The 4D pixel challenge

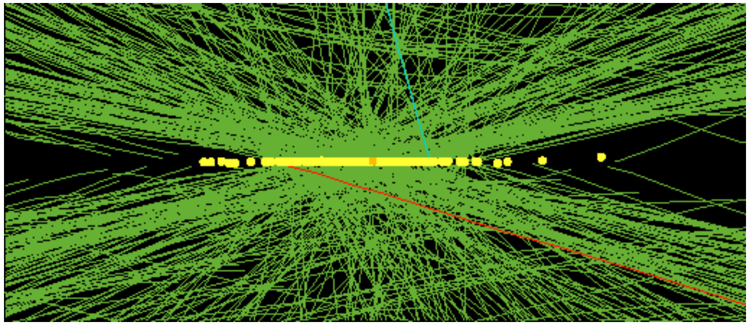
Is it possible to build a tracker with concurrent excellent time and position resolution?

Can we provide from the same detector and readout chain:

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

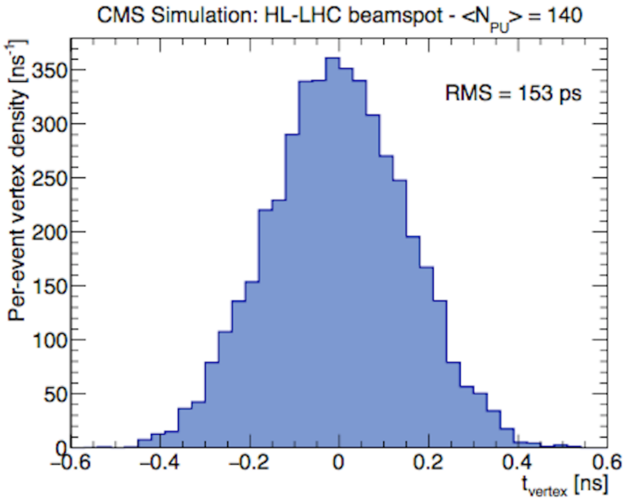
Tracking in 4 Dimensions

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, Mu3e):

Timing is key to background rejection

The effect of timing information

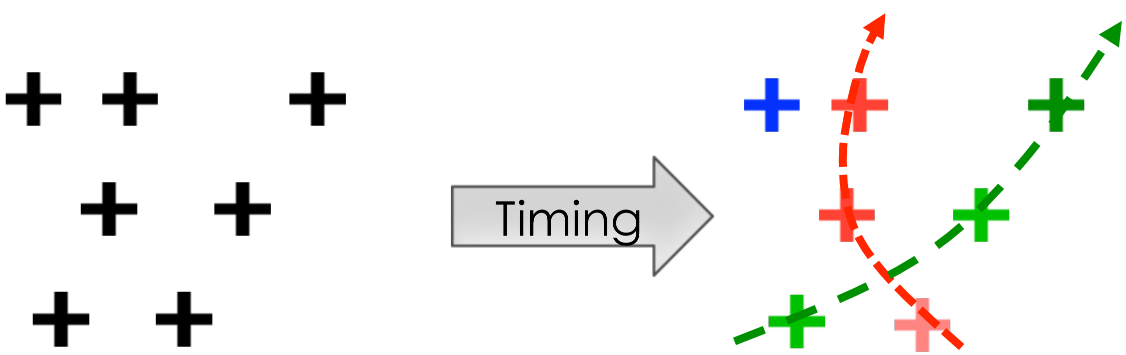
The inclusion of track-timing in the event information has the capability of changing radically how we design experiments.

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

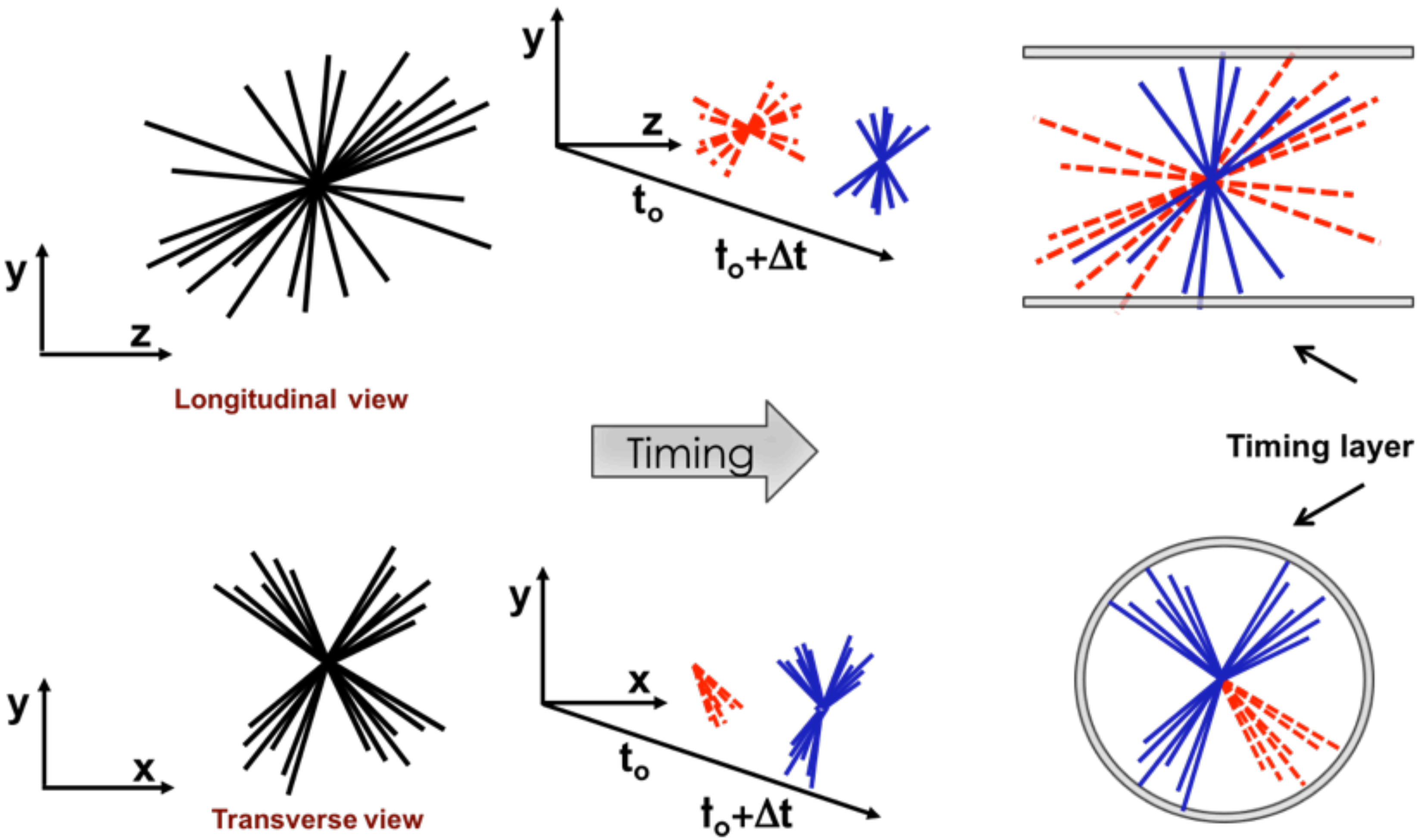
Timing at each point along the track

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



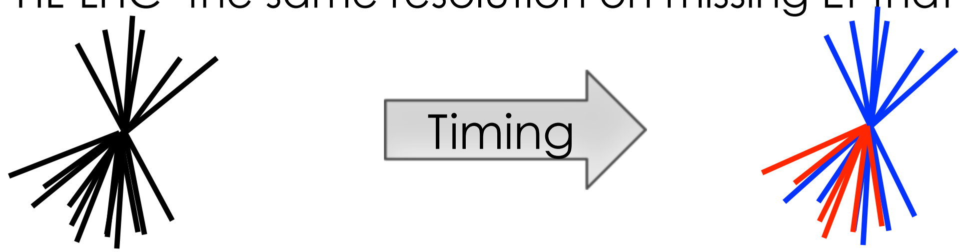
Timing in the event reconstruction - I

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

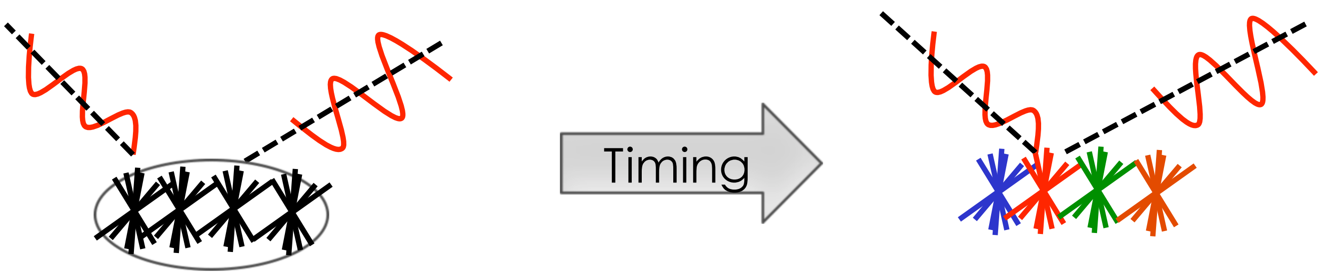


Timing in the event reconstruction - II

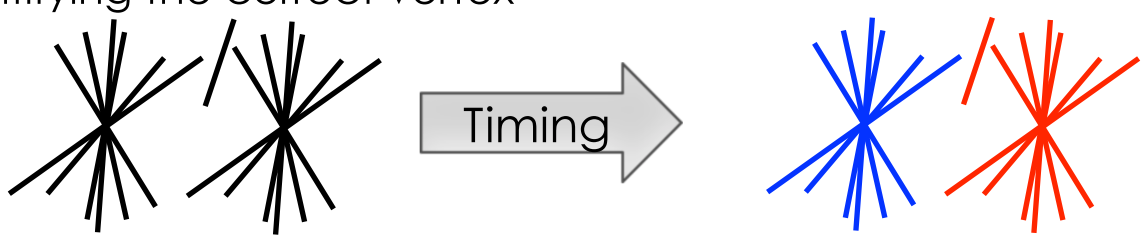
Missing Et: consider overlapping vertexes, one with missing Et: Timing allows obtaining at HL-LHC the same resolution on missing Et that we have now



H ➔ 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

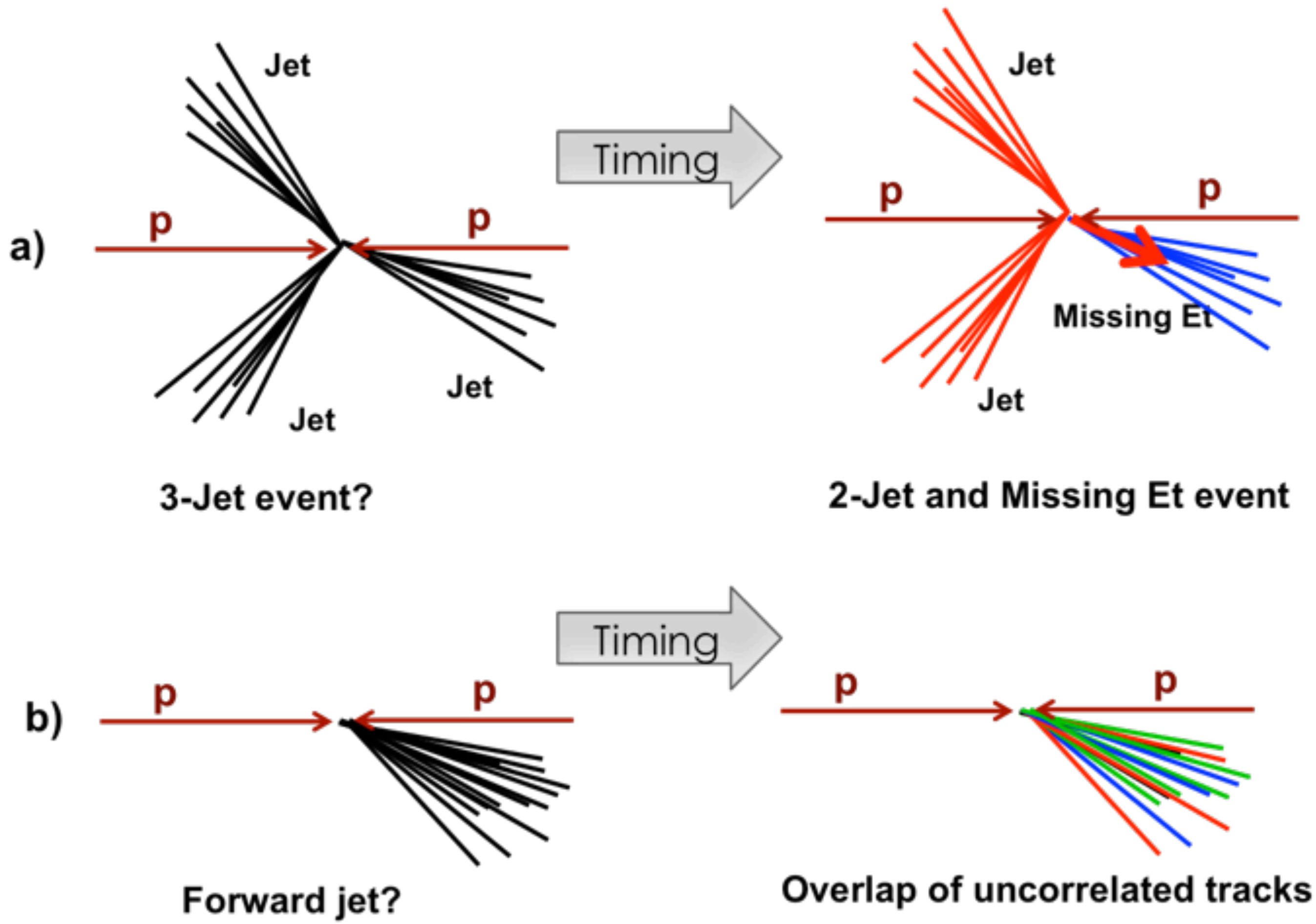


Displaced vertexes: The timing of the displaced track and that of each vertex allow identifying the correct vertex



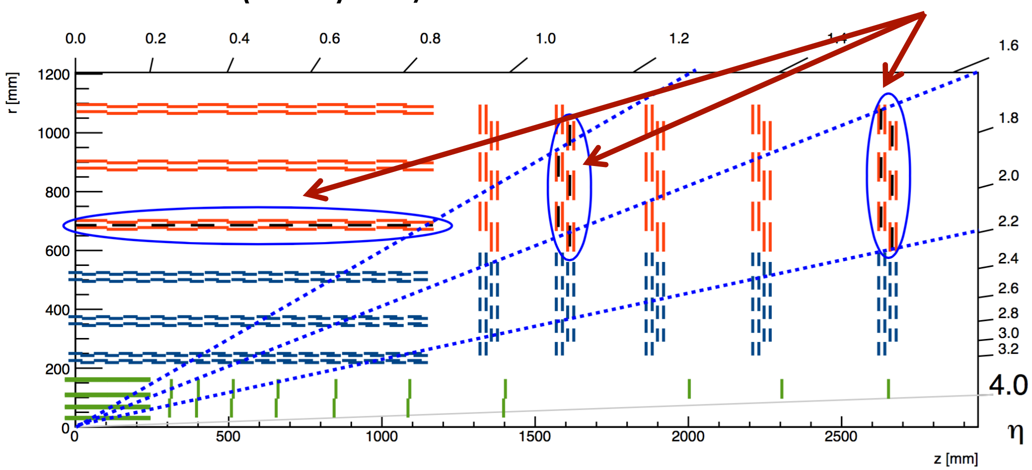
The effect of timing information:

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

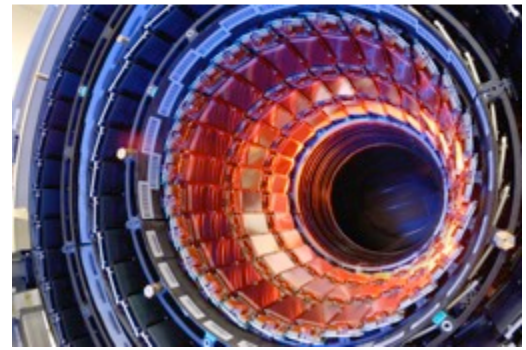


Where do we place a track-timing detector?

