

# Ultra-Fast Silicon Detector

- The “4D” challenge
- A parameterization of time resolution
- The “Low Gain Avalanche Detectors” project
- Laboratory measurements
- UFSD: LGAD optimized for timing measurements
- WeightField2: a simulation program to optimize UFSD
- First measurements
- Future directions

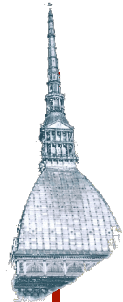
Nicolo Cartiglia

With

INFN Gruppo V, LGAD group of RD50, FBK and Trento University, Micro-Electronics Turin group  
Rome2 - INFN.

# Acknowledgement

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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*

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The work at SCIPP was partially supported by the United States Department of Energy, grant DE-FG02-04ER41286.

# The **4D** challenge

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

Can we provide in the same detector and readout chain:

- **Ultra-fast timing resolution [ ~ 10 ps]**
- **Precision location information [10's of  $\mu\text{m}$ ]**

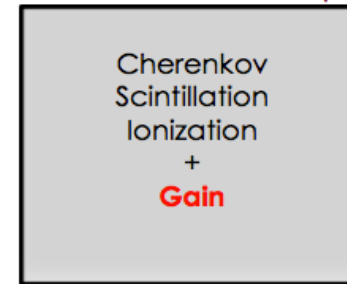
# Our path: Ultra-fast Silicon Detectors

Is it possible to build **a silicon detector** with concurrent excellent timing and position resolutions?

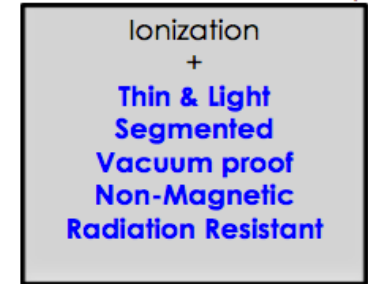
## Why silicon?

- It already has excellent position resolution
- Very well supported in the community
- Finely segmented
- Thin
- Light
- A-magnetic
- Small
- Radiation resistant

