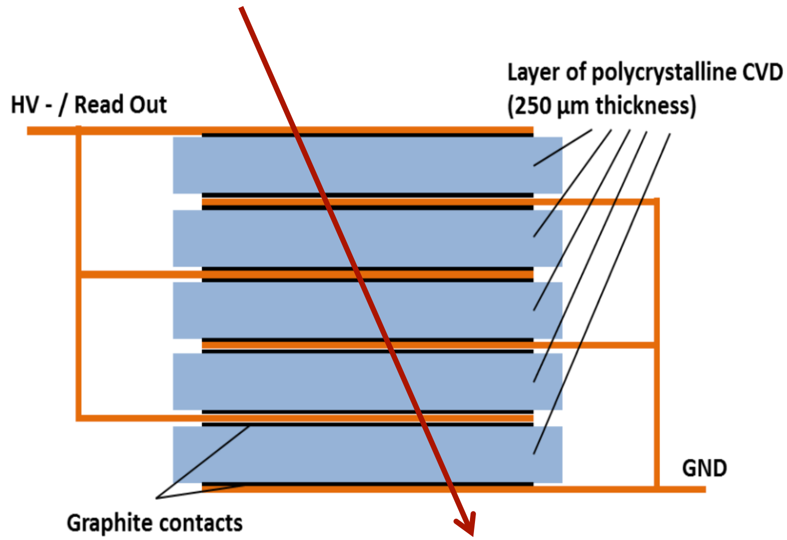
- Radiation hardness above 10^{14} n_{eq}/cm^2
- Fine Segmentation
- How to deal with shot noise (proportional to gain)

The Diamond approach

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

1) Multilayer stack

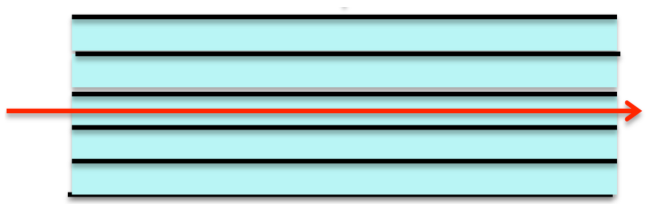
The signal is increased by the sum of many layers while keeping the rise time short



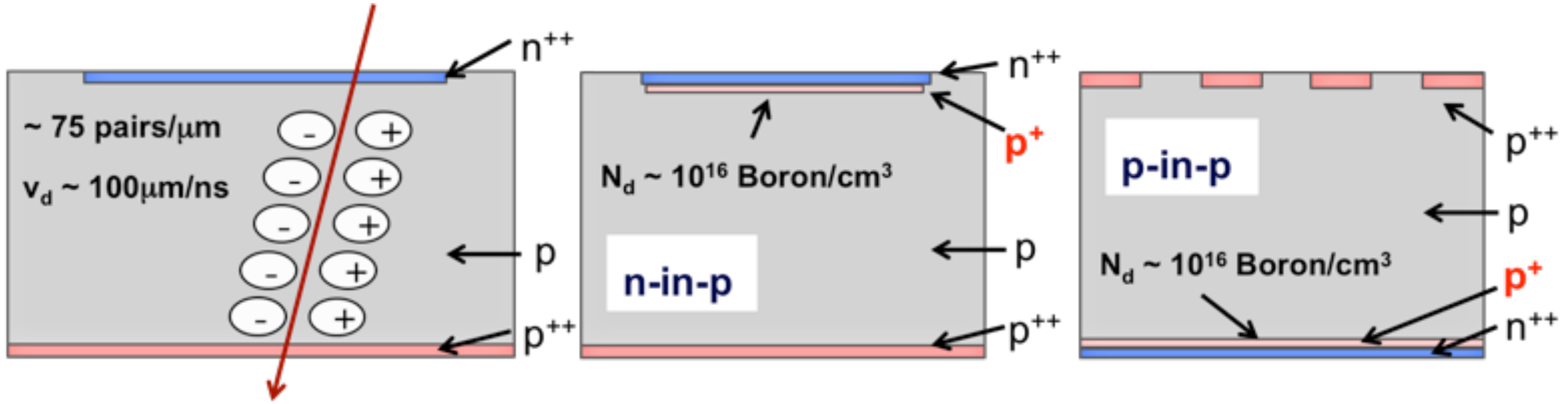
Best resolution: ~ 100 ps

2) Grazing

The particle crosses the diamond sensor along the longitudinal direction



LGAD - Ultra-Fast Silicon Detector

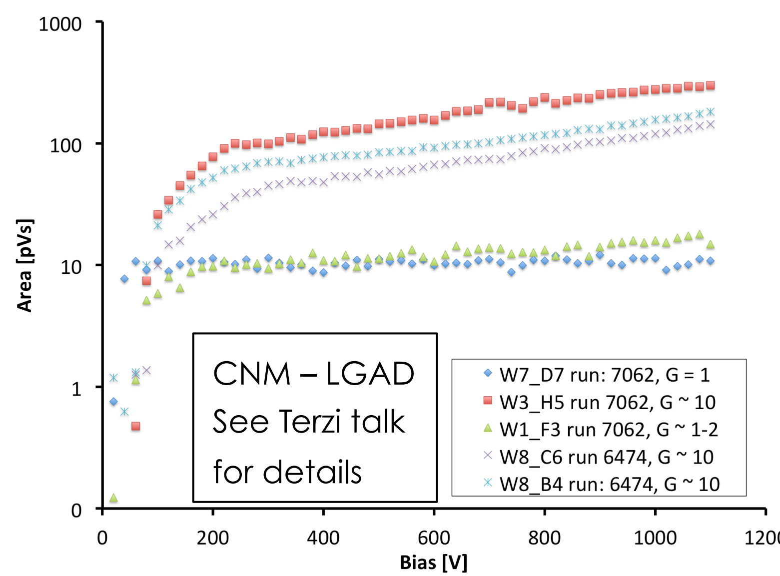


Traditional Silicon Detector **Ultra-Fast Silicon Detector**

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.