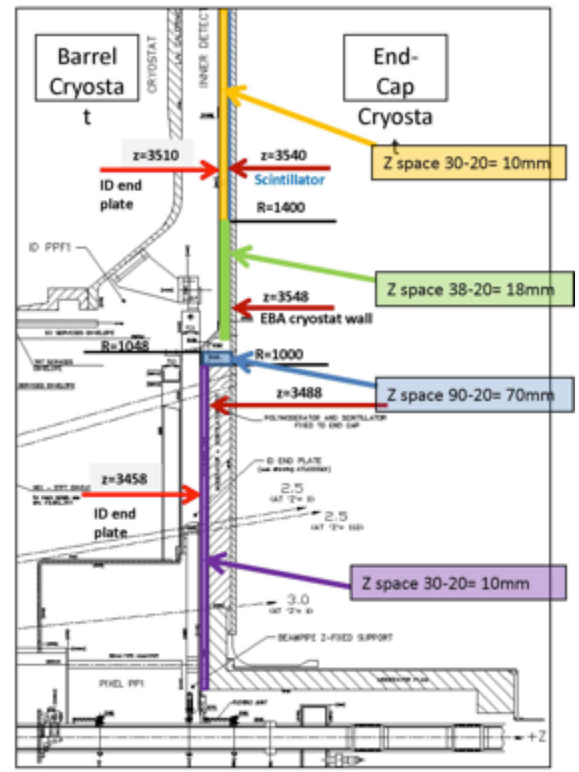
Some (all?) layers in a silicon tracker can provide timing information



Lindsey Gray, FNAL



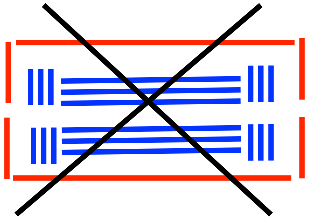
An additional detector can provide timing information, separated from the tracker

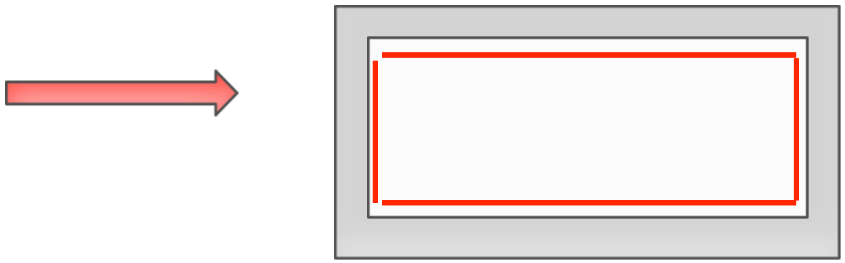


How do we build a 4D tracking system?

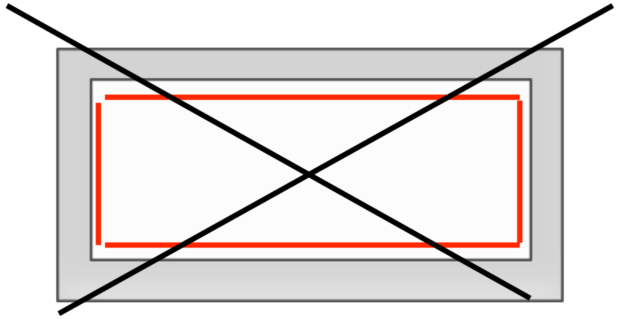
Where do we stand?

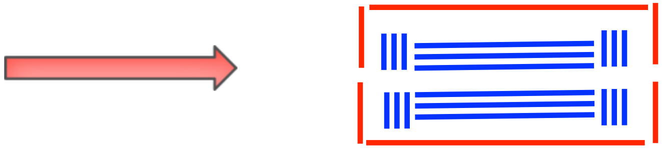
The tracking community thinks it is a wonderful idea, clearly to be implemented **outside the tracker volume**, in front of the calorimeter





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



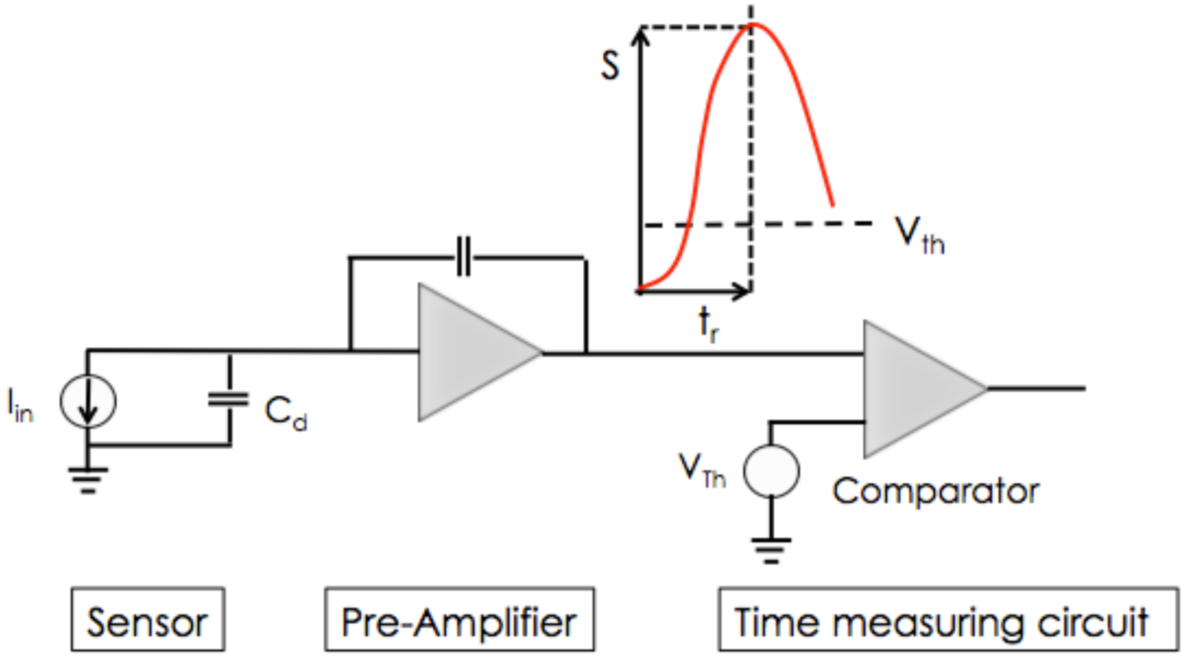


We are now in contact with **the muon community….**

N. Cartiglia, INFN, Torino - 4D pixel - Sestri 2016

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.

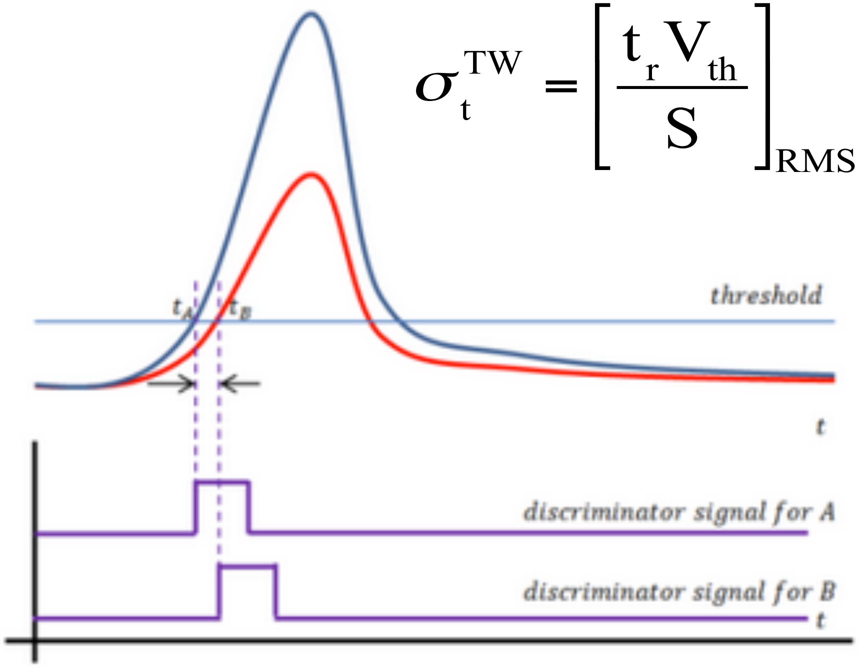
Strong interplay between sensor and electronics

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

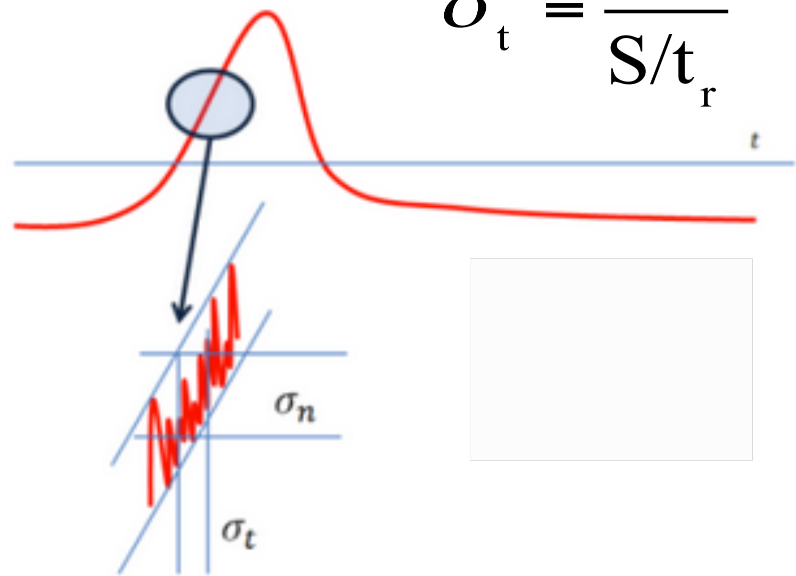
Jitter: the noise is summed to the signal, causing amplitude variations

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



Due to the physics of signal formation

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



Mostly due to electronic noise

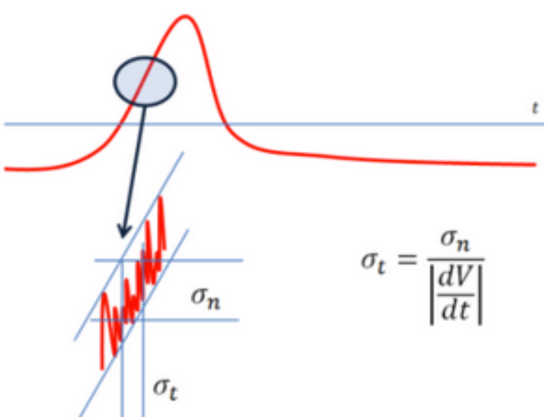
Time walk and jitter ~ $N/(S/t_r) = N/(dV/dt)$

Time resolution

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

Usual "Jitter" term

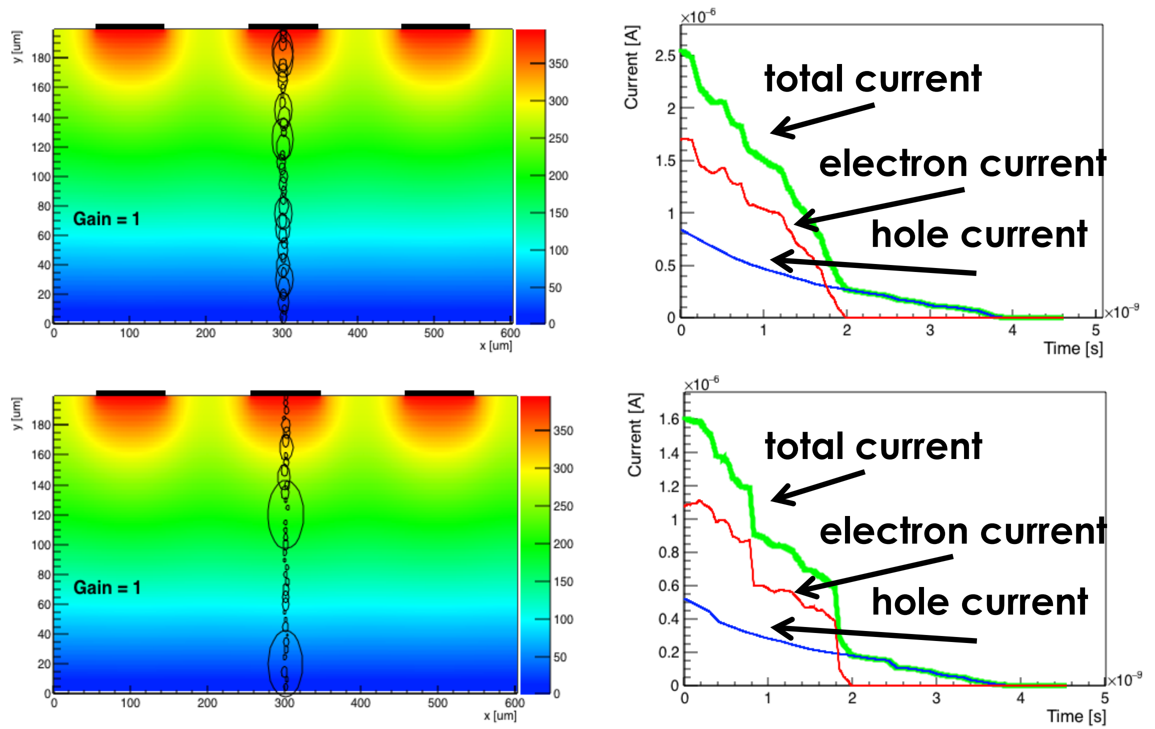
Here enters everything that is "Noise" and the steepness of the signal



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

Time walk: time correction circuitry

Shape variations: non homogeneous energy deposition



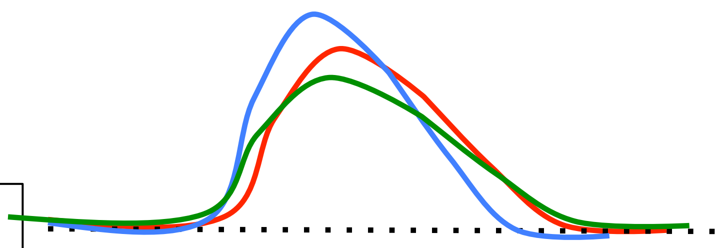
Not all geometries are possible

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

Drift velocity → v

Weighting field → E_w

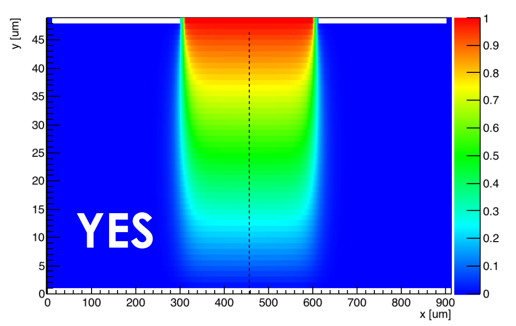


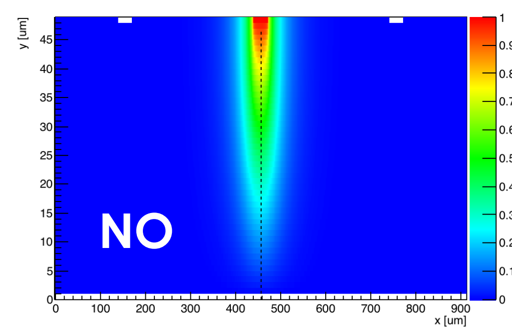
The key to good timing is the uniformity of signals:

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

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

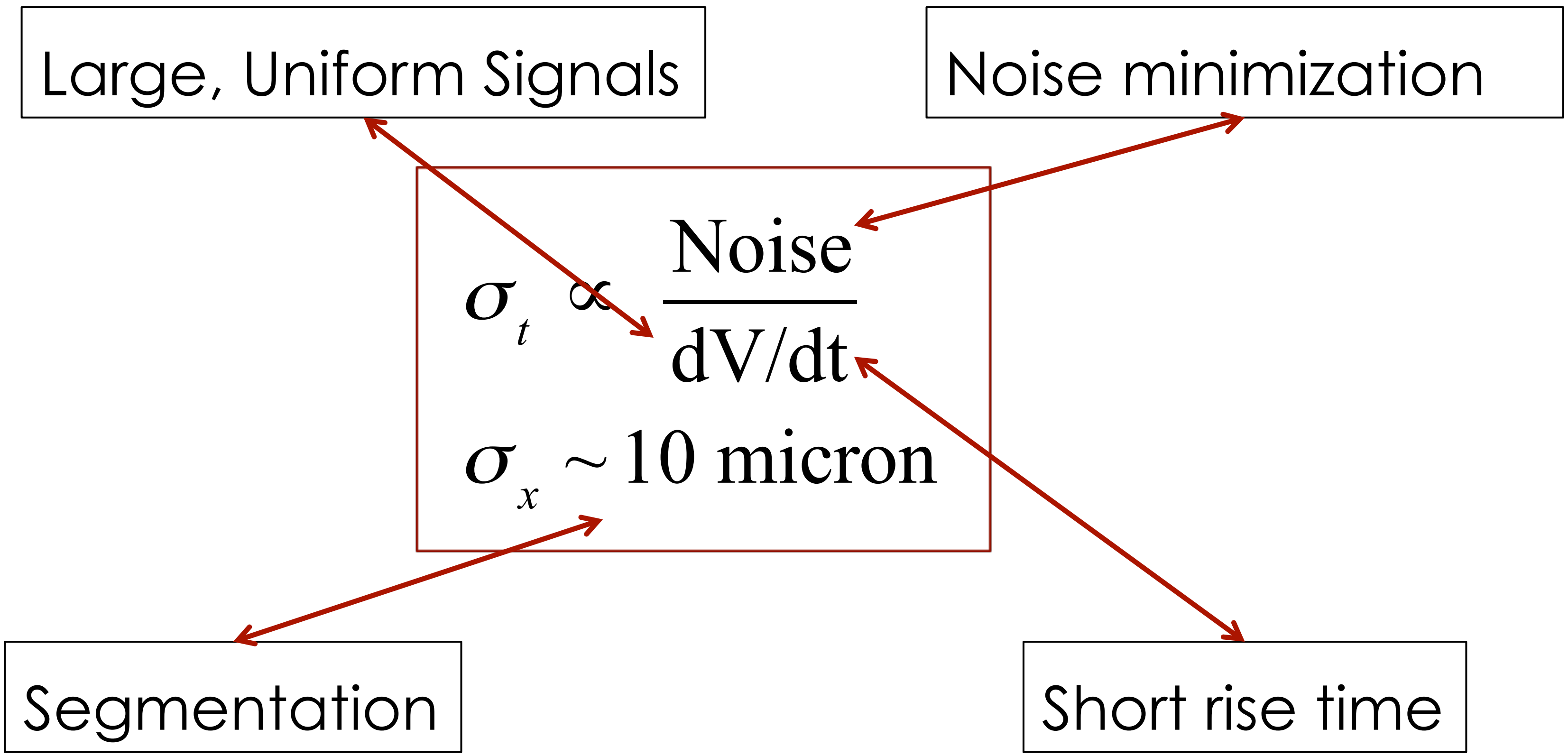
Everything else does not work





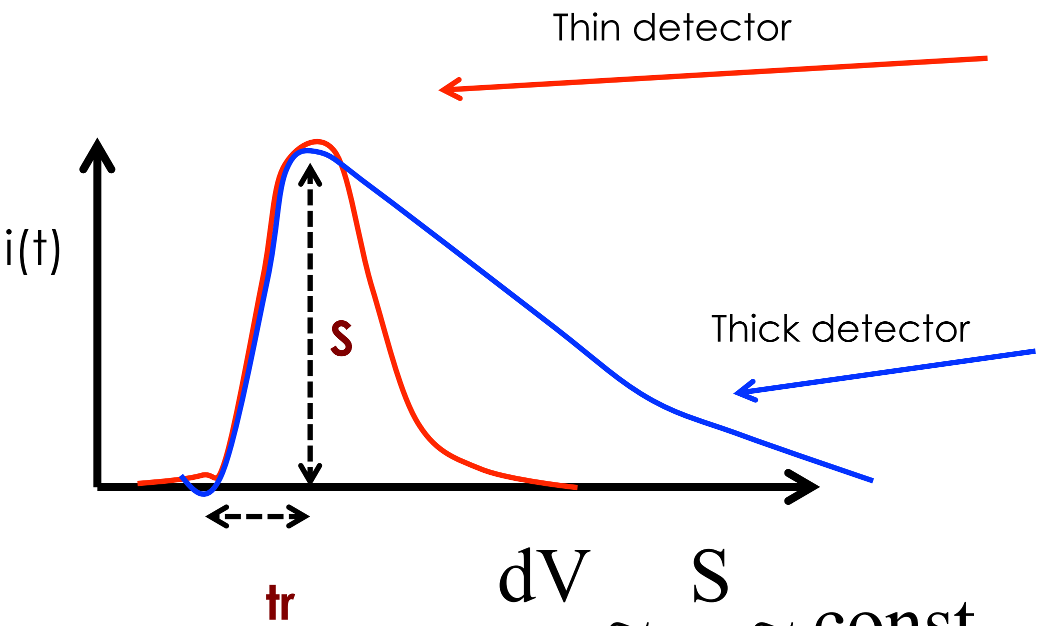
4-Dimensional High Precision Tracking

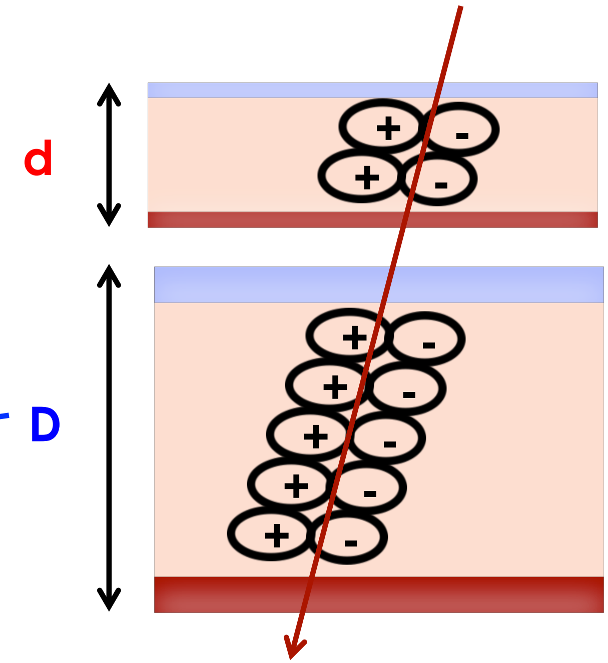
The R&D program



Thin vs Thick detectors

(Simplified model for pad detectors)





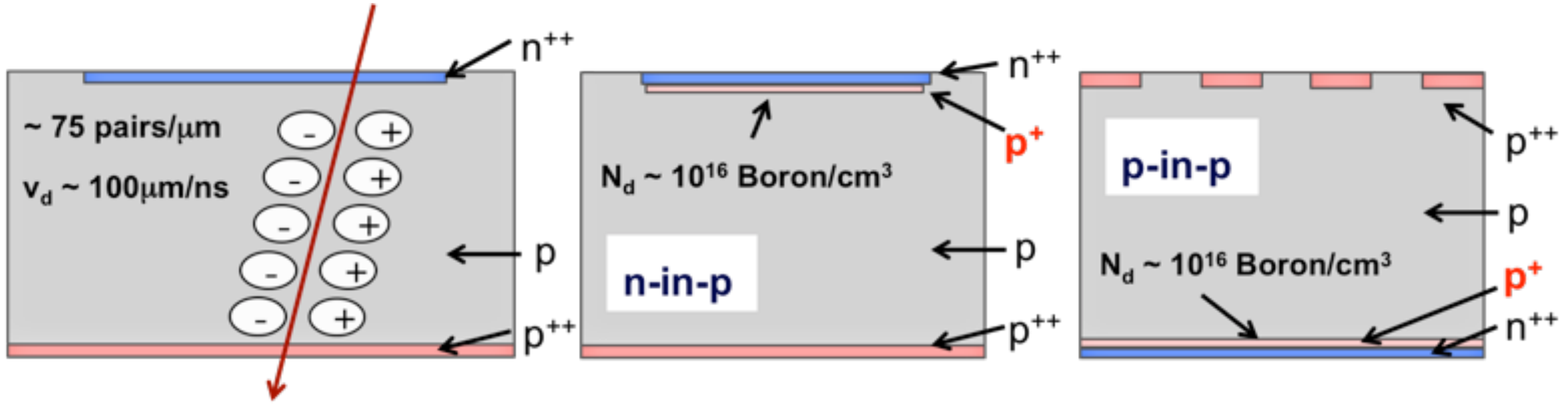
$$\frac{dV}{dt} \sim \frac{S}{t_r} \sim \text{const}$$

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?

LGAD - Ultra-Fast Silicon Detector

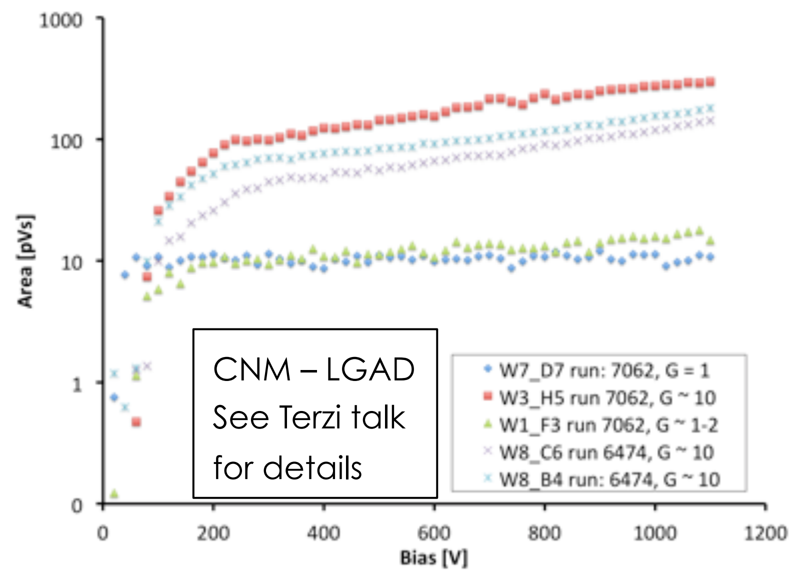


Traditional Silicon Detector **Ultra-Fast Silicon Detector**

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.

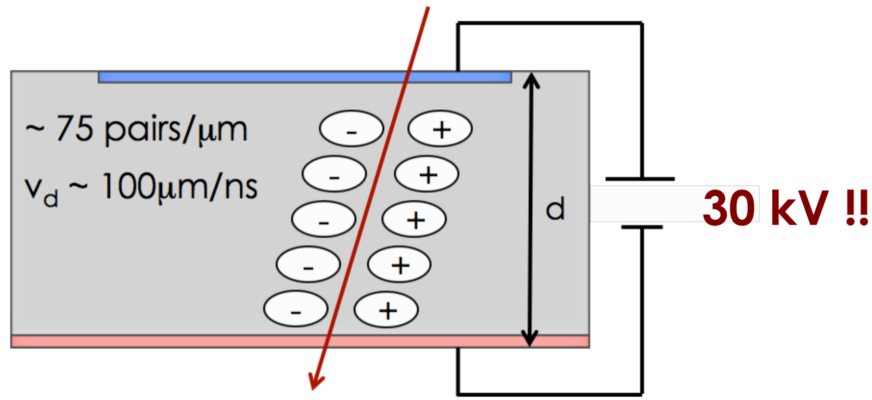
Easy to set the value of gain requested.



How can we achieve E ~ 300kV/cm?

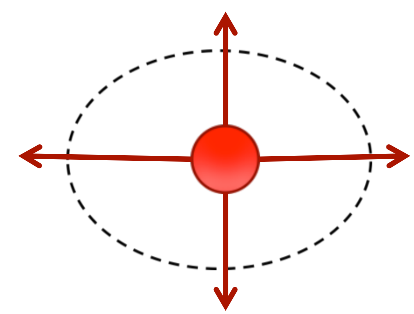
1) Use external bias: assuming a 300 micron silicon detector, we need $\mathbf{V_{bias}}$ **= 30 kV**

Not possible



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 !!

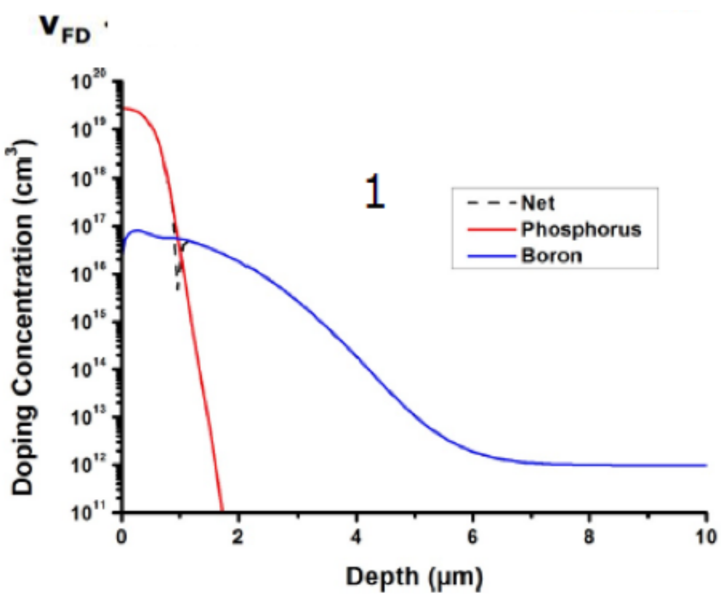
Low Gain Avalanche Detectors (LGADs)

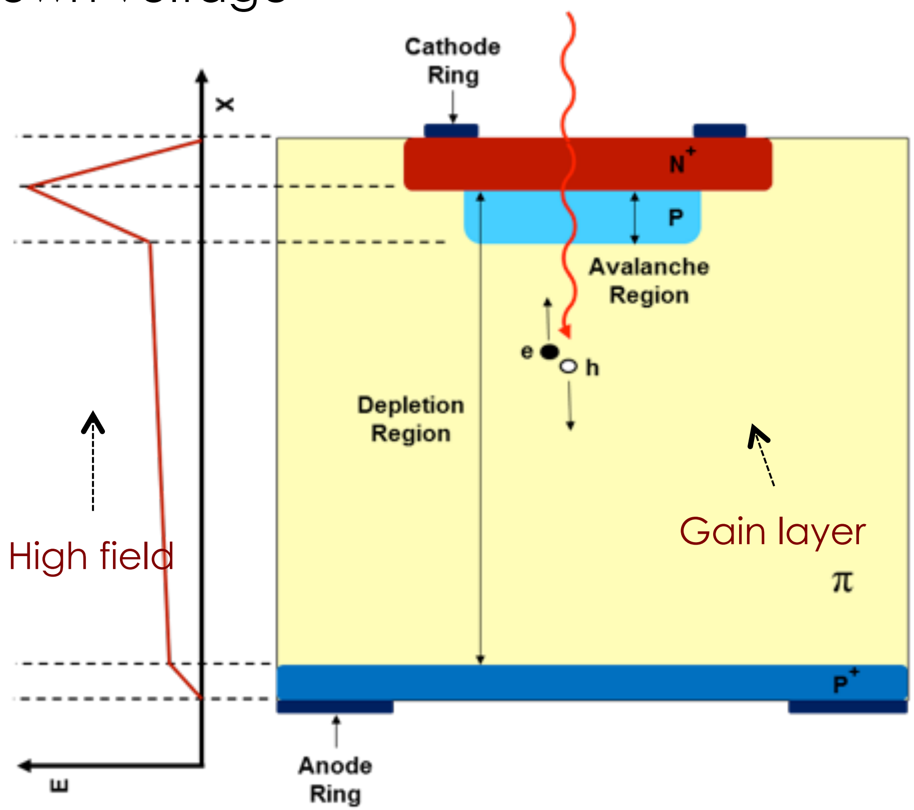
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage





Simulation

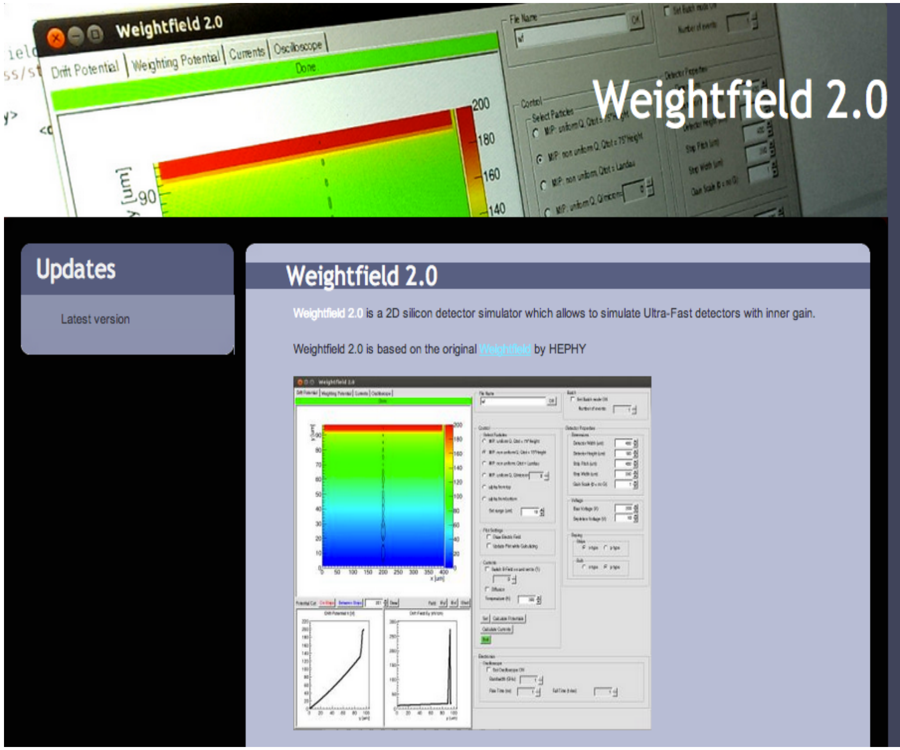
We developed a full sensor simulation to optimize the sensor design