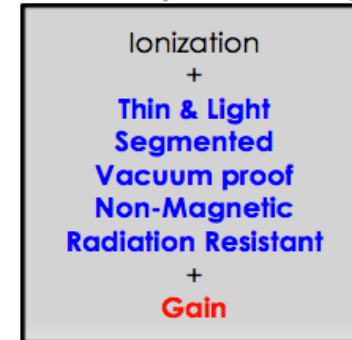
Time Detectors: 10-20 ps



Position Detectors: 10-20  $\mu\text{m}$



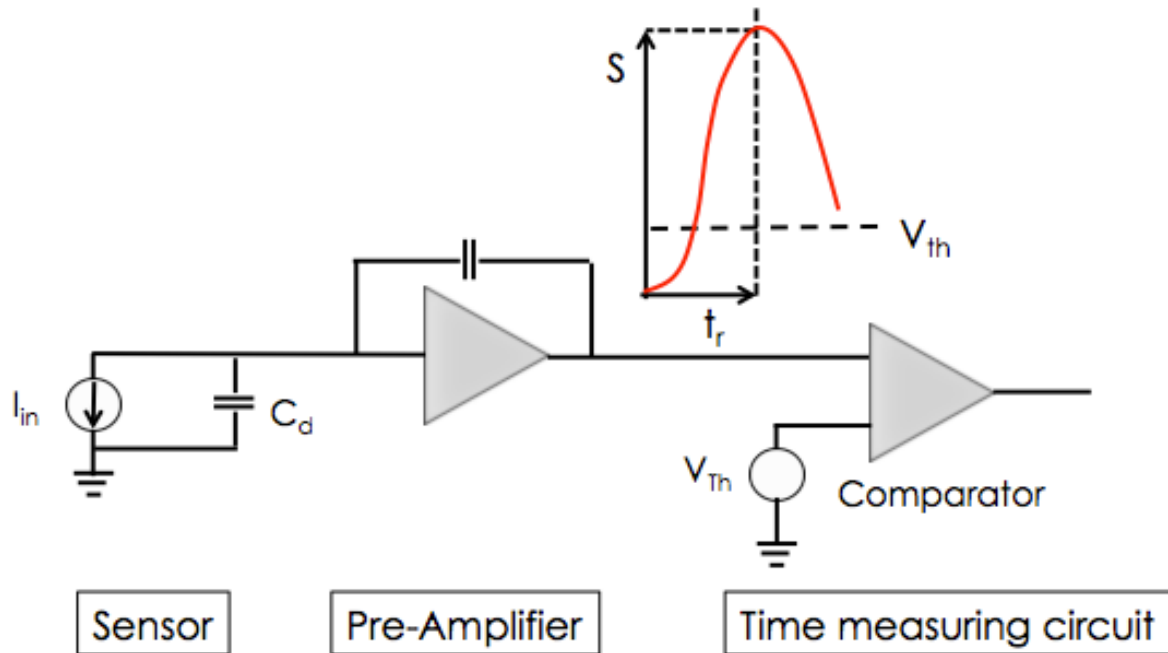
UFSD: 10-20 ps and 10-20  $\mu\text{m}$



**But can it be precise enough?**

# 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.

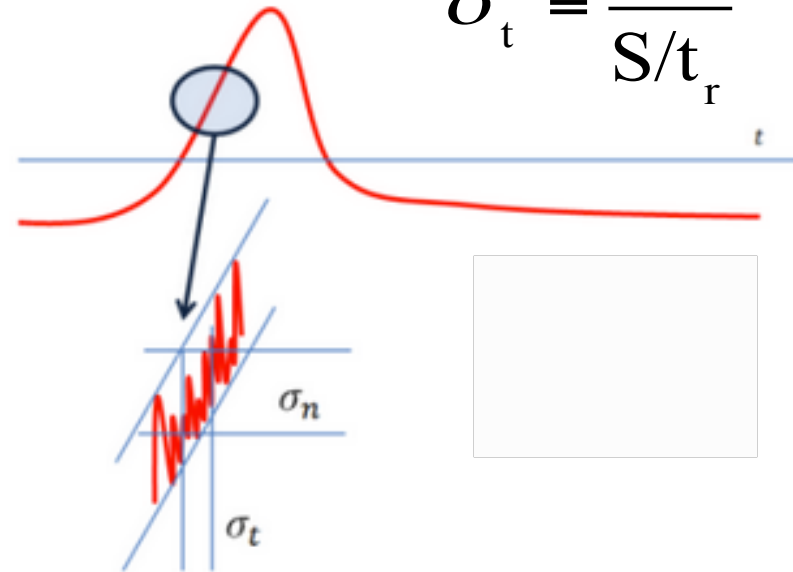
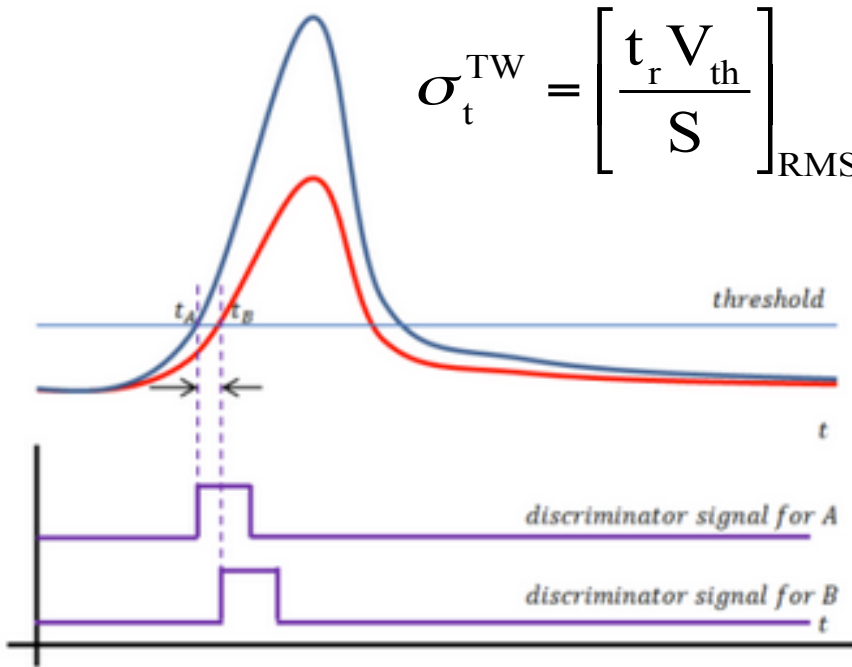
# Noise source: Time walk and Time jitter