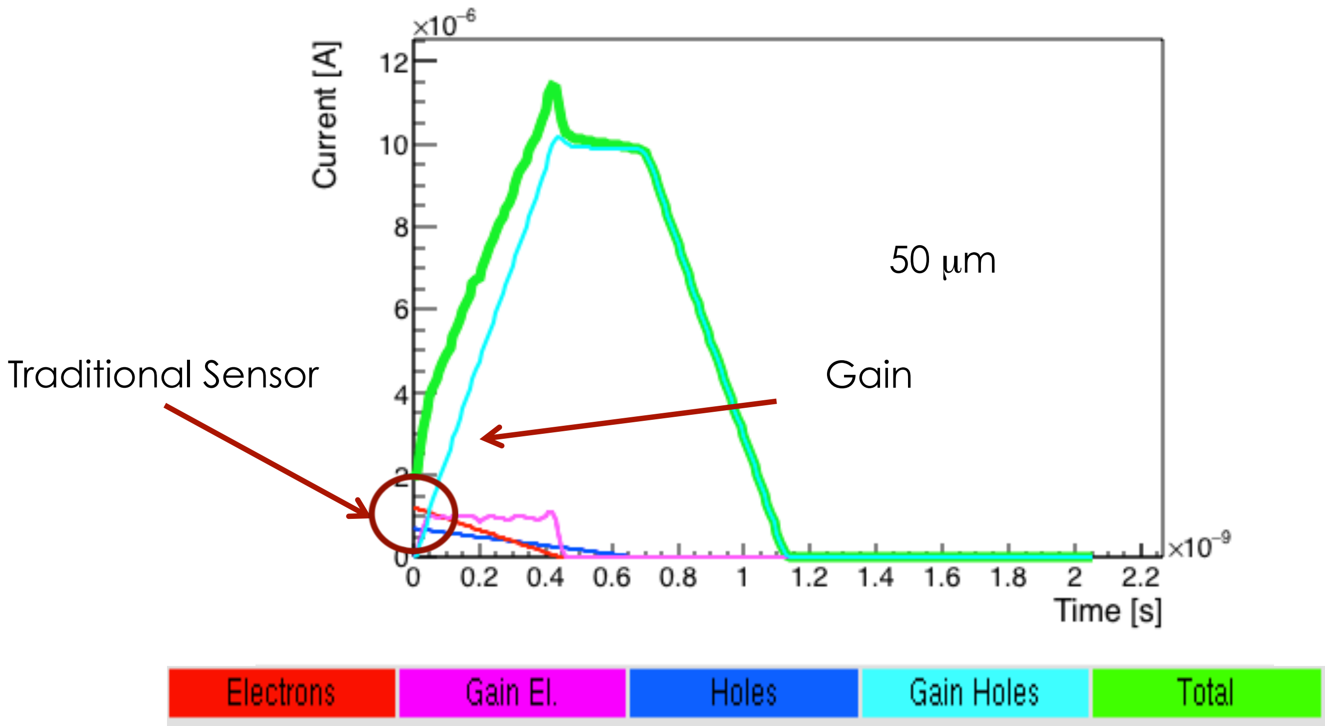
Easy to set the value of gain requested.



UFSD Signal characteristics

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

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



Traditional sensors

Charges generated uniquely by the incident particle

Ultra-Fast Silicon Detectors

Current due to gain holes creates a longer and higher signal

Simulation

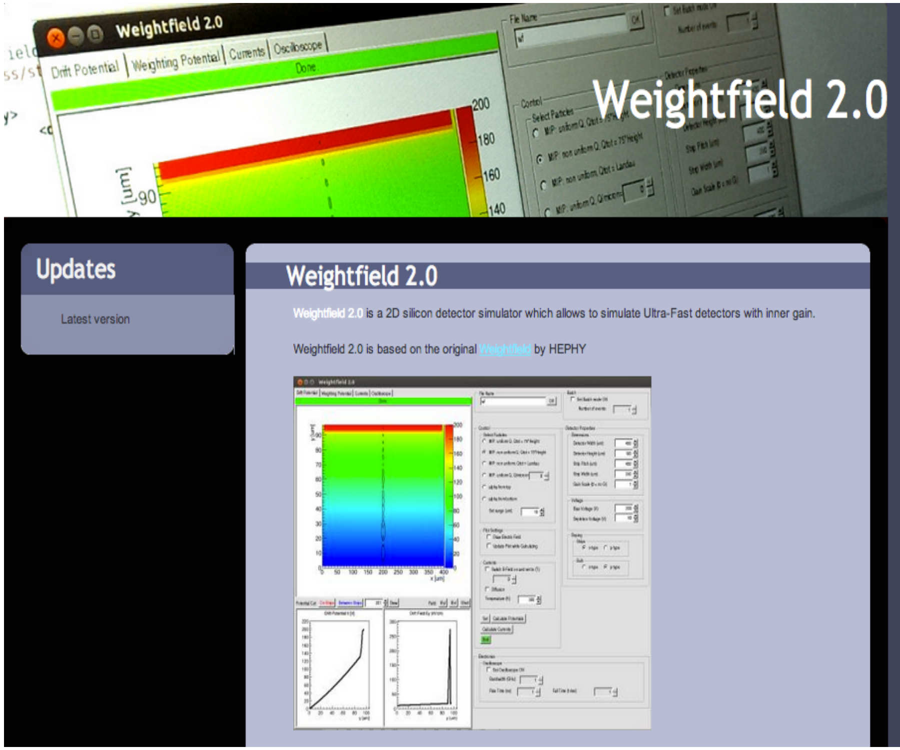
We developed a full sensor simulation to optimize the sensor design