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

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

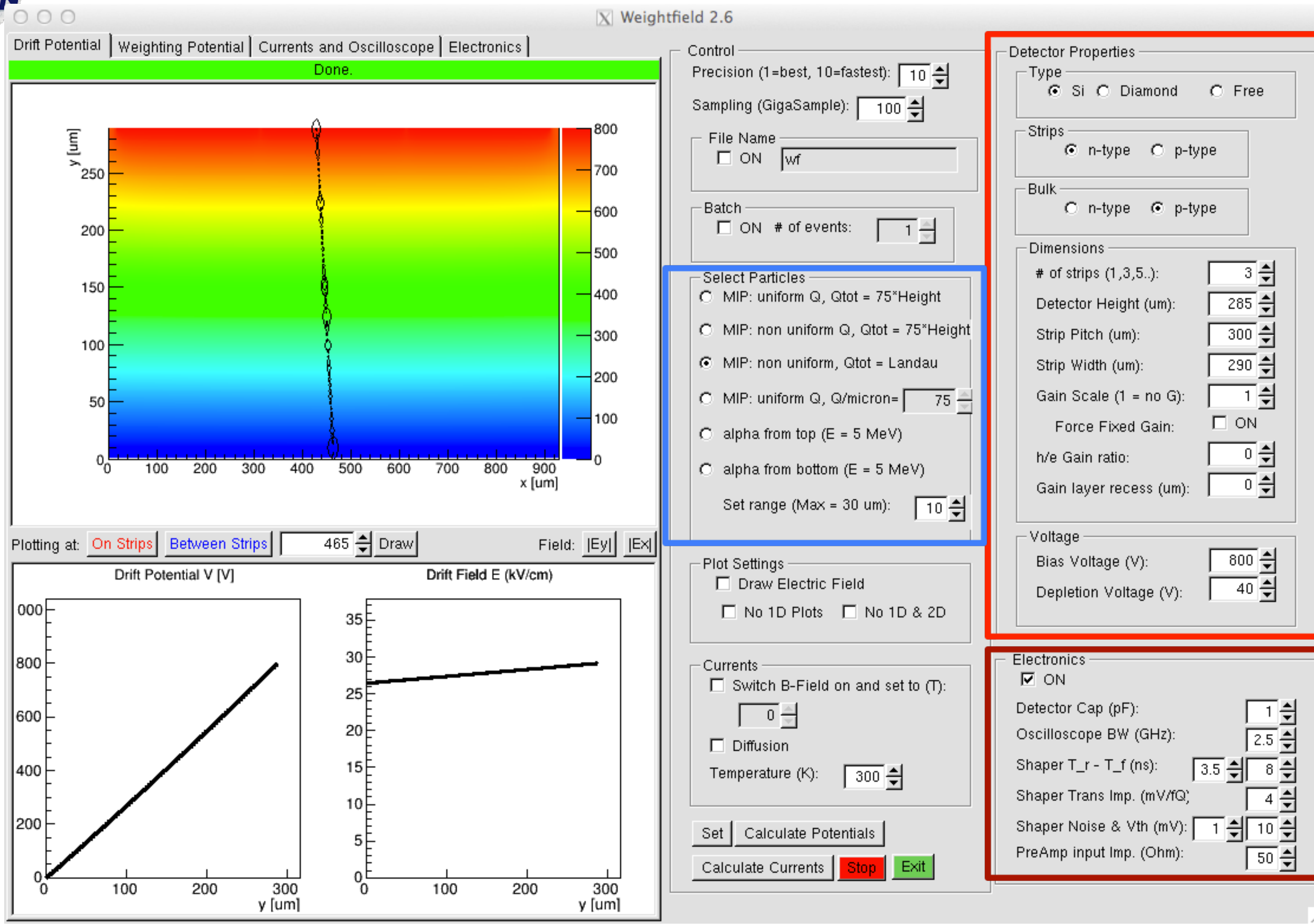
It includes:

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



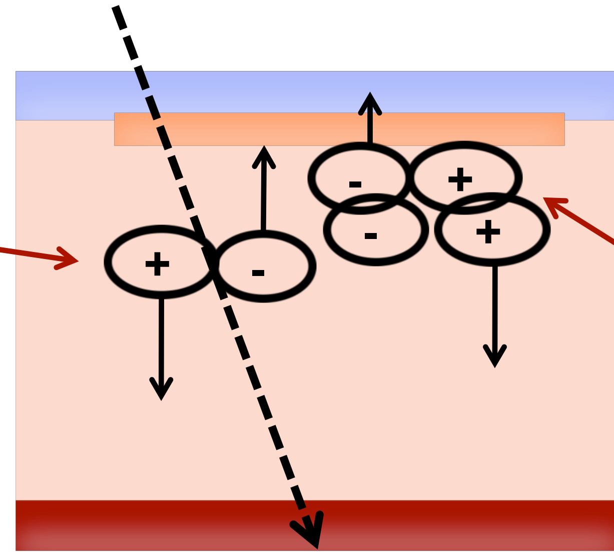
For each event, it produces a file with the current output that can be used as input in the simulation of the electronic response.

WeightField2: a program to simulate silicon detectors

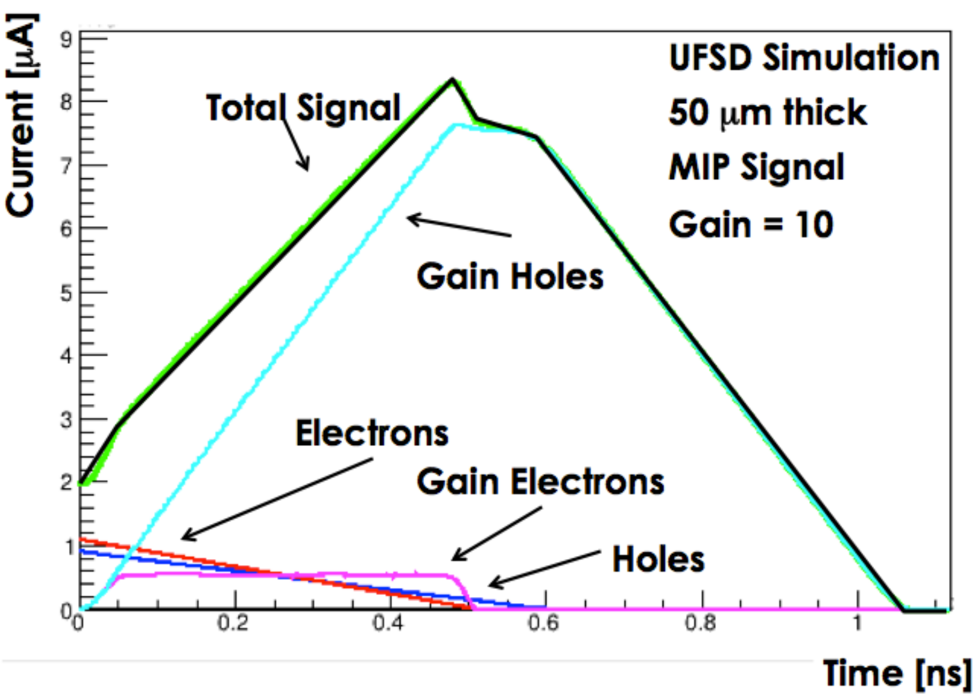


How gain shapes the signal

Initial electron, holes



Gain electron:
absorbed immediately
Gain holes:
long drift home

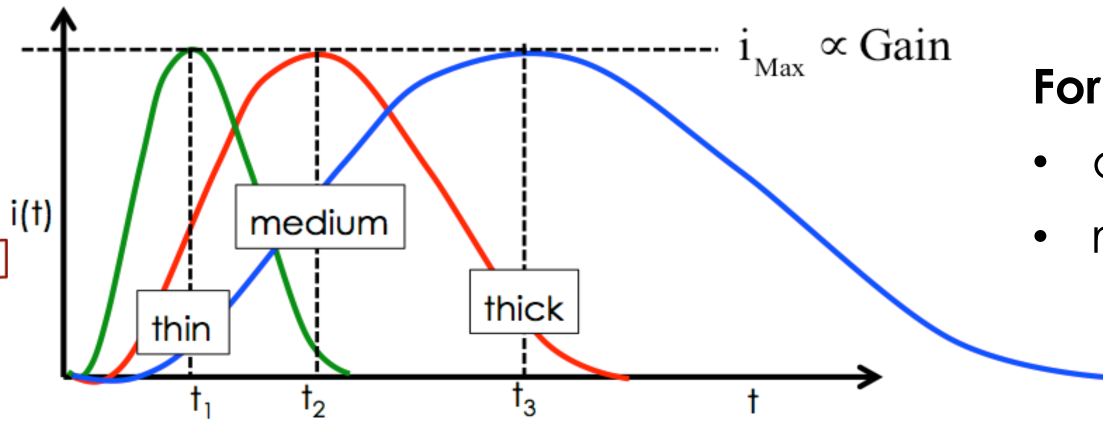


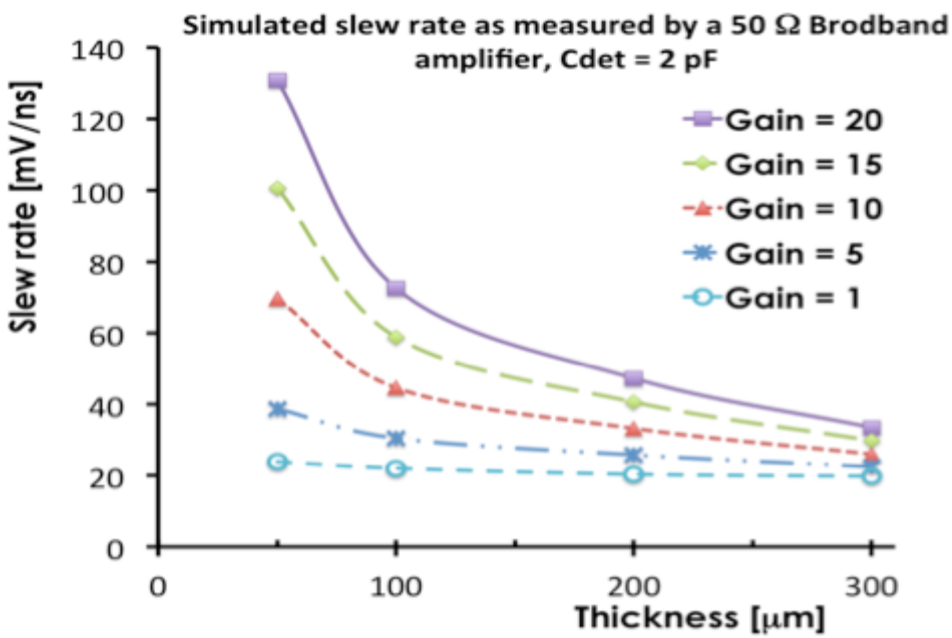
Electrons multiply and produce additional electrons and holes.

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

➔ **No holes multiplications**

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

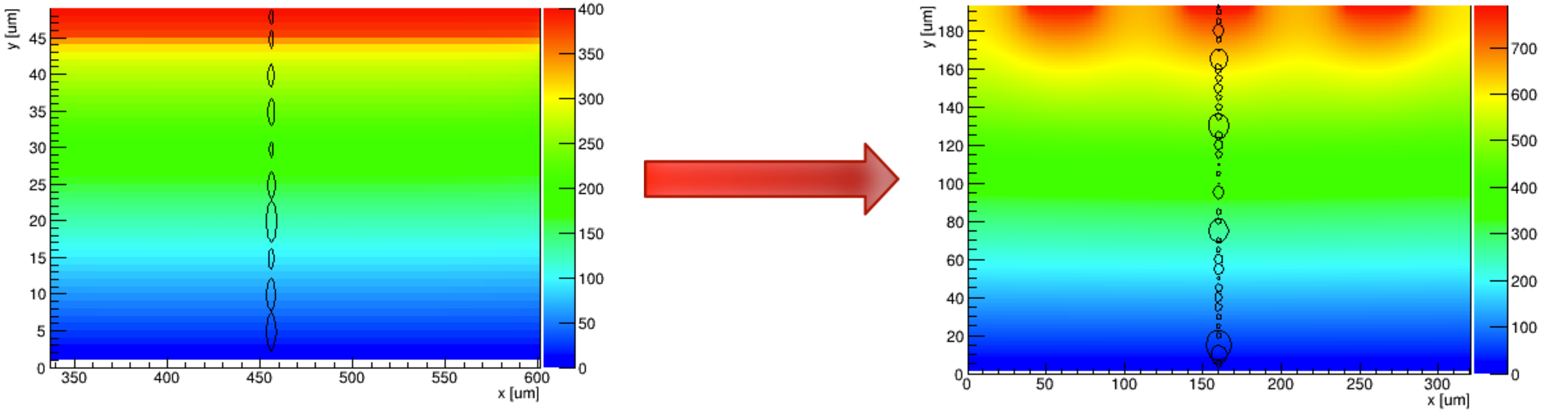
UFSD are LGAD detectors optimized to achieve the best possible time resolution

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)

Merging timing with position resolution

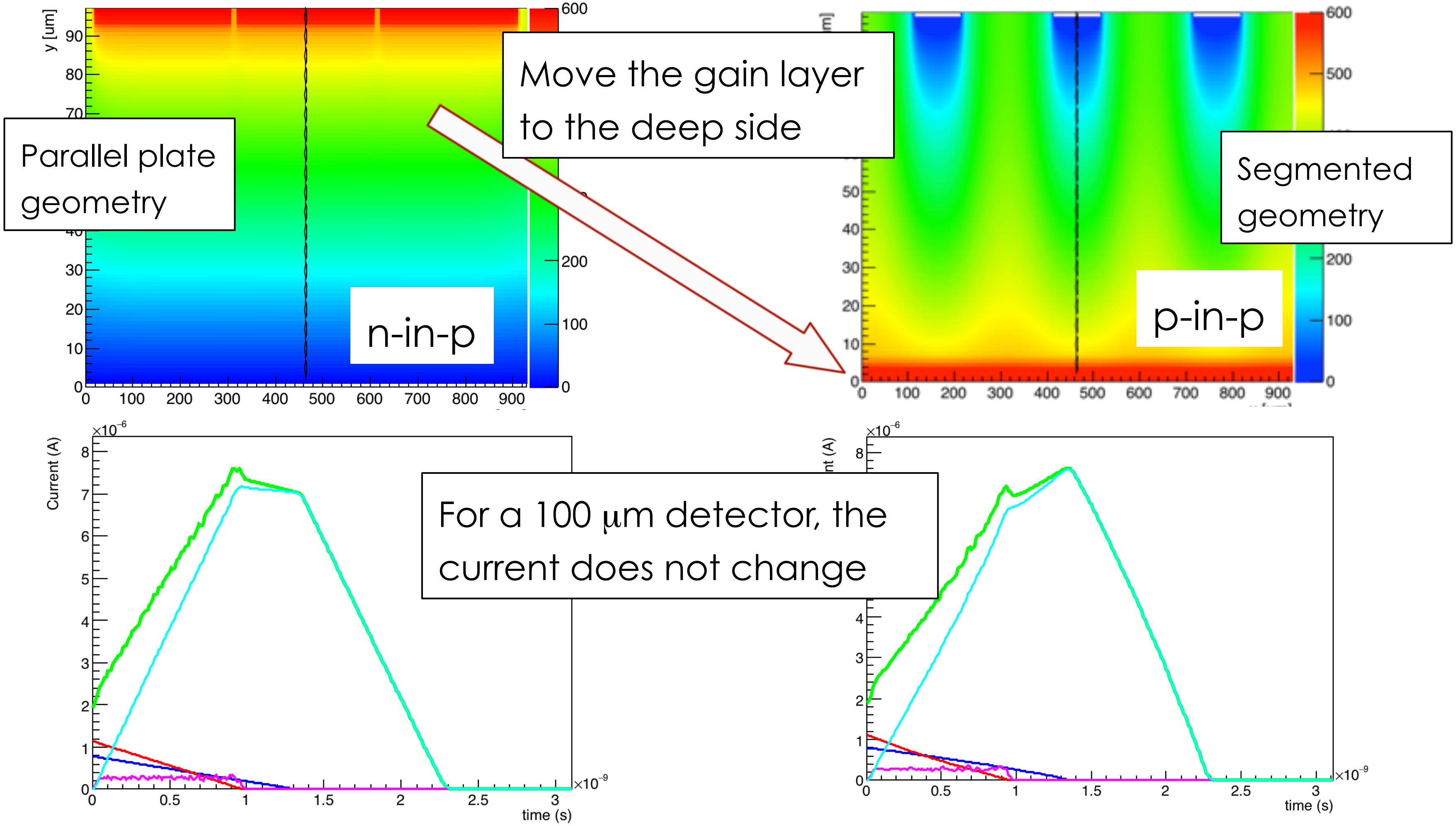
Electrode segmentation makes the E field very non uniform, and therefore ruins the timing properties of the sensor



We need to find a geometry that has very uniform E field and gain, while allowing electrode segmentation.