**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

$$\sigma_{Total}^2 = \sigma_{Jitter}^2 + \sigma_{Time Walk}^2 + \sigma_{TDC}^2$$

# Time Resolution and slew rate

Using the expressions in the previous page, we can write

$$\sigma_t^2 = \left( \left[ \frac{V_{th}}{S/t_r} \right]_{RMS} \right)^2 + \left( \frac{N}{S/t_r} \right)^2 + \left( \frac{TDC_{bin}}{\sqrt{12}} \right)^2$$

where:

- $S/t_r = dV/dt =$  slew rate
- $N =$  system noise
- $V_{th} = 10 N$

Assuming constant noise, to minimize time resolution  
**we need to maximize the  $S/t_r$  term**  
(i.e. the slew rate  $dV/dt$  of the signal)

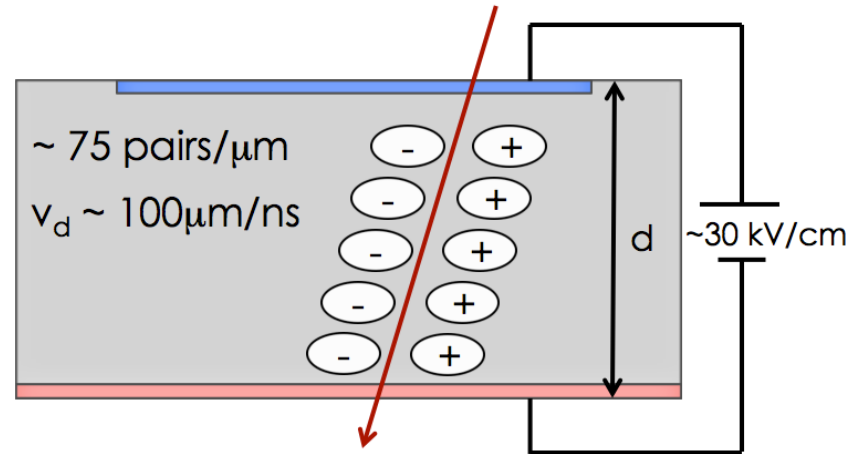
**➔ We need large and short signals ←**

# Signal formation in silicon detectors

We know we need a large signal, but **how is the signal formed?**

**What is controlling the slew rate?**

$$\frac{dV}{dt} \propto ?$$



A particle creates charges, then:

- The charges start moving under the influence of an external field
- The motion of the charges induces a current on the electrodes
- The signal ends when the charges reach the electrodes



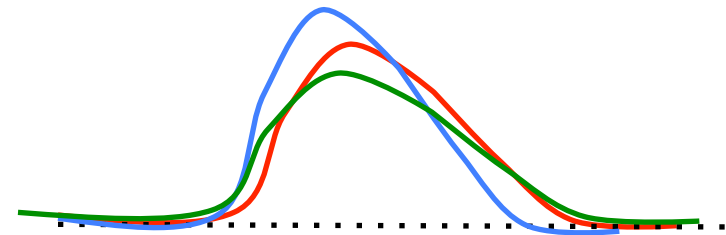
# How to make a **good** signal

Signal shape is determined by Ramo's Theorem:

$$i \propto qvE_w$$

**Drift velocity**

**Weighting field**



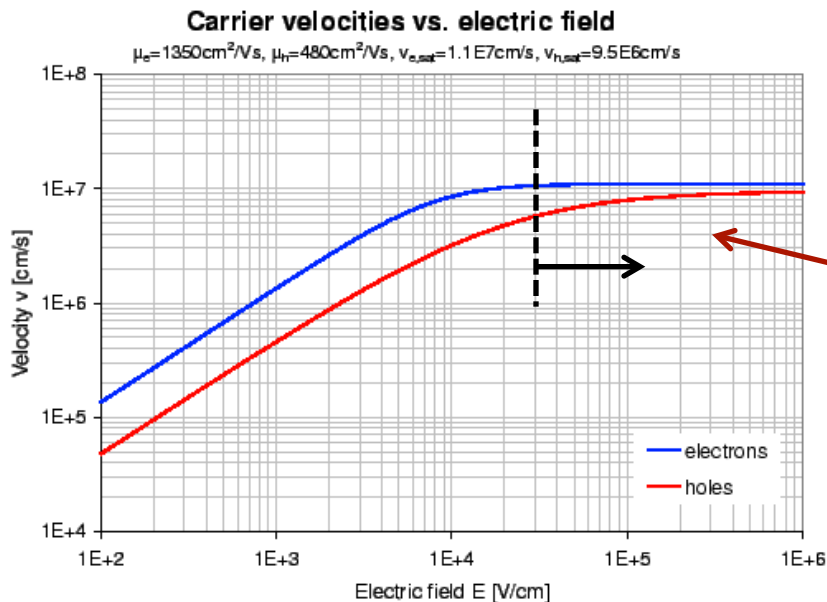
A key to good timing is the uniformity of signals:

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

# Drift Velocity

$$i \propto qvE_w$$

- Highest possible E field to saturate velocity
- Highest possible resistivity for velocity uniformity



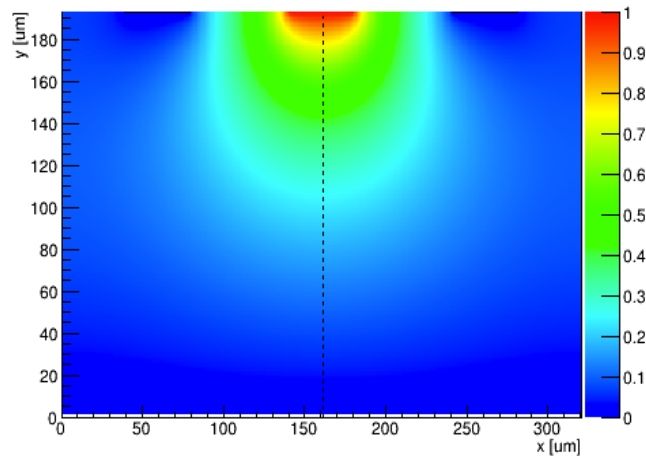
**Figure:** Electron and hole velocities vs. the electric field strength in silicon.