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

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

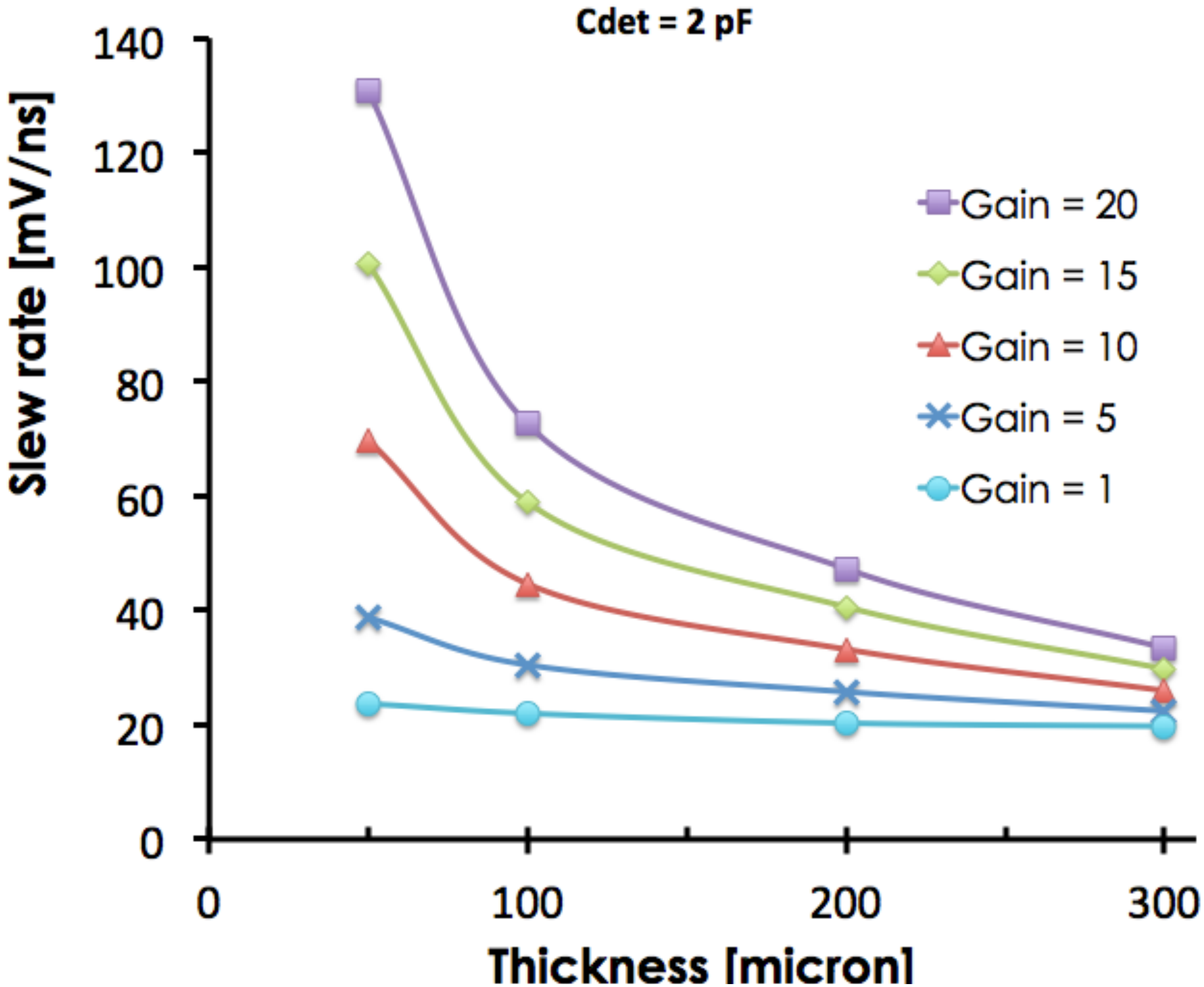
It includes:

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



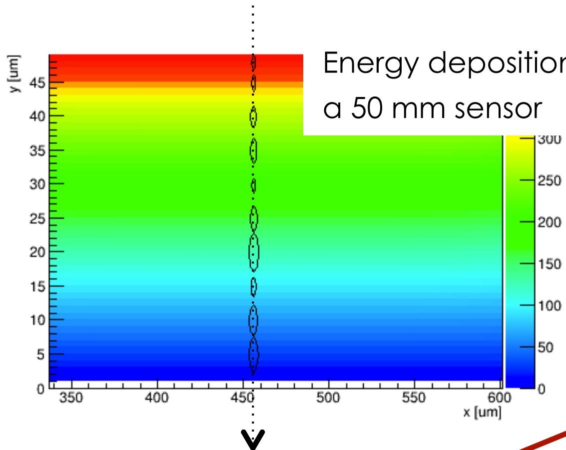
For each event, it produces a file with the current output that can be used as input in the simulation of the electronic response.

UFSD key points: low gain and thin sensors

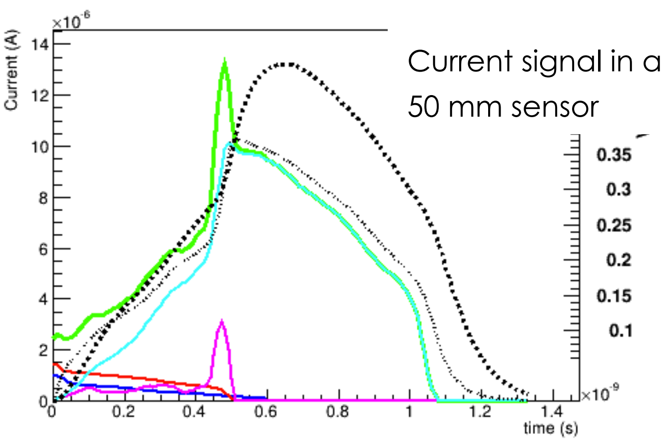


Thin sensors with low gain offer very large slew rate

What is the best pre-amp choice?