1) Segmentation: buried junction

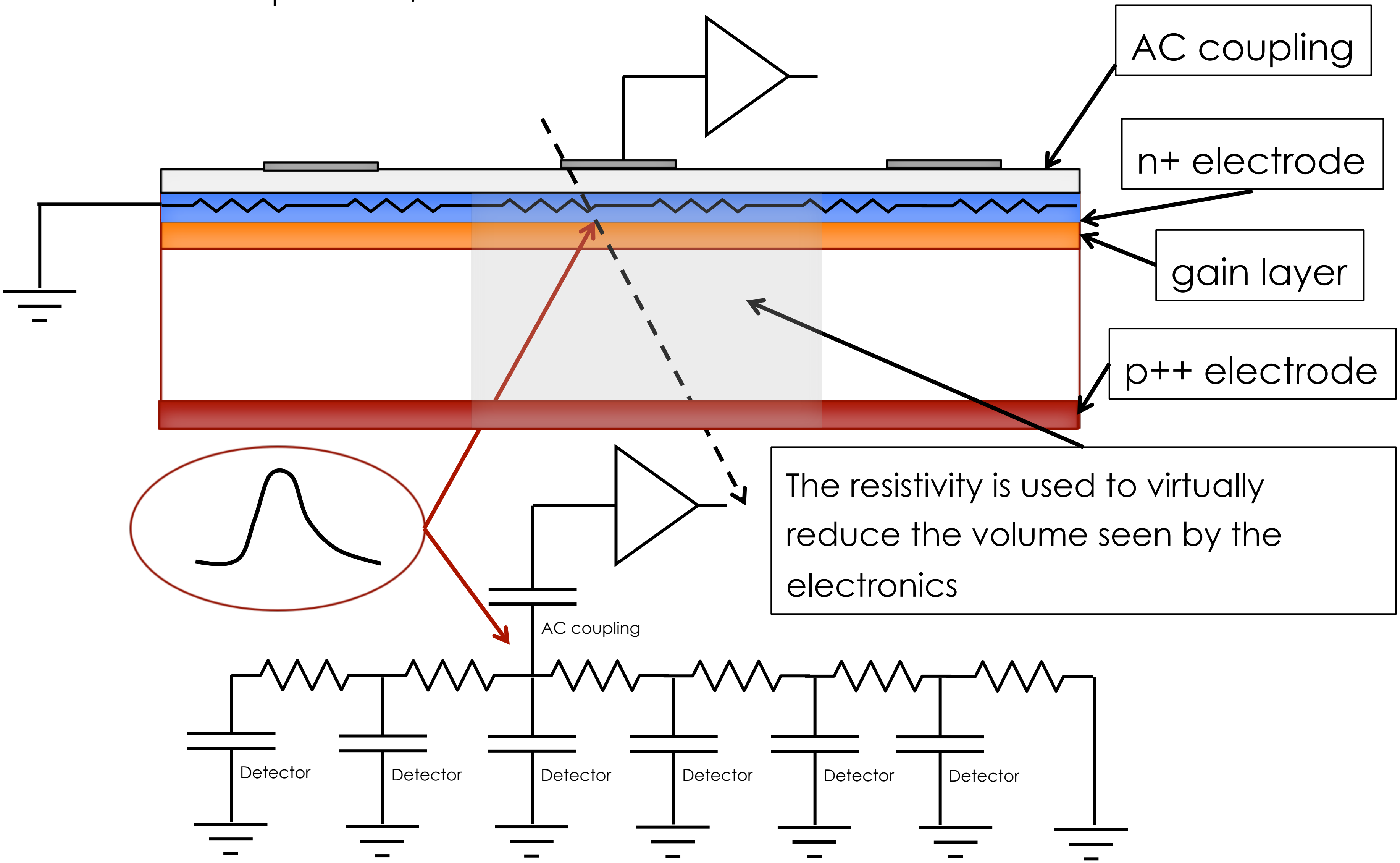
Separate the multiplication side from the segmentation side



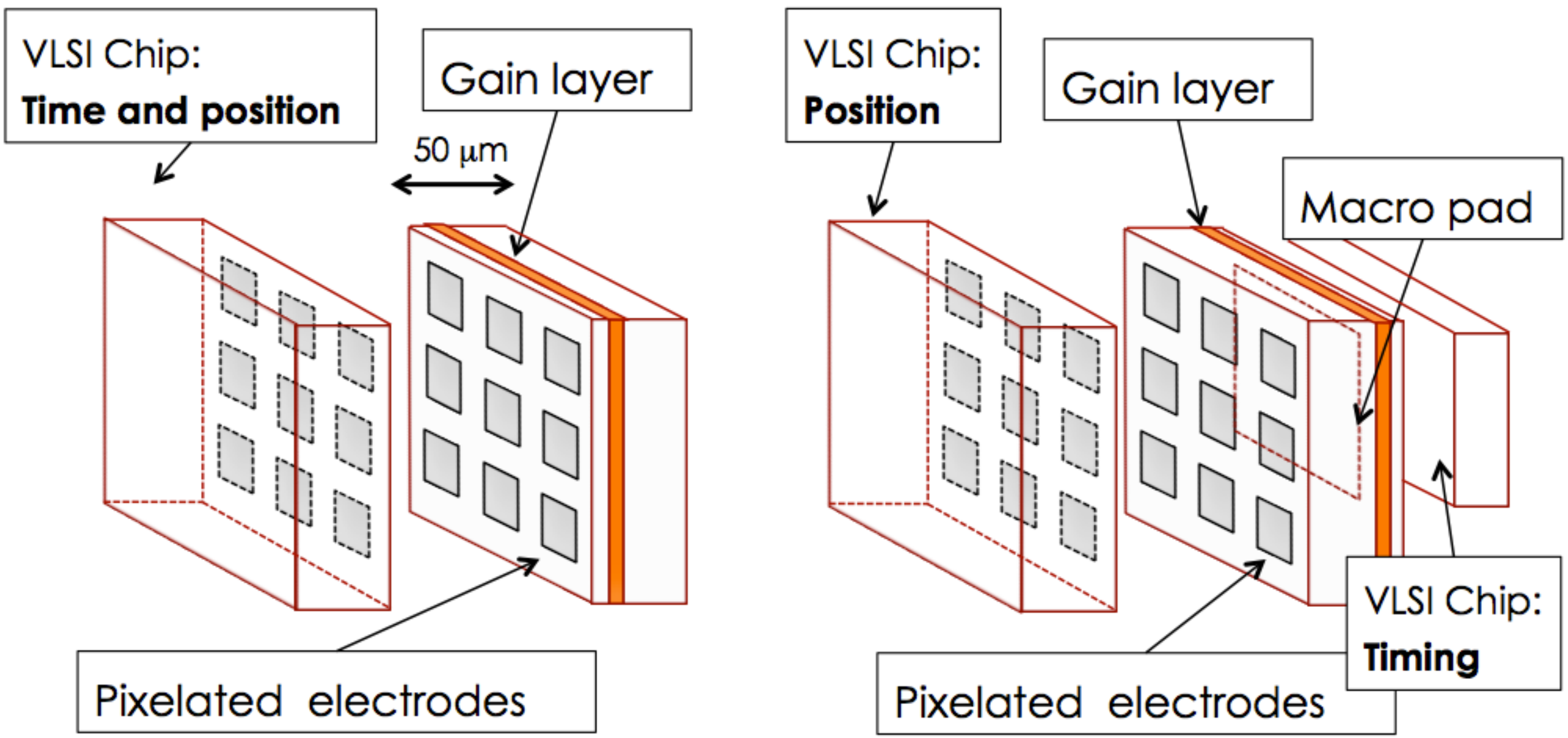
Moving the junction on the deep side allows having a very uniform multiplication, regardless of the electrode segmentation

2) Segmentation: AC coupling

Standard n-in-p LGAD, with AC read-out



3) Segmentation: splitting gain and position measurements

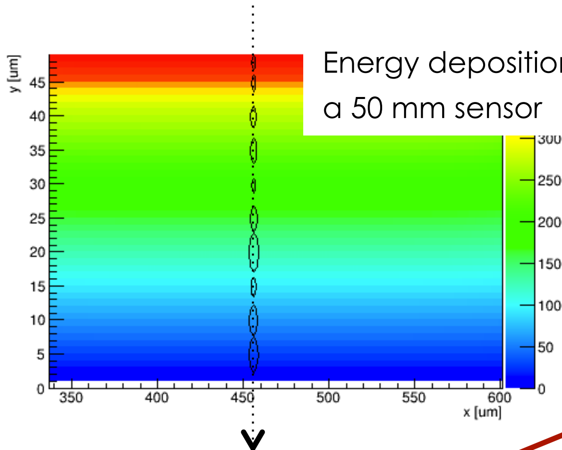


The real solution: monolithic

> 10 years

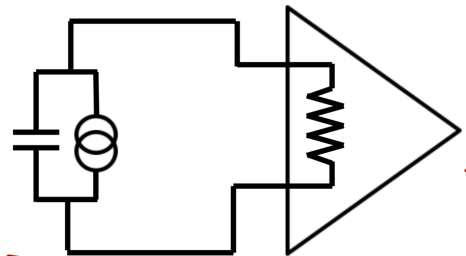
This is the correct approach, however it will take time.

What is the best pre-amp choice?

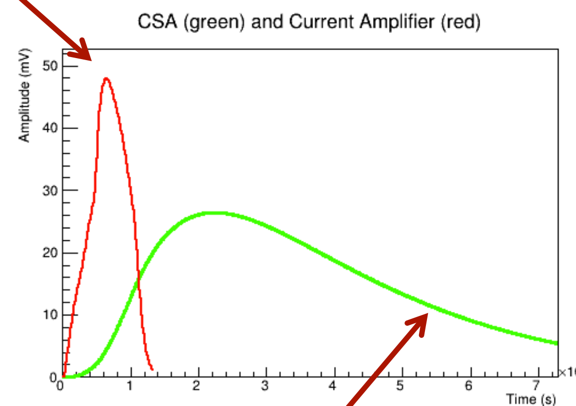


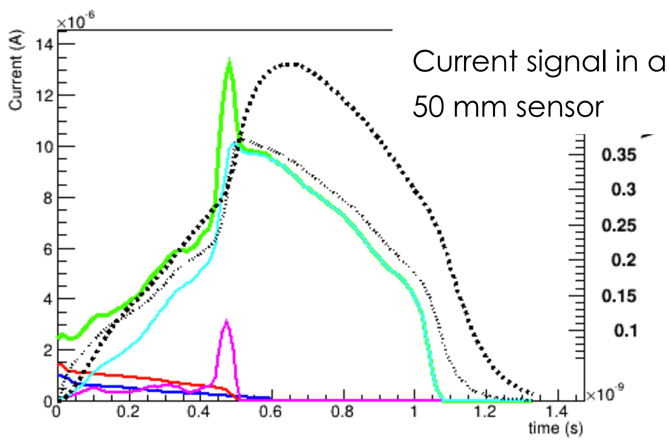
Energy deposition in a 50 mm sensor

Current Amplifier



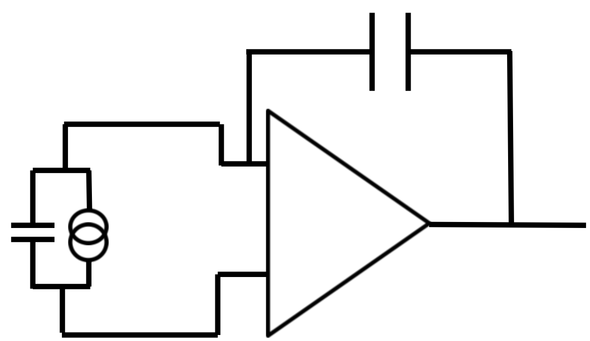
- Fast slew rate
- Higher noise
- Sensitive to Landau bumps
- More power





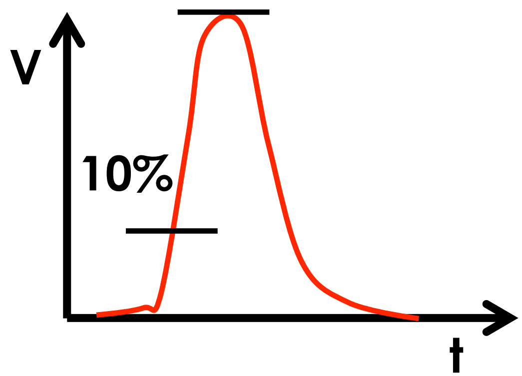
Current signal in a 50 mm sensor

Integrating Amplifier



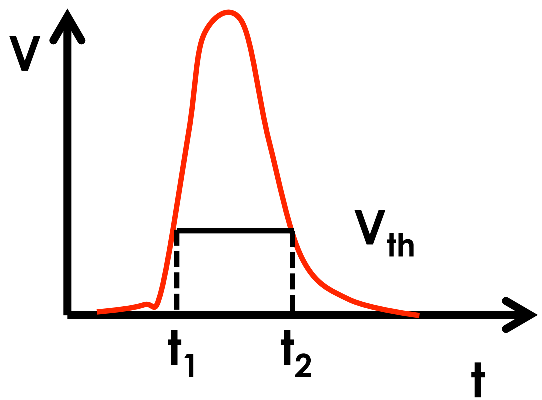
- Slower slew rate
- Lower noise
- Signal smoothing
- Less power

What is the best "time measuring" circuit?



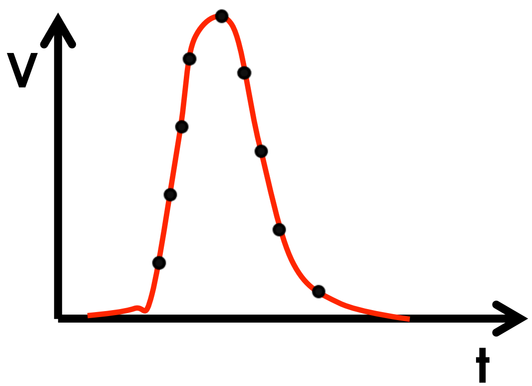
Constant Fraction Discriminator

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



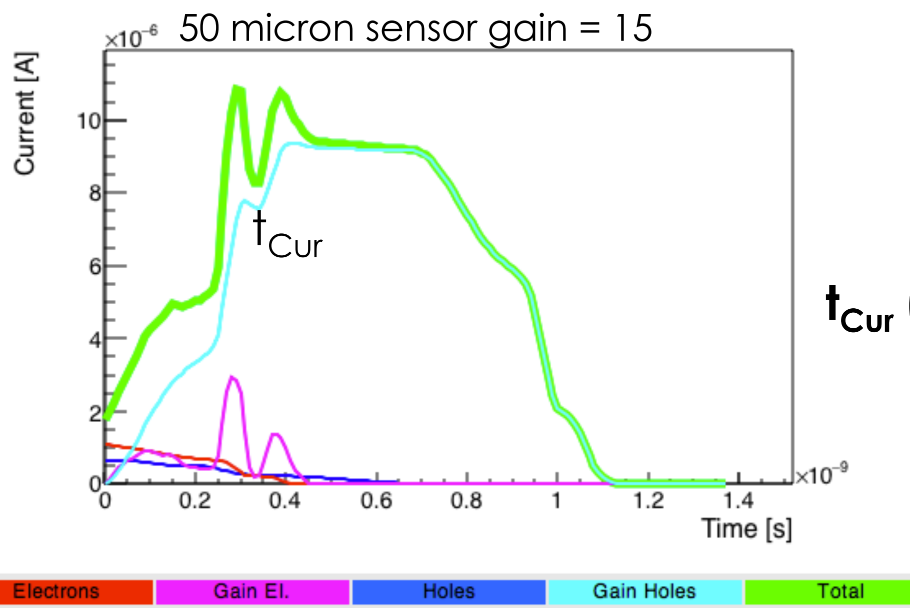
Multiple sampling

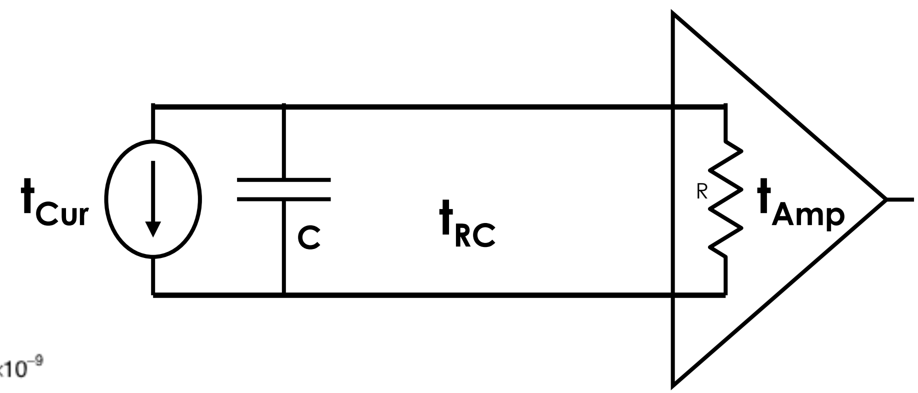
Most accurate method, needs a lot of computing power.

Possibly too complicated for large systems

The players: signal, noise and slope

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



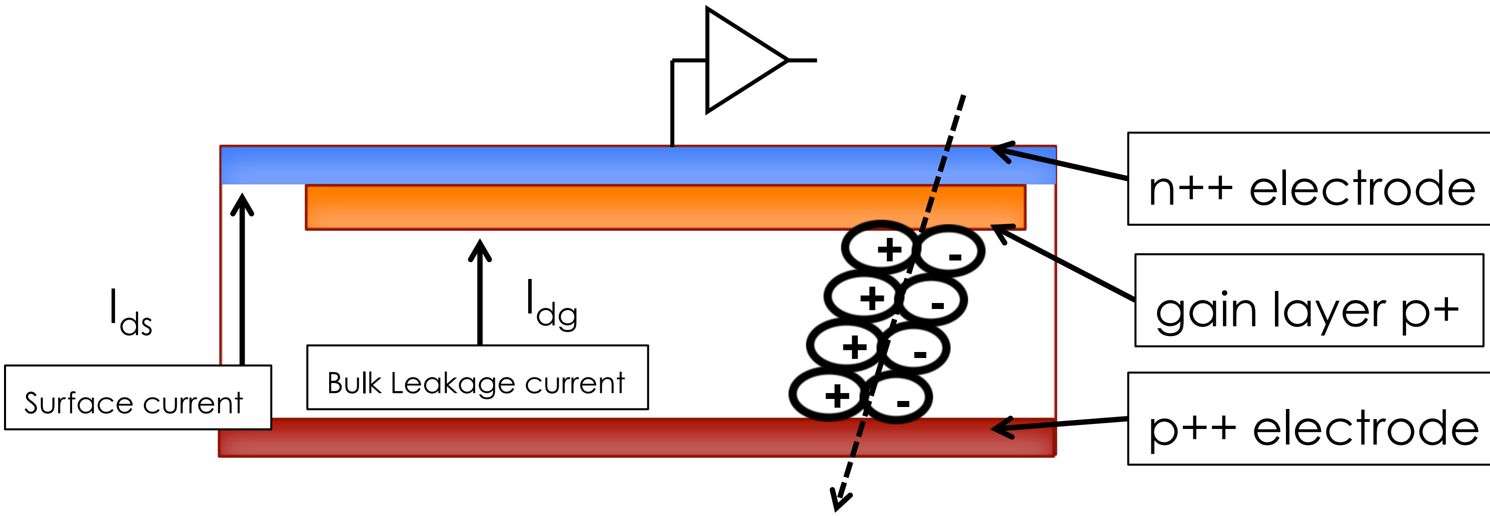


The current rise time (t_{Cur}) | The RC circuit (t_{RC}) | Amplifier rise time (t_{Amp})

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})

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

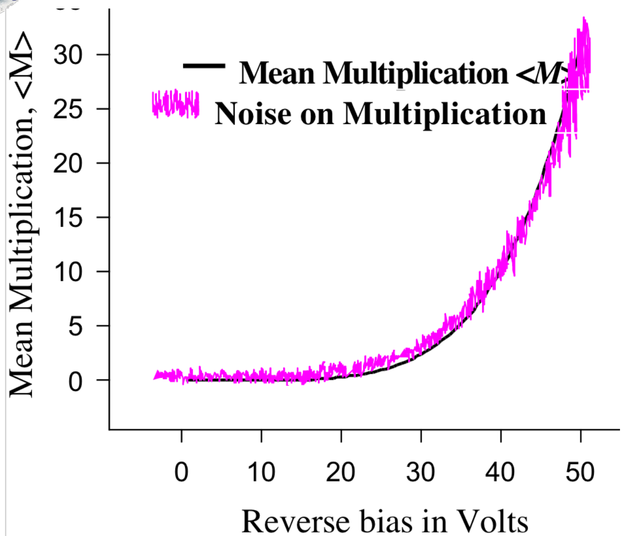
$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

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

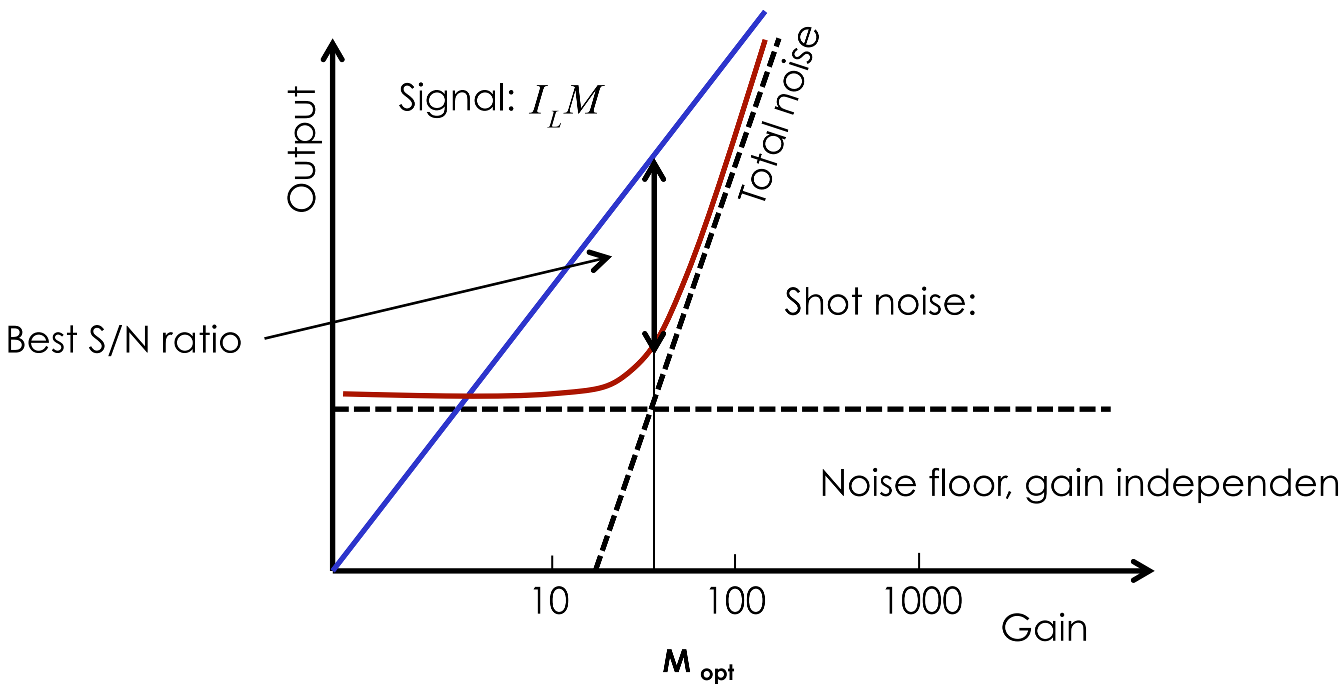
k = e/h ionization rate
x = excess noise index
M = gain

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

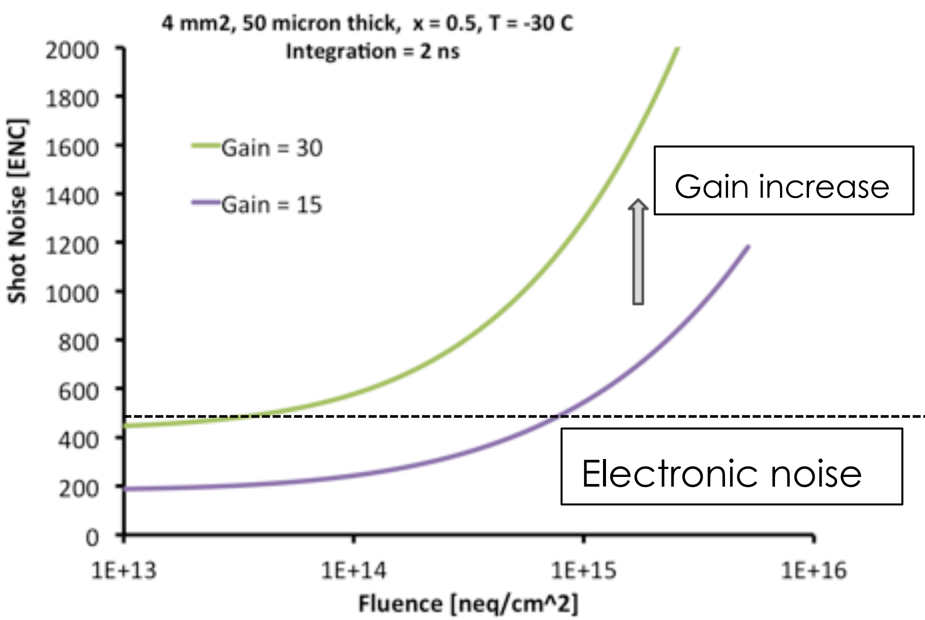
Let's assume a 4 mm² pad, 50 micron thick, and a electronic noise of 500 ENC

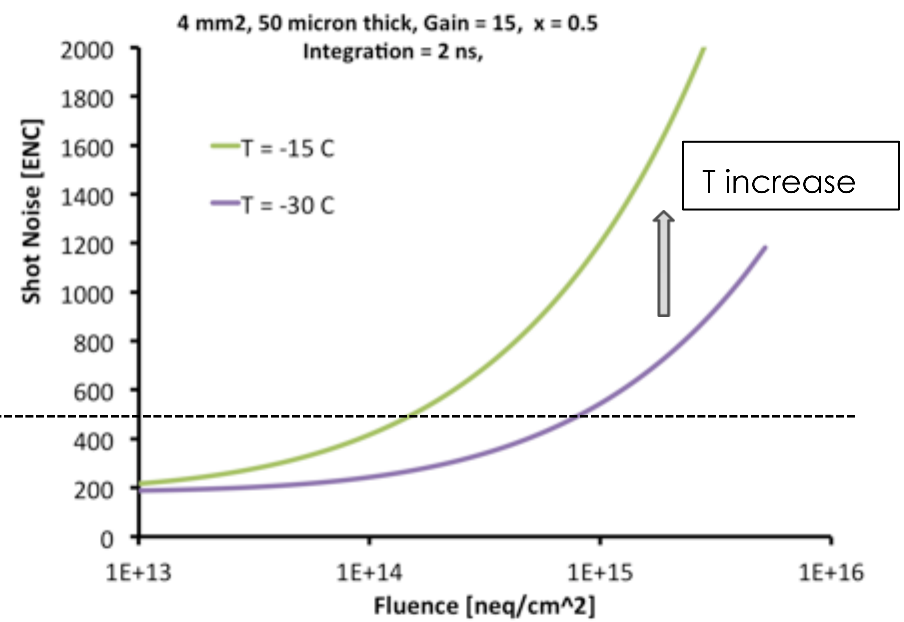
What is the effect of shot noise as a function of radiation?

Steep dependence on gain

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

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





To minimize Shot noise:

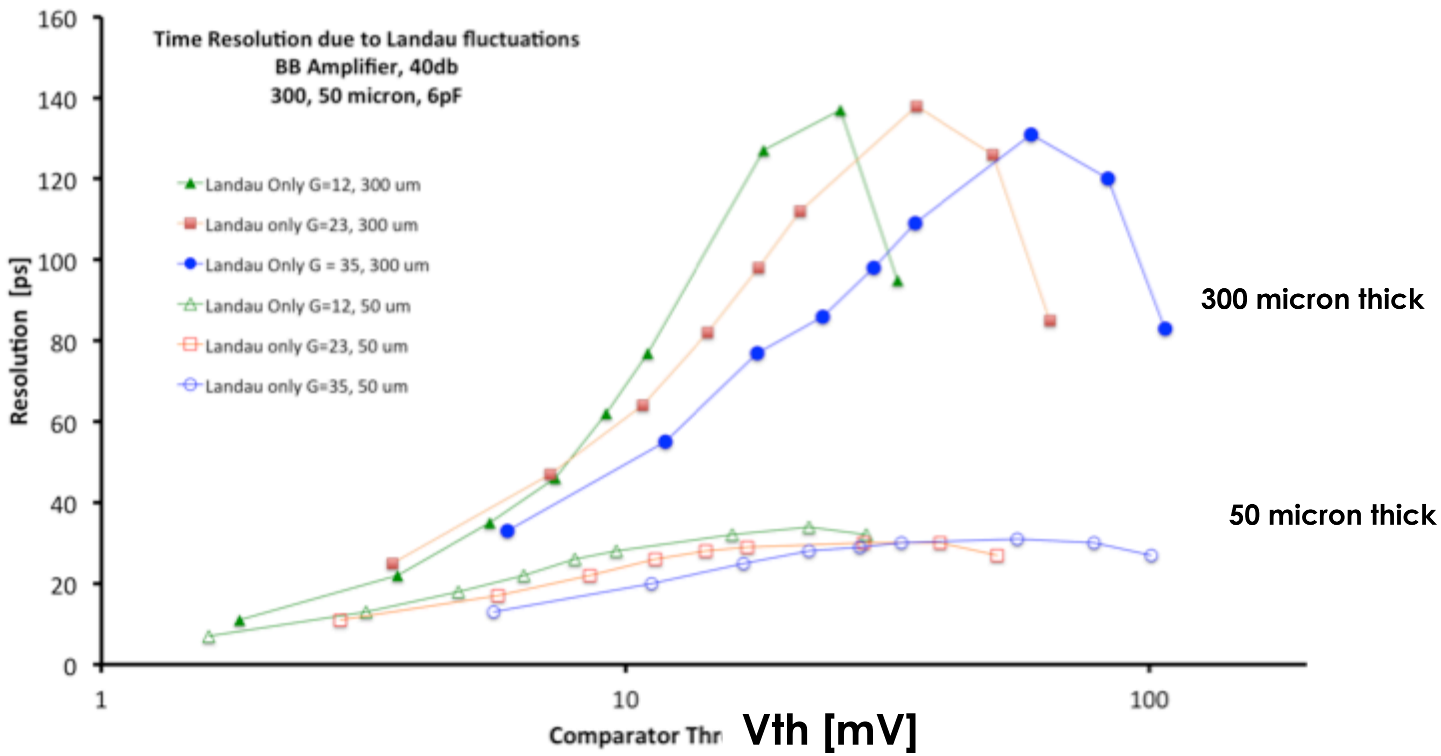
➔ Low gain!! Keep the gain below ~ 20

➔ 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

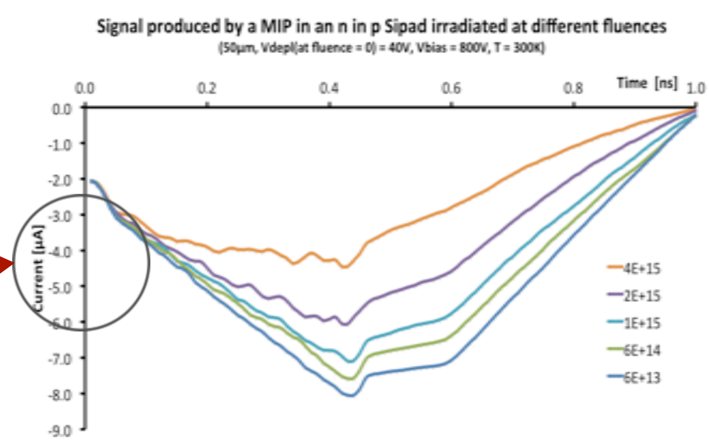
Irradiation - I

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:

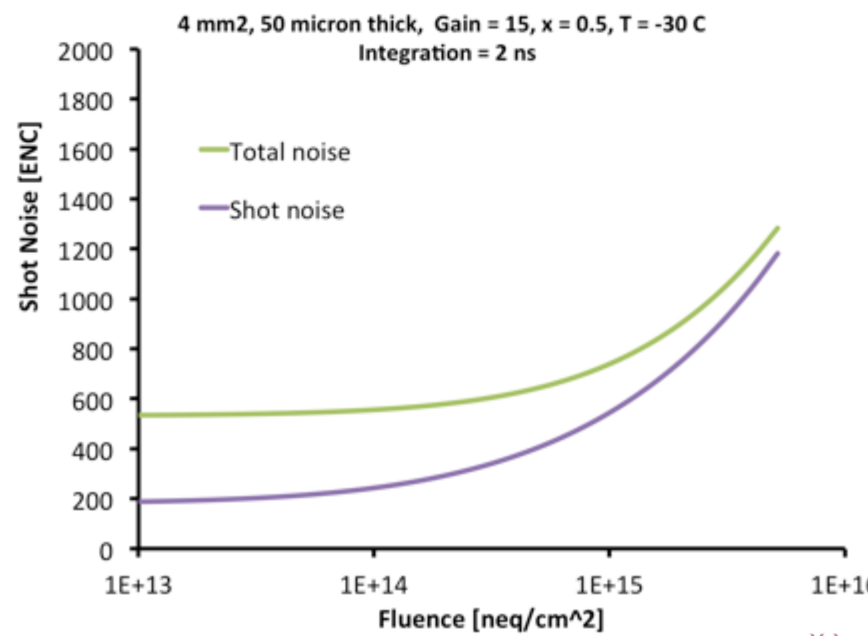
- Use Vbias to compensate for the loss on gain
- Use thin sensors: weaker dynamic effects
- Long term: Gallium doping