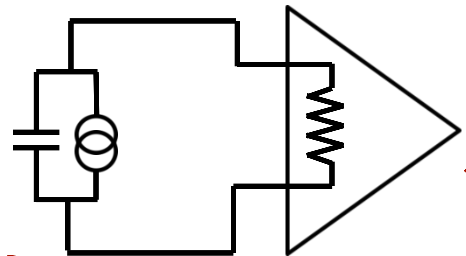


Energy deposition in a 50 mm sensor

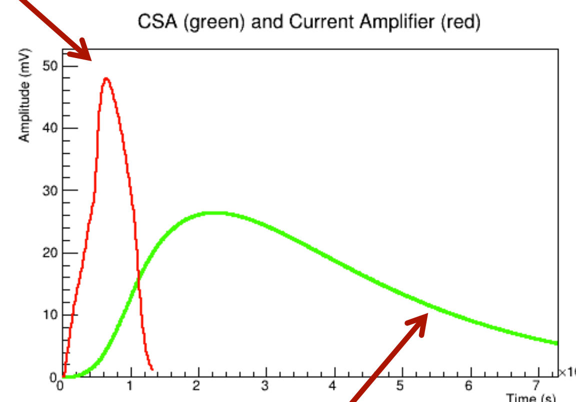


Current signal in a 50 mm sensor

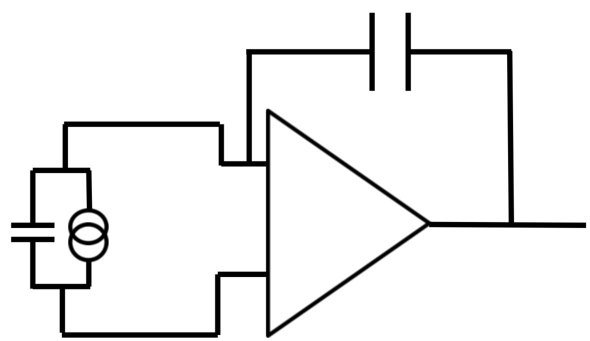
Current Amplifier



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

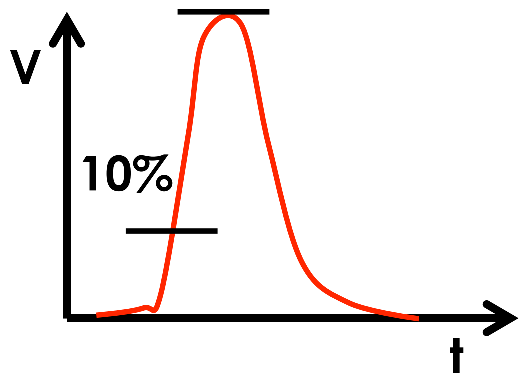


Integrating Amplifier



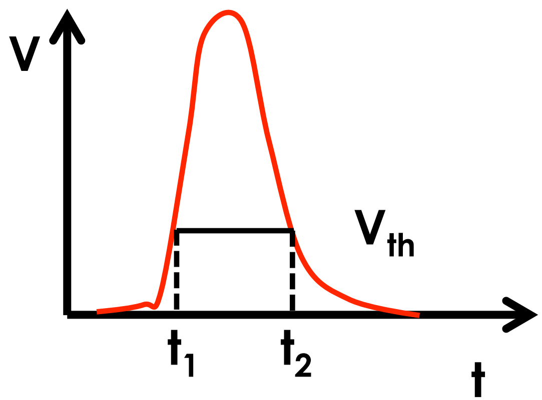
- Slower slew rate
- Lower noise
- Signal smoothing
- Less power

What is the best "time measuring" circuit?



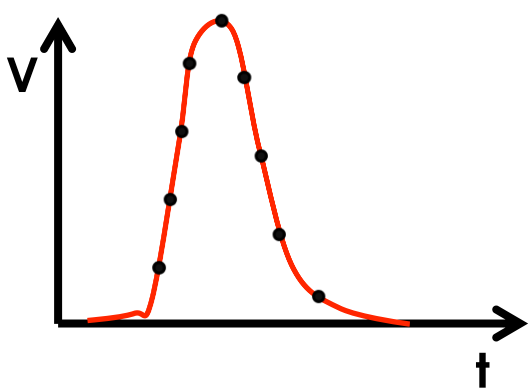
Constant Fraction Discriminator

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



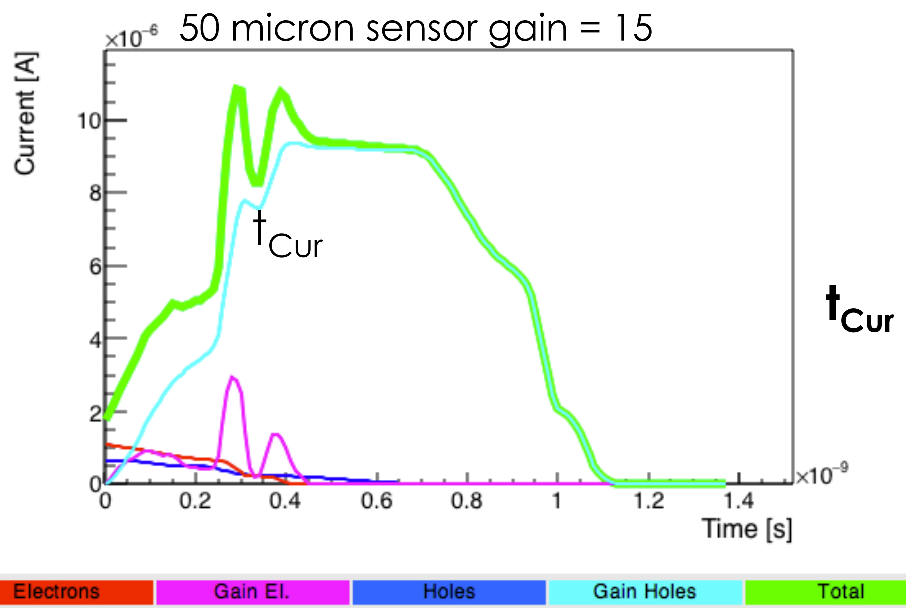
Multiple sampling

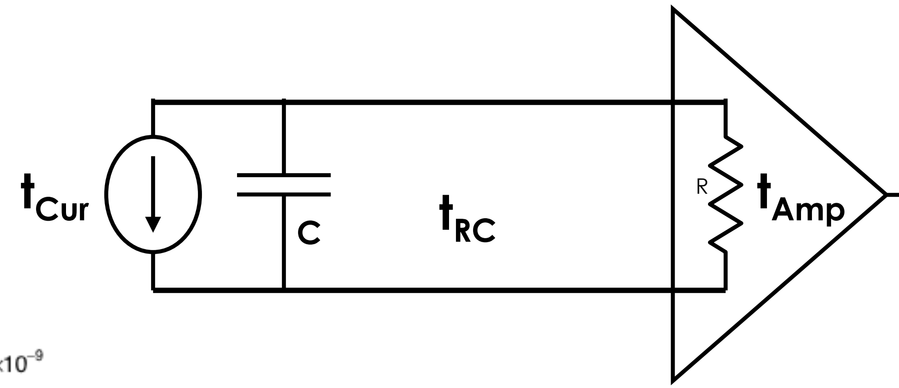
Most accurate method, needs a lot of computing power.