3) Increased leakage current

Assuming Gain ~ 15, T = -30C,

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

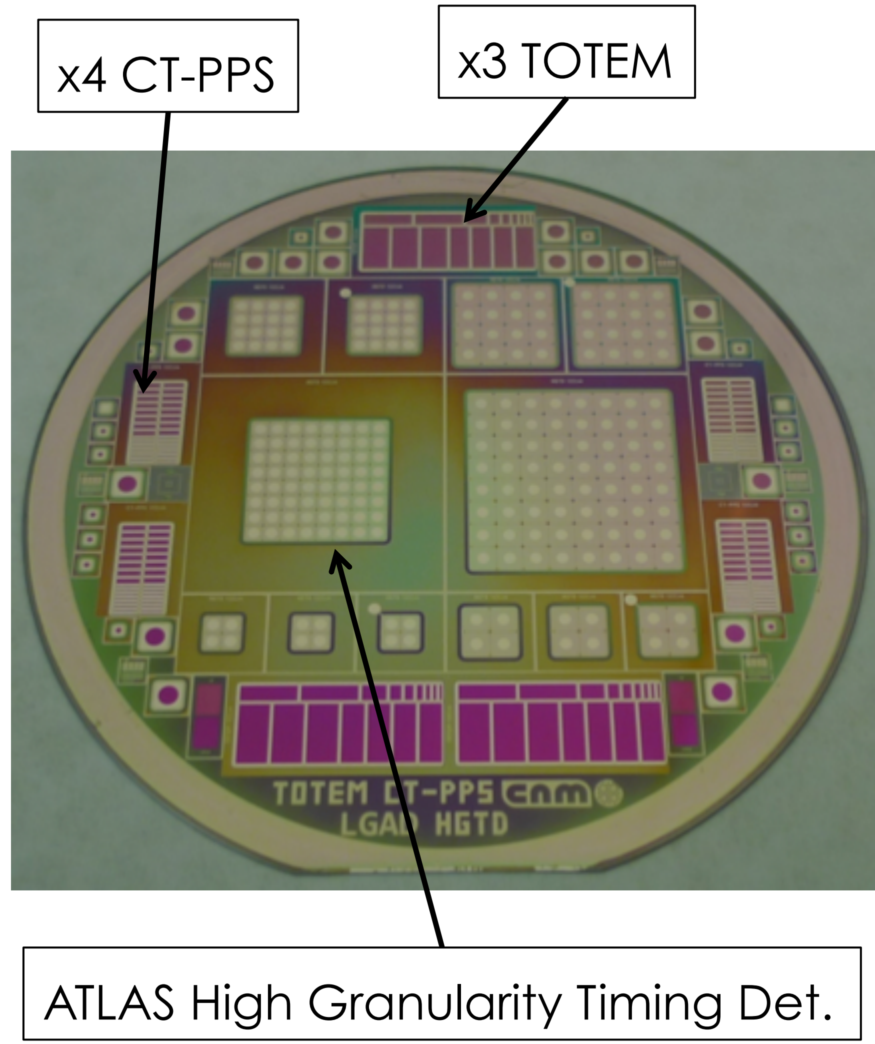
- Keep the sensor cold
- Low gain
- Small sensor



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

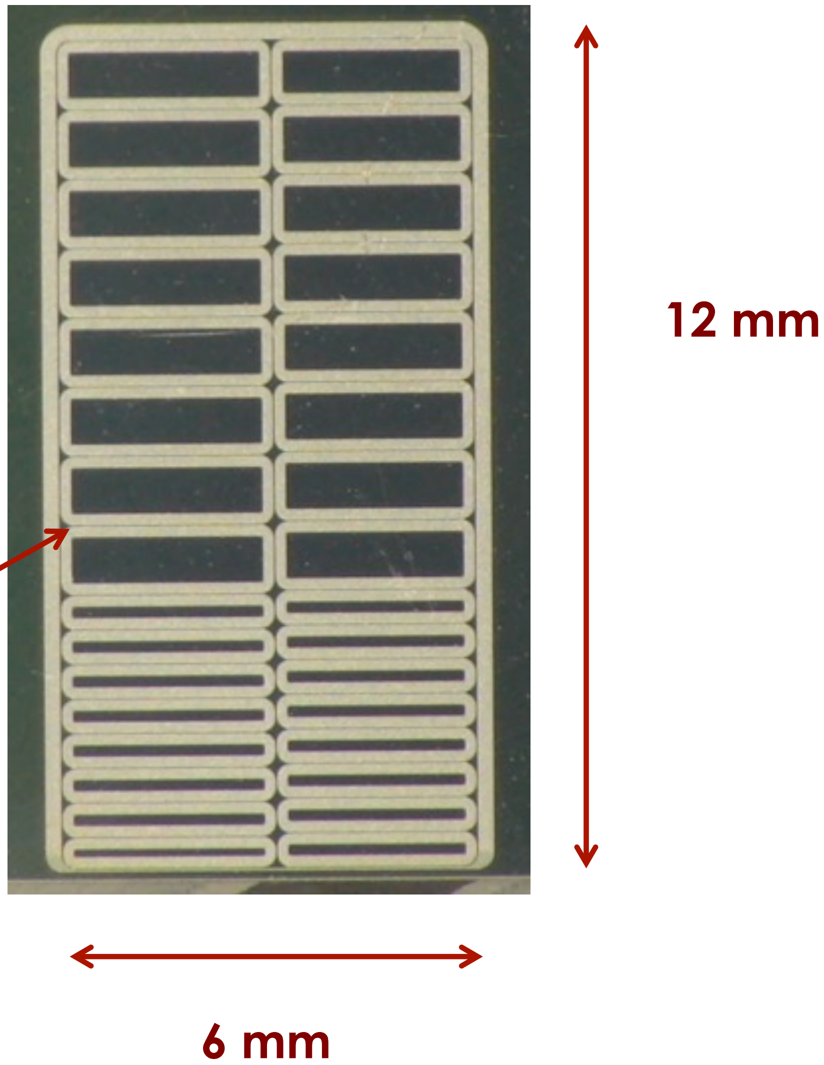
Strips:

3 mm x 0.5 mm

3 mmx x 1 mm

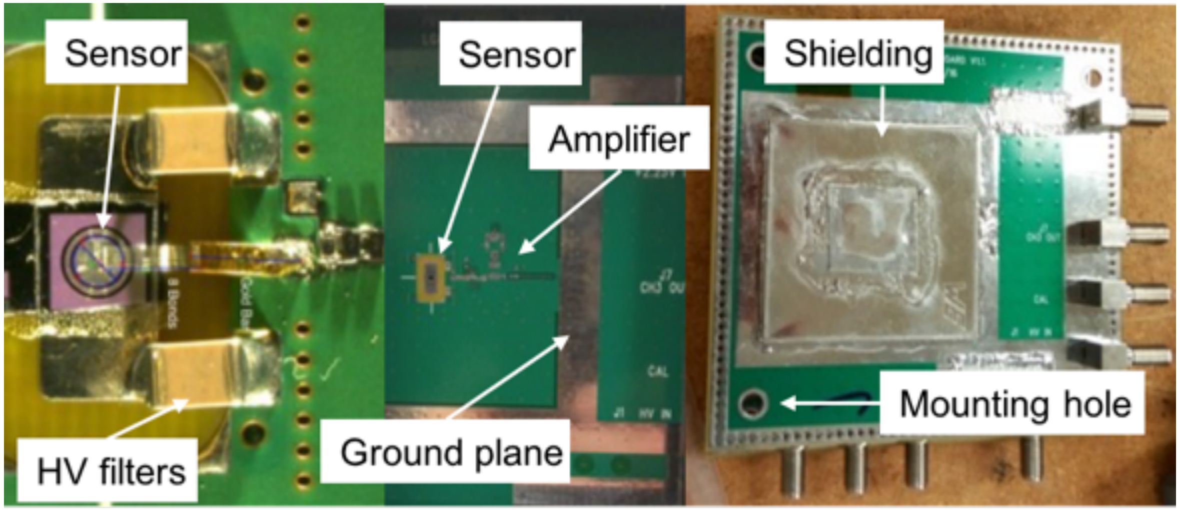
Distance between pads: 50 micron

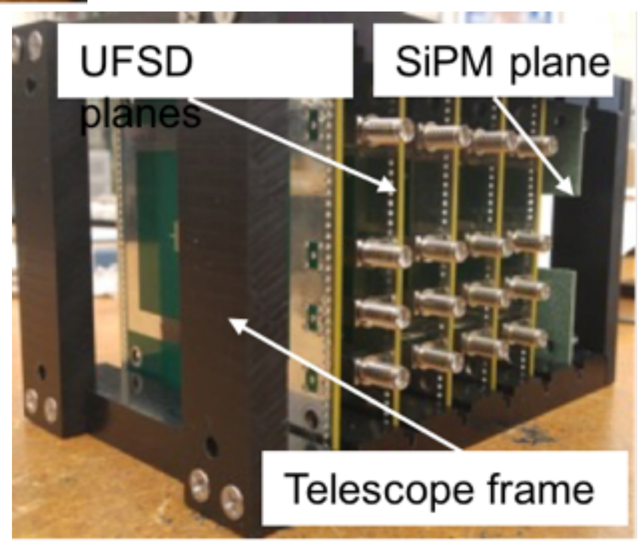
➔ Able to produce segmented UFSD



Latest results on UFSD time resolution

Fully custom made UFSD read-out (UCSC)



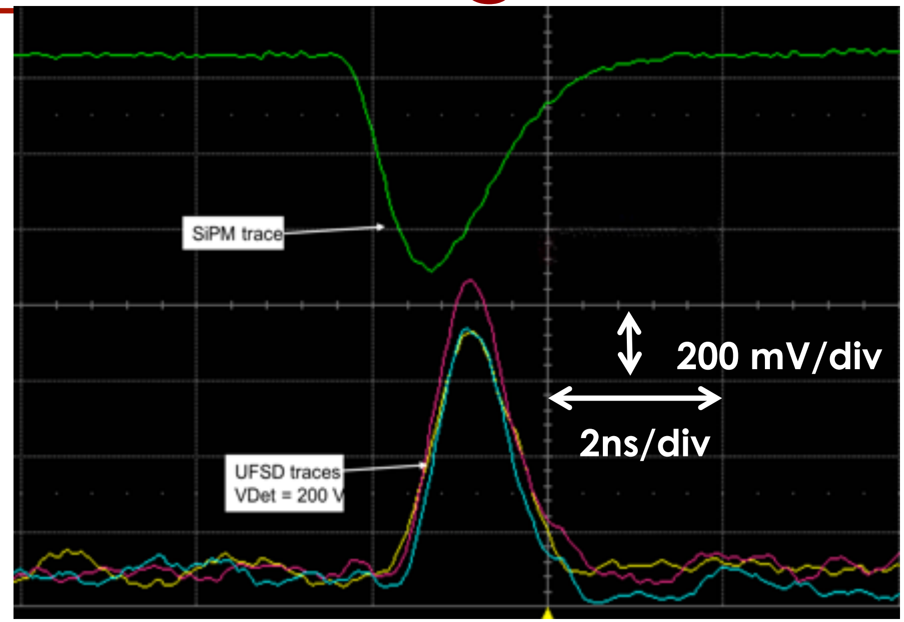


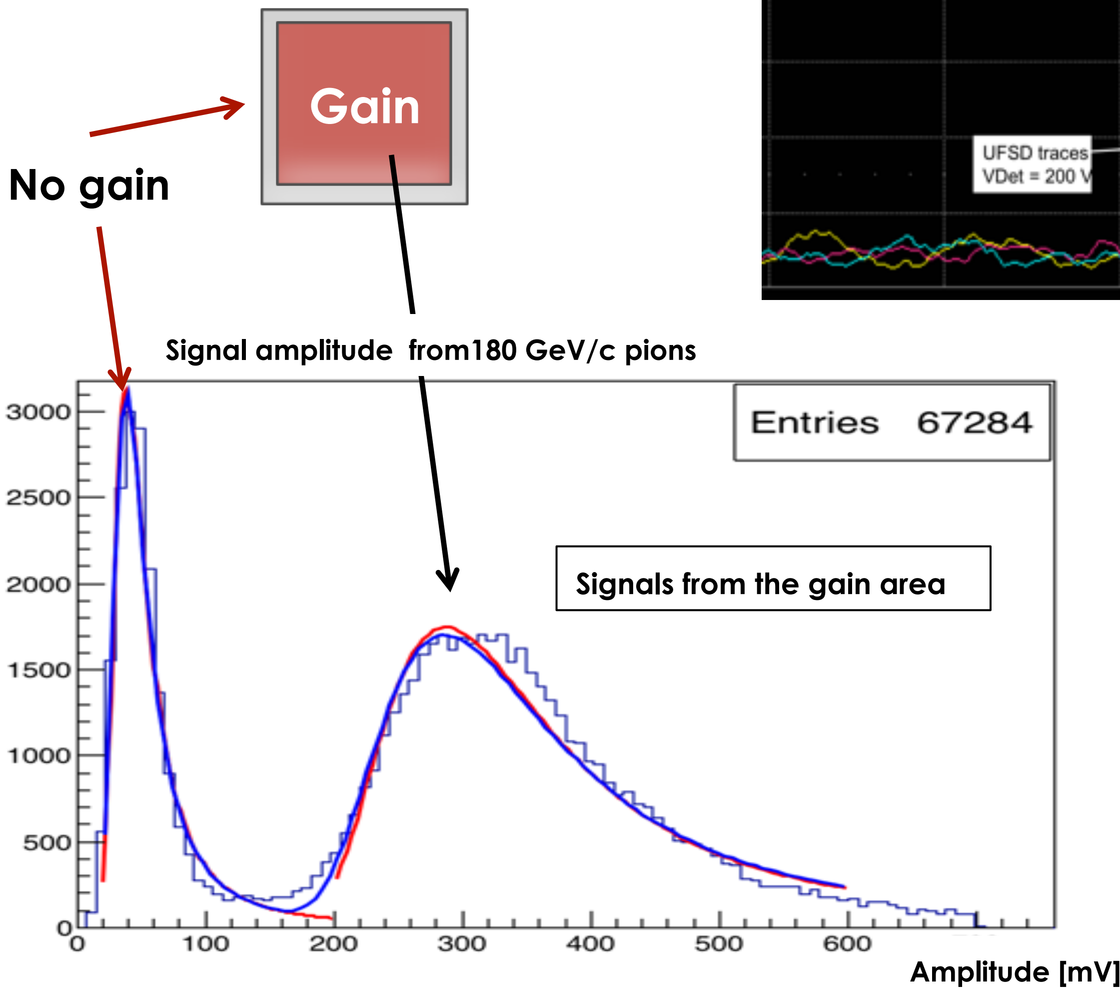
CNM production of thin sensors (50 micron)

An example of the signals

Fast, low noise signals, ideal for timing

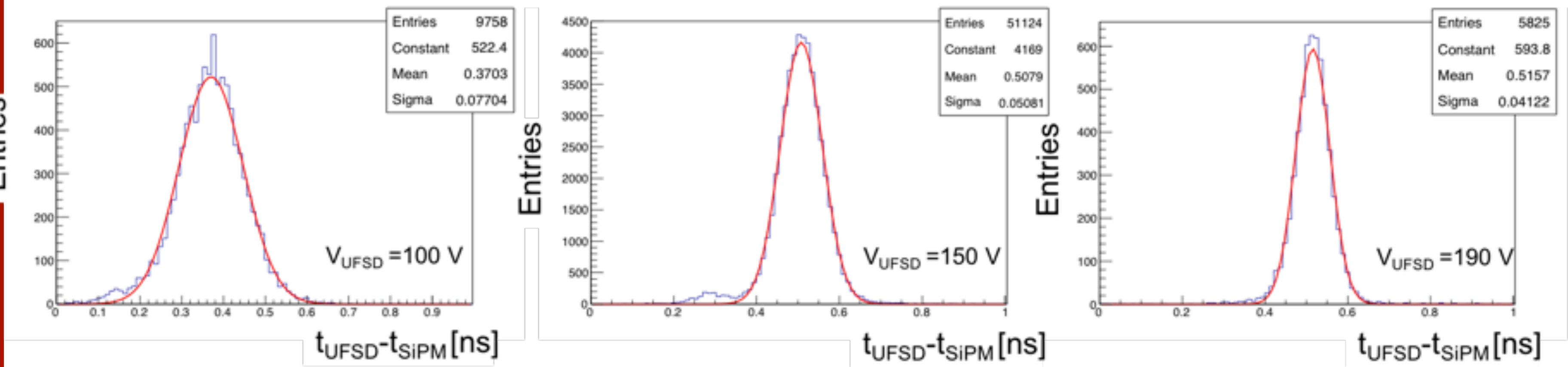
The sensor has a “no gain” frame, ideal for gain calibration with MIPS