Possibly too complicated for large systems

The players: signal, noise and slope

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



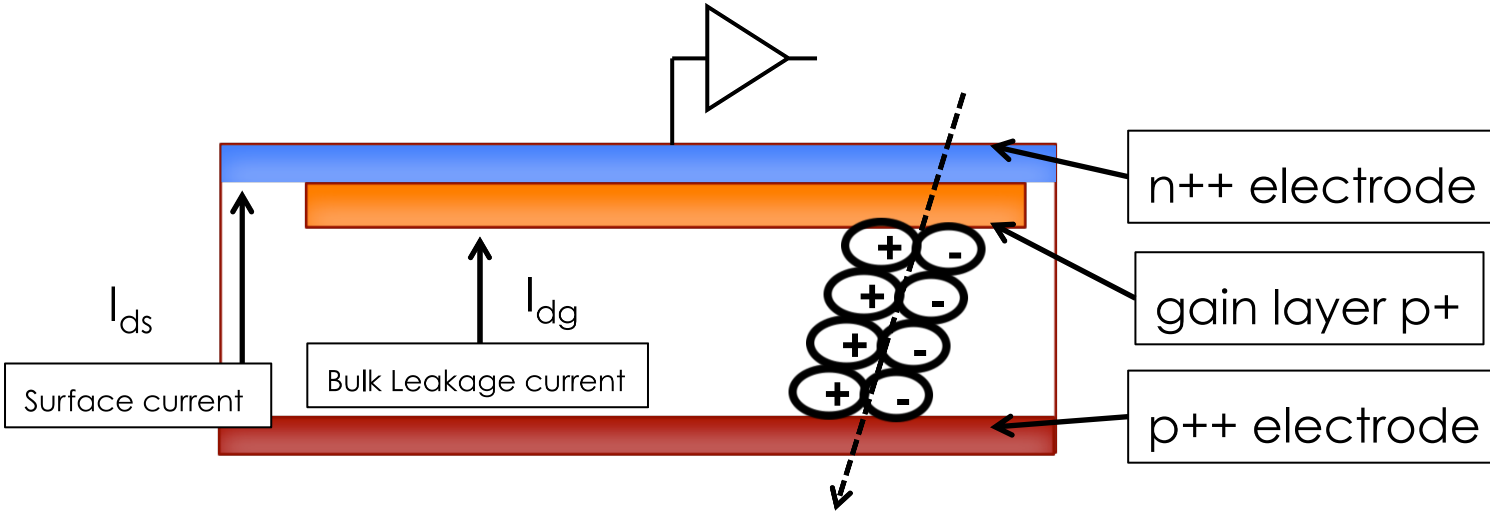


The current rise time (t_{Cur}) | The RC circuit (t_{RC}) | Amplifier rise time (t_{Amp})

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})

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

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

$$F \sim M^x$$

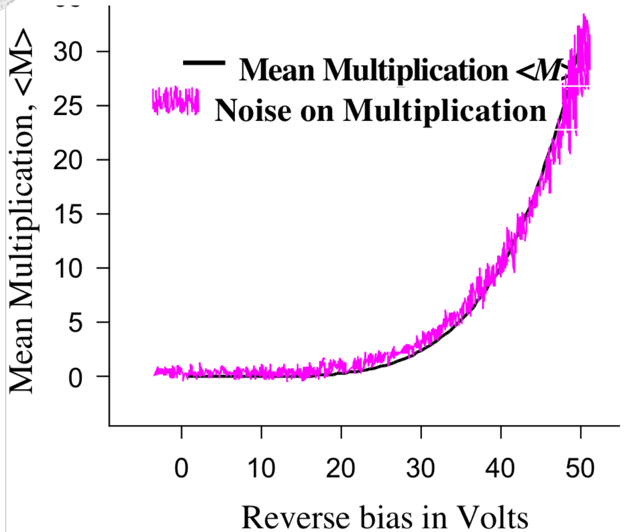
k = e/h ionization rate

x = excess noise index

M = gain

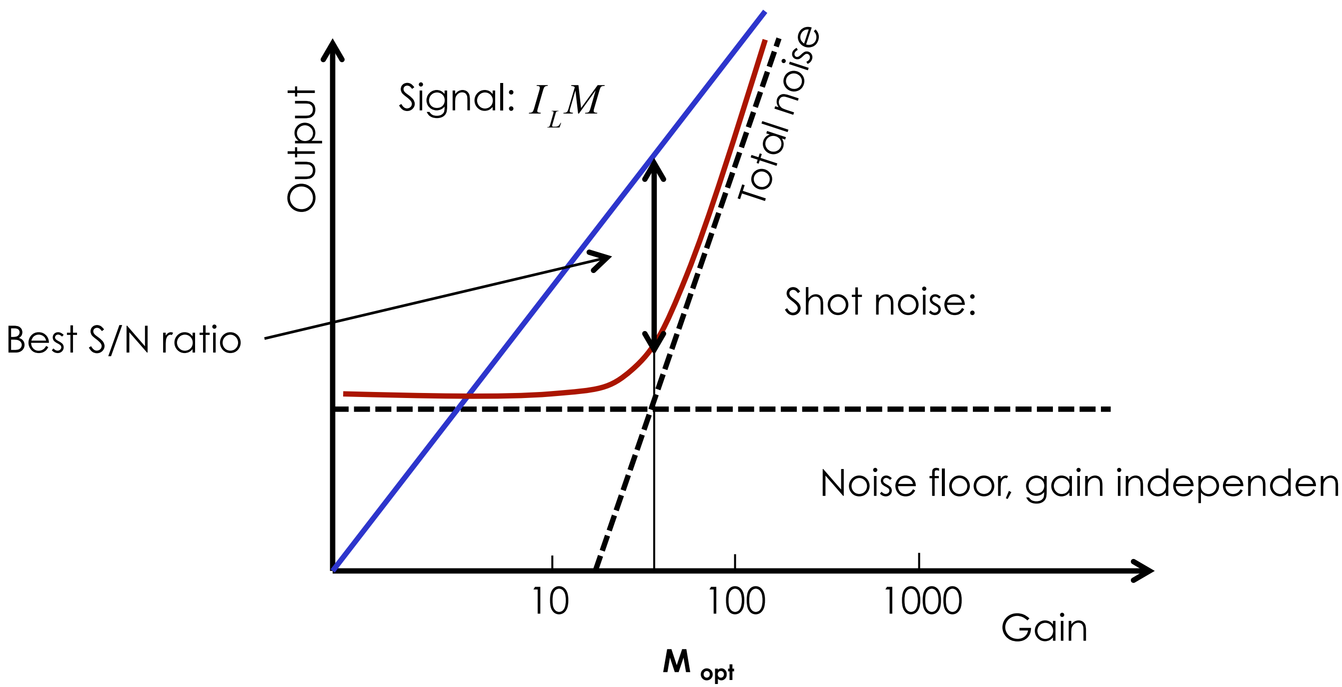
$$F = \frac{\langle M^2 \rangle}{\langle M \rangle^2} \Rightarrow \langle M^2 \rangle = \langle M \rangle^2 F$$