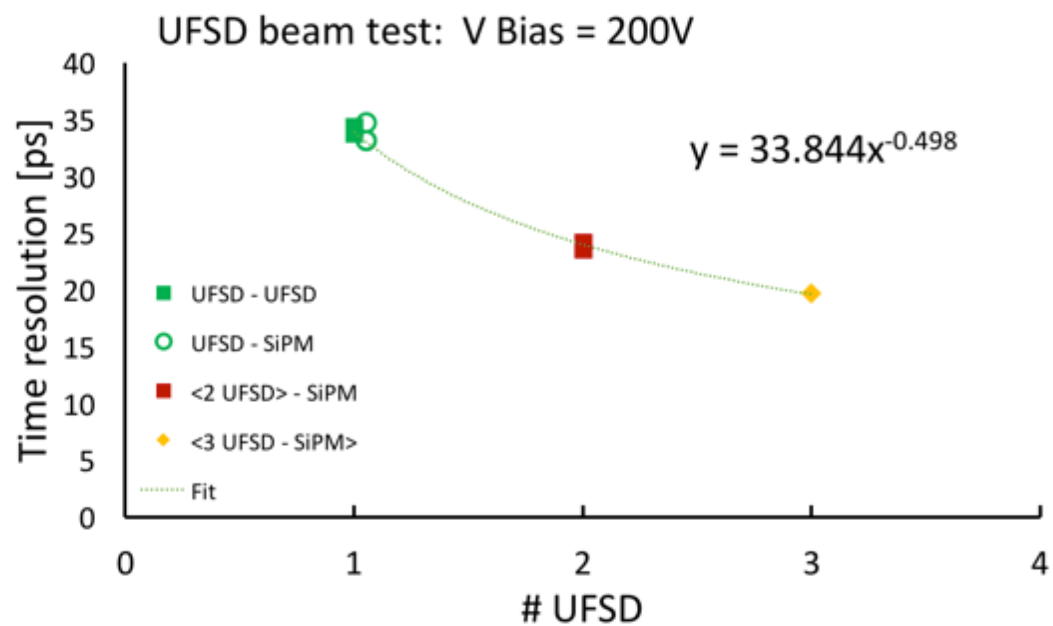
Time resolution as difference UCSC-SiPM

We used a very accurate (~ 15 ps) SiPM as trigger



Multiple UFSD tracking system

Timing Resolution [ps]		
Vbias [V]	**200V**	**240V**
N=1 :	34.6	25.6
N=2 :	23.9	18.0
N=3 :	19.7	14.8



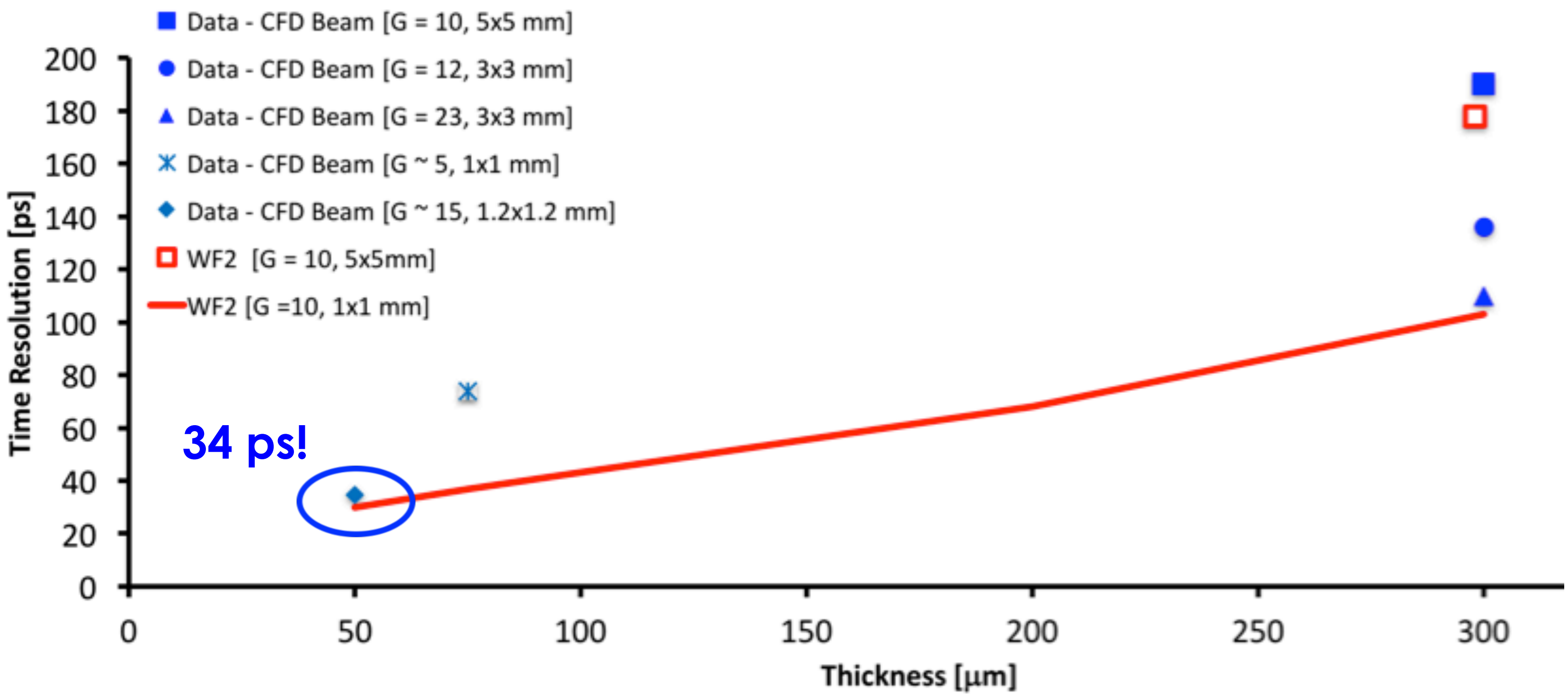
Submitted to NIMA

http://arxiv.org/abs/1608.08681v1

Summary of UFSD beam test results

2014 Frascati: UFSD 7x7mm² 300μm (C = 12pF, Gain =10)
2014 CERN: UFSD 7x7mm² 300 μm (C = 12pF, Gain =10)
2015 CERN: UFSD 3x3mm² 300 μm (C = 4pF, Gain =10 - 20)
2015 CERN: UFSD 1x1mm² 75 μm (C = 2pF, Gain =5)
2016 CERN: UFSD 1.2x1.2mm² 50 μm (C = 3pF, Gain =15)

CNM - LGAD



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

Next steps:

- Radiation hard studies
- Electronics for larger sensors (20-30 pF)

Acknowledgments

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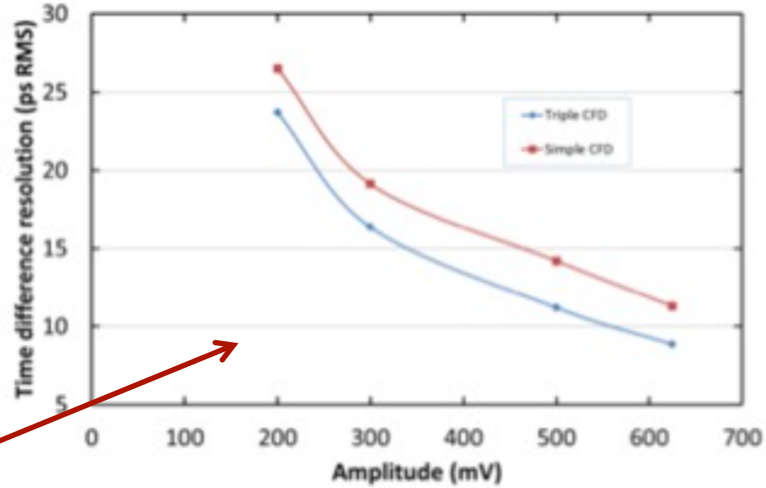
- Horizon 2020 Grant URC 669529
- Ministero degli Affari Esteri, Italy, MAE
- U.S. Department of Energy grant number DE-SC0010107
- The RD50 collaboration

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:

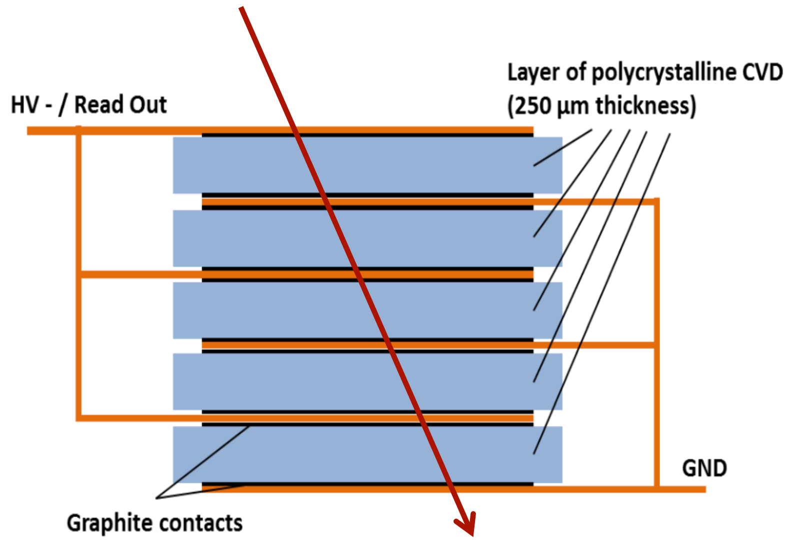
- Radiation hardness above 10^{14} n_{eq}/cm^2
- Fine Segmentation
- How to deal with shot noise (proportional to gain)

The Diamond approach

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

1) Multilayer stack

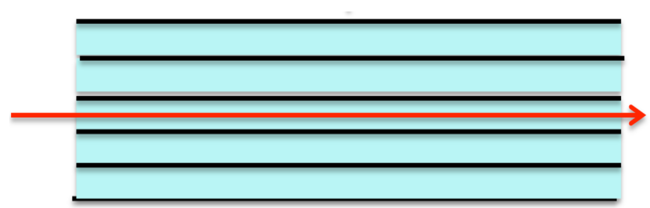
The signal is increased by the sum of many layers while keeping the rise time short



Best resolution:
~ 100 ps

2) Grazing

The particle crosses the diamond sensor along the longitudinal direction



Gain in Silicon detectors

Gain in silicon detectors is commonly achieved in several types of sensors. It's based on the avalanche mechanism that starts in high electric fields: **E ~ 300 kV/cm**

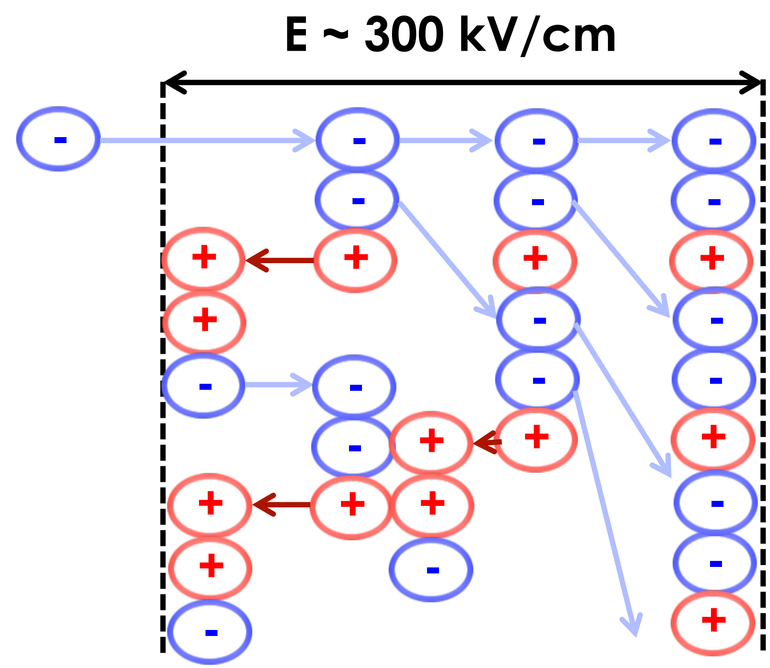
Charge multiplication

$$N(l) = N_0 \cdot e^{\alpha \cdot l}$$

Gain:

$$G = e^{\alpha\, l} \qquad \alpha_{e,h}(E) = \alpha_{e,h}(\infty) * \exp\left(-\frac{b_{e,h}}{|E|}\right)$$

α = strong E dependance
α ~ 0.7 pair/μm for electrons,
α ~ 0.1 for holes



Concurrent multiplication of electrons and holes generate very high gain

Silicon devices with gain:

- **APD: gain 50-500**
- **SiPM: gain ~ 10^4**

TOFFEE chip

Fully custom made chip for UFSD read-out

8 input channels

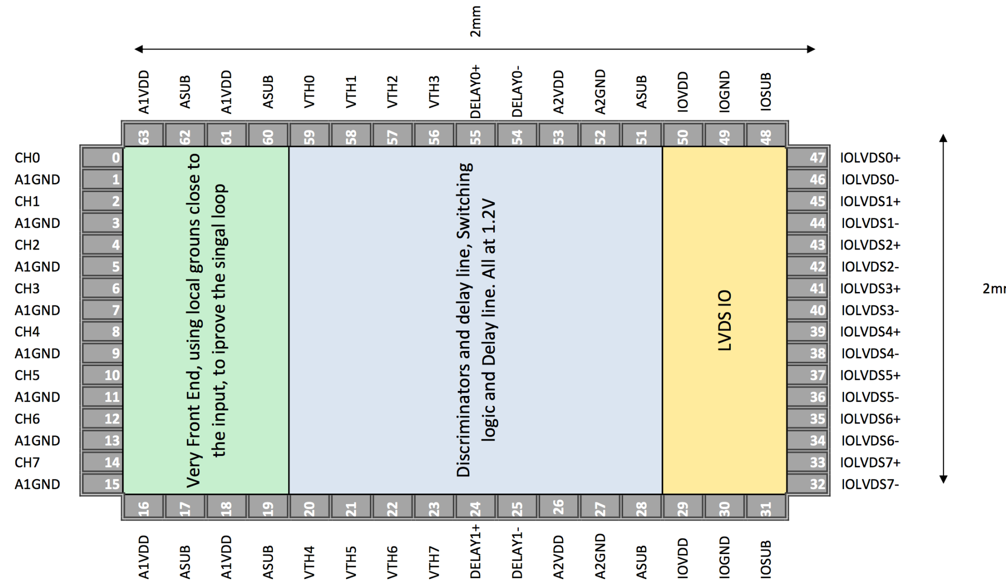
8 LVDS output suited for HPTDC

Available mid summer

Time resolution:

~ 50 ps with 6 fC

~ 30 ps with 10 fC



What is the signal of one e/h pair?

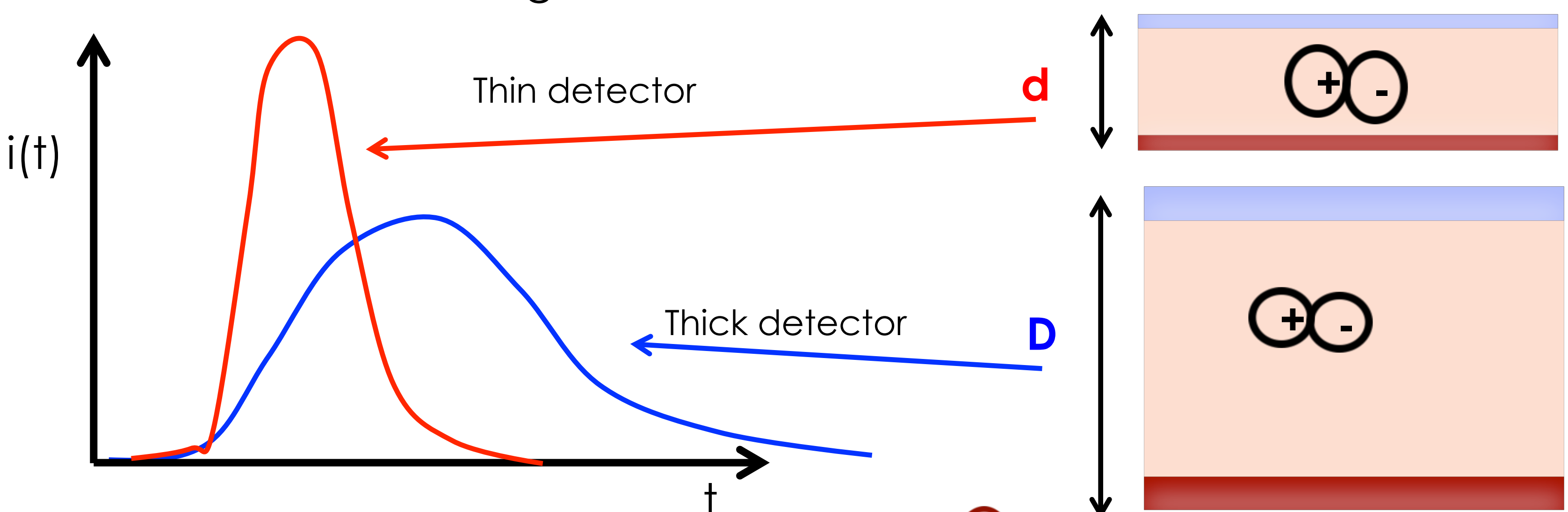
(Simplified model for pad detectors)

Let's consider **one single electron-hole pair.**

The integral of their currents is equal to the electric charge, q:

$$\int [i_{el}(t)+i_h(t)]dt = q$$

However **the shape of the signal depends on the thickness** d:
thinner detectors have higher slew rate



→ **One e/h pair generates higher current in thin detectors**

$$i \propto qv\frac{1}{d}$$

Weighting field

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