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

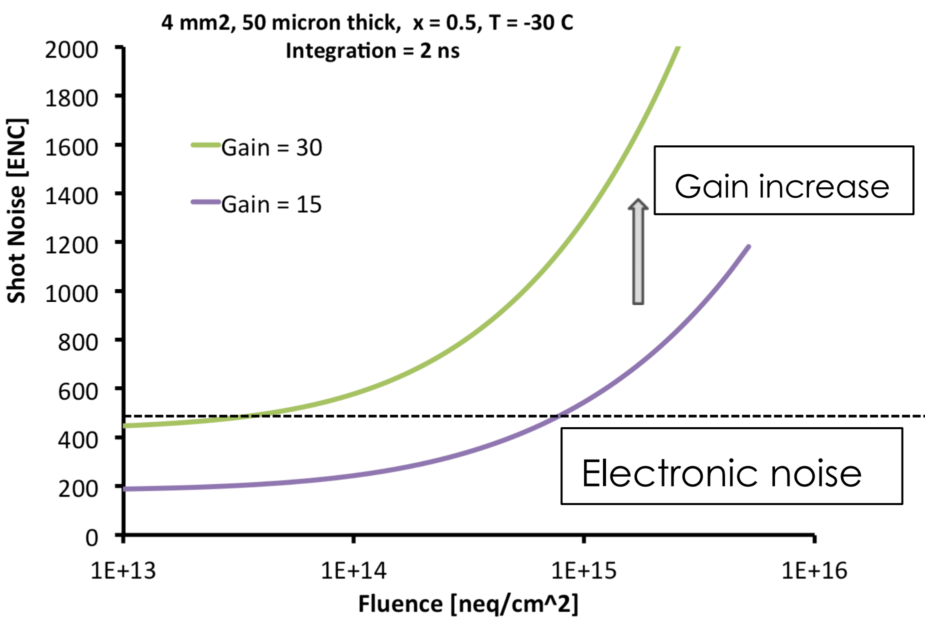
Let's assume a 4 mm^2 pad, 50 micron thick, and a electronic noise of 500 ENC

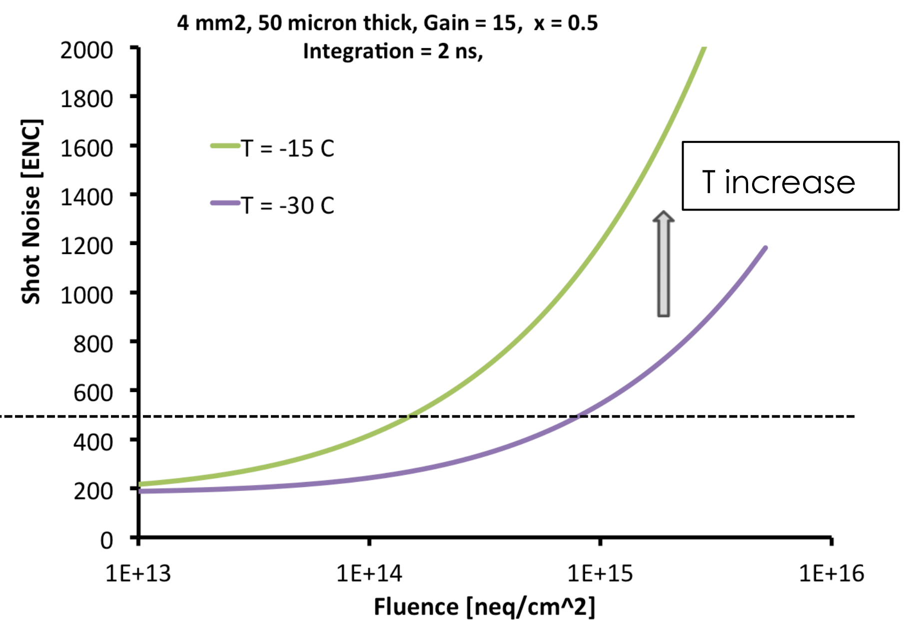
What is the effect of shot noise as a function of radiation?

Steep dependence on gain

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

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



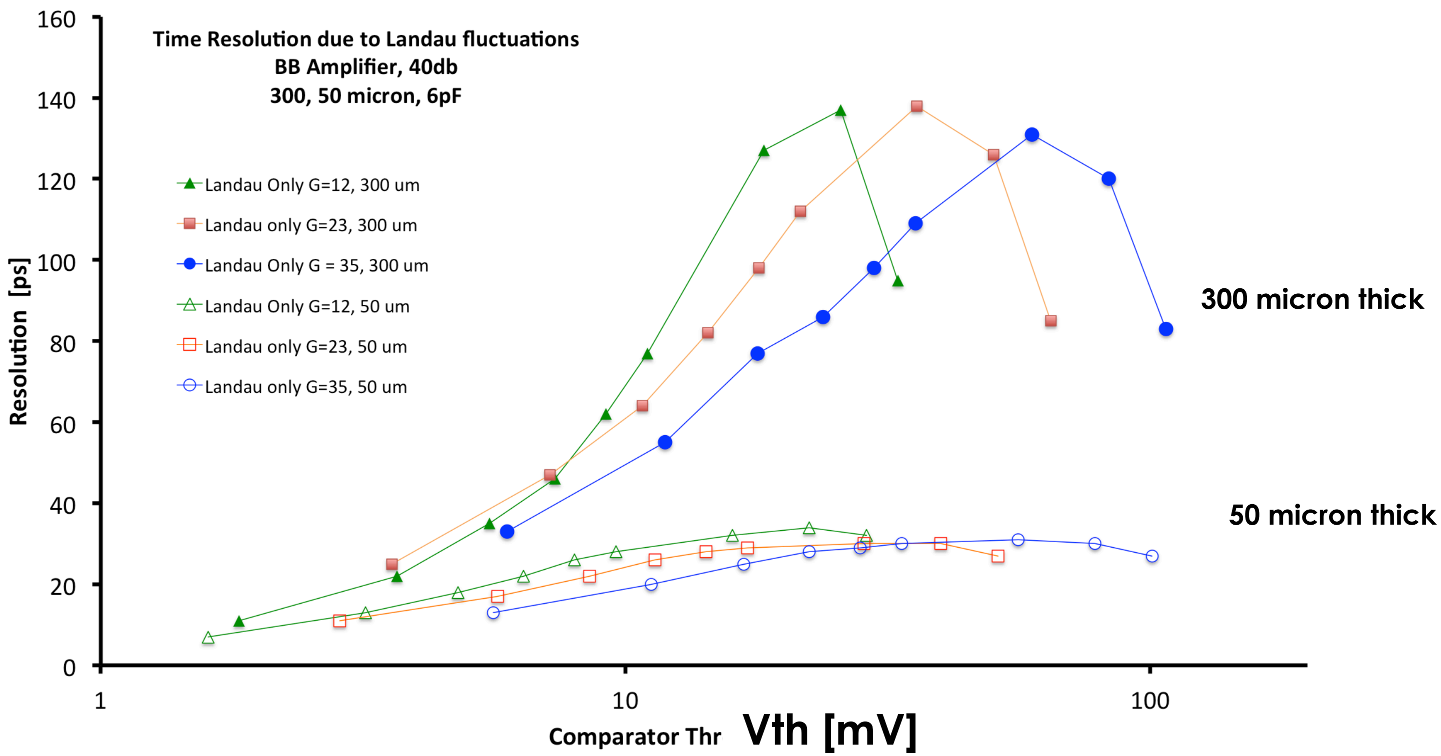


To minimize Shot noise:

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

Landau noise

Resolution due only to shape variation, assuming perfect time walk compensation



To minimize Landau noise:

➔ Set the comparator threshold as low as you can

➔ Use thin sensors

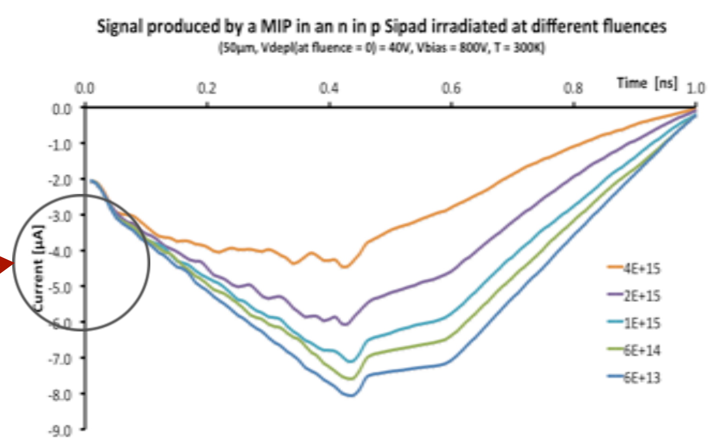
Irradiation - I

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.**
(poster Sec. A, B. Baldassarri)



Electronics need to be calibrated for different signal shapes

Irradiation - II

2) Changes in doping concentration

There is evidence **that in thick sensors** dynamic effects cause an apparent "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.

R&D paths:

- Use Vbias to compensate for the loss on gain
- Use thin sensors: weaker dynamic effects
- Long term: Gallium doping

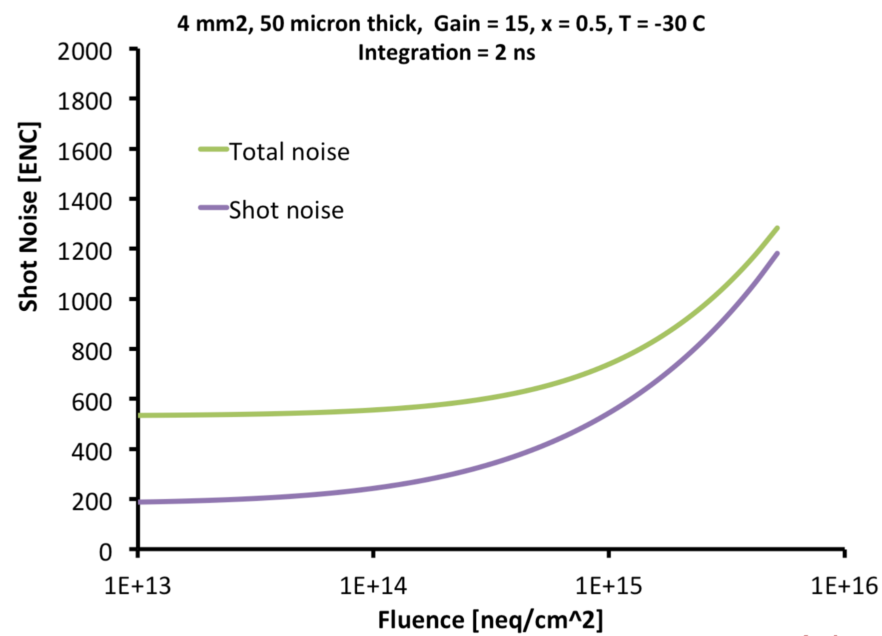
3) Increased leakage current

Assuming Gain ~ 15, T = -30C,

Shot noise starts to be important

at fluences above ~ 10^{15} n^{eq}/cm^2

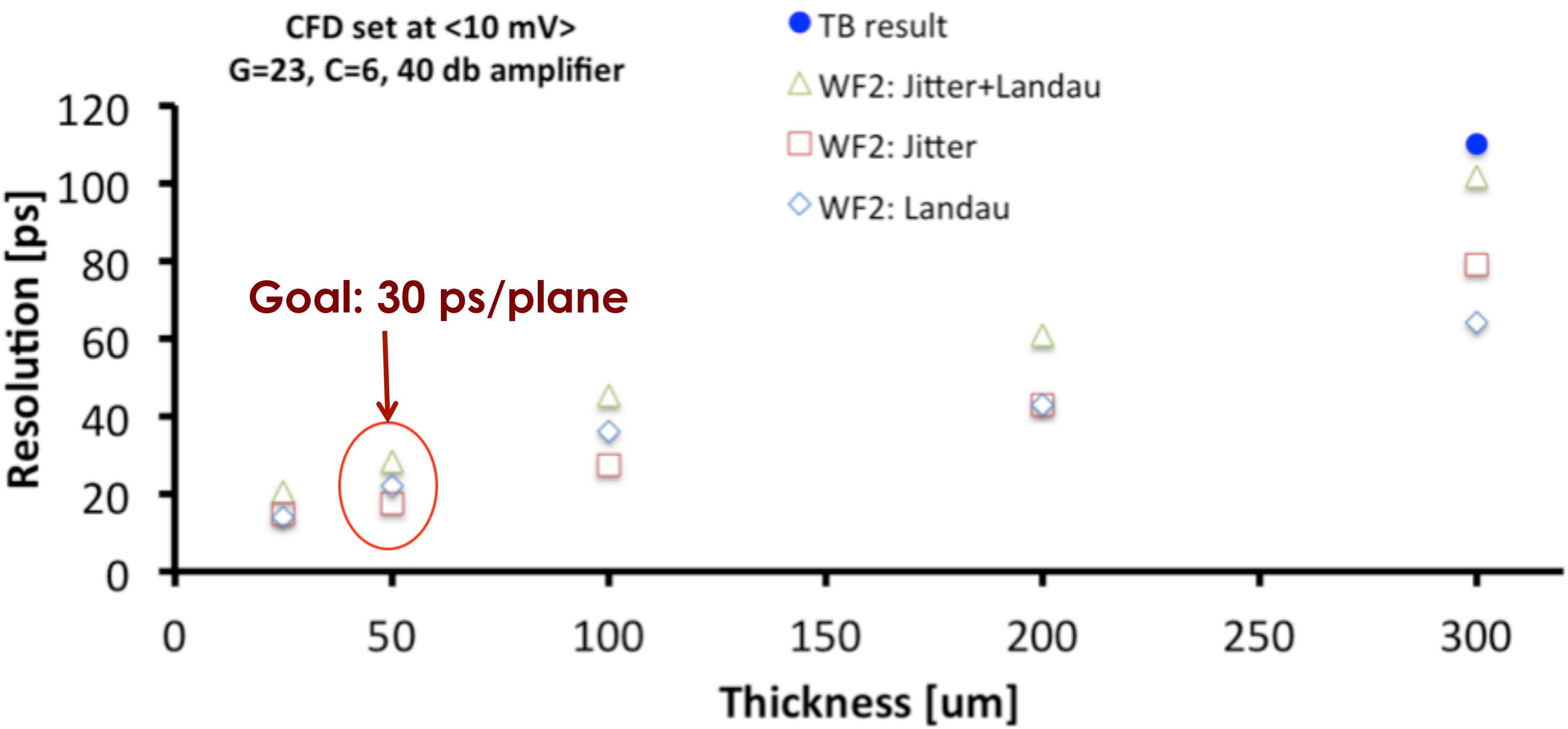
- Keep the sensor cold
- Low gain
- Small sensor



UFSD: 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)

CNM - LGAD



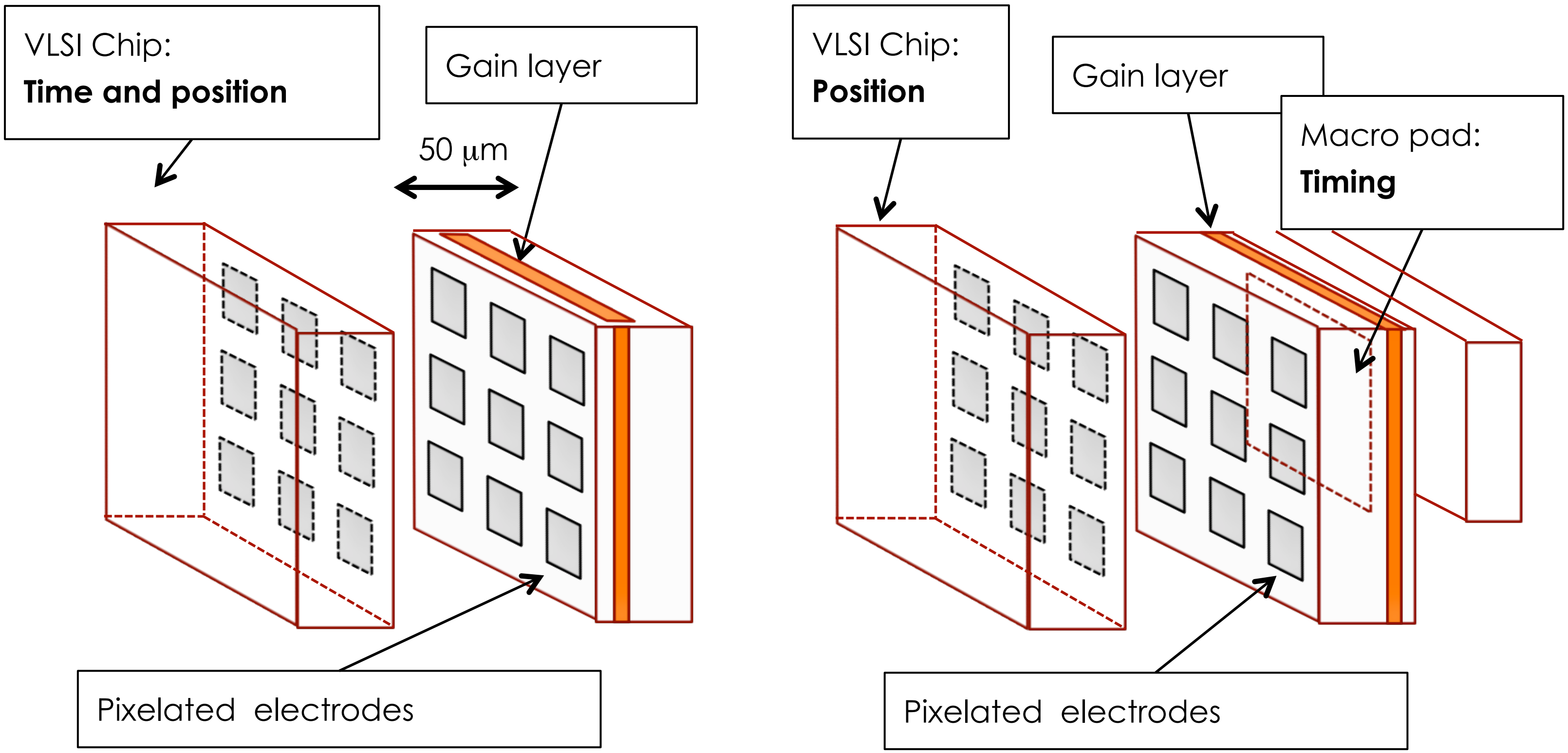
WF2 = Weightfield2, simulation program.

Contribution of the Jitter and Landau parts to the total time resolution as a function of the sensor thickness.

Roadmap

More of the same: hybrid semiconductor systems

Various idea on segmentation



The real solution: monolithic

> 10 years

This is the correct approach, however it will take time.

Acknowledgments

We kindly acknowledge the following funding agencies:

- INFN – Gruppo V
- Horizon 2020
- Ministero degli Affari Esteri, Italy, MAE
- U.S. Department of Energy grant number DE-SC0010107

Summary and outlook

Tracking is 4 Dimensions is a very powerful tool

Low gain Avalanche Detectors have the potential to bring this technique to full fruition using gain ~ 10 and thin sensors

Why **low** gain?

Milder electric fields, possible electrodes segmentation, lower shot noise, no dark count, behavior similar to standard Silicon detectors

Why **thin** sensors?

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

UFSD activities 2016:

- Thin sensor prototypes (CNM, FBK)
- Irradiation program. Gallium instead of Boron?
- Sensor demonstrator for ATLAS, CMS
- Discrete component read-out amplifier
- First custom chip, 8 channel, analog-comparator
- Installation of system demonstrator in CMS
- **Goal: 30 ps**