**We want to operate in this regime**

# Weighting Field: coupling the charge to the electrode

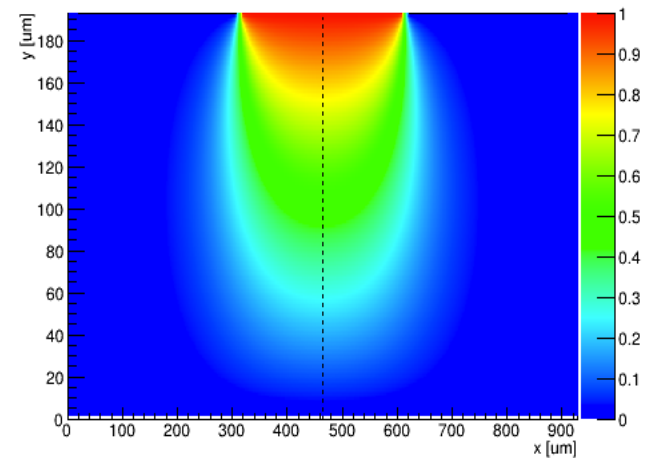
$$i \propto qvE_w$$

**Strip:** 100  $\mu\text{m}$  pitch, 40  $\mu\text{m}$  width



**Bad:** almost no coupling away from the electrode

**Pixel:** 300  $\mu\text{m}$  pitch, 290  $\mu\text{m}$  width



**Good:** strong coupling almost all the way to the backplane

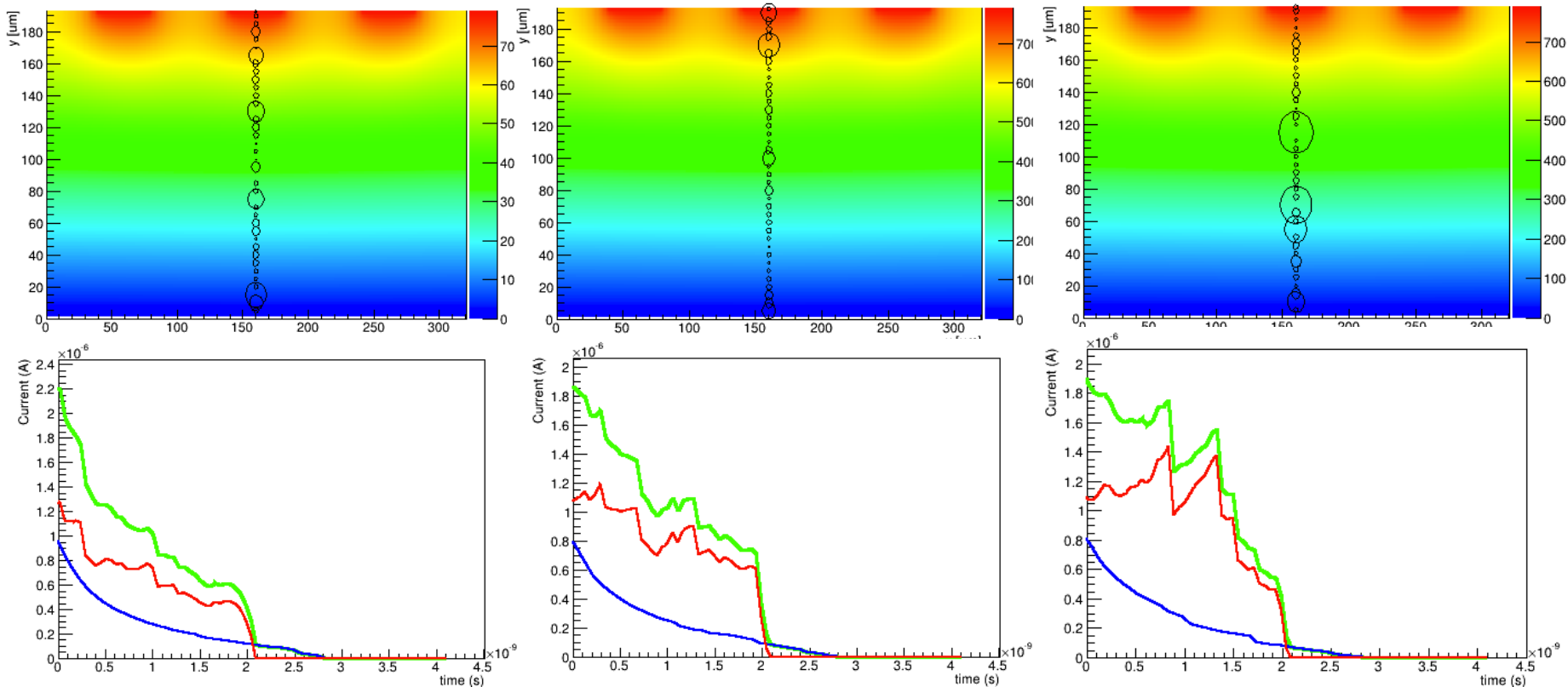
The weighting field needs to be as uniform as possible, so that the coupling is always the same, regardless of the position of the charge

# Non-Uniform Energy deposition

**Landau Fluctuations** cause two major effects:

- Amplitude variations, that can be corrected with time walk compensation
- For a given amplitude, the charge deposition is non uniform.

These are 3 examples of this effect:



# What is the signal of one e/h pair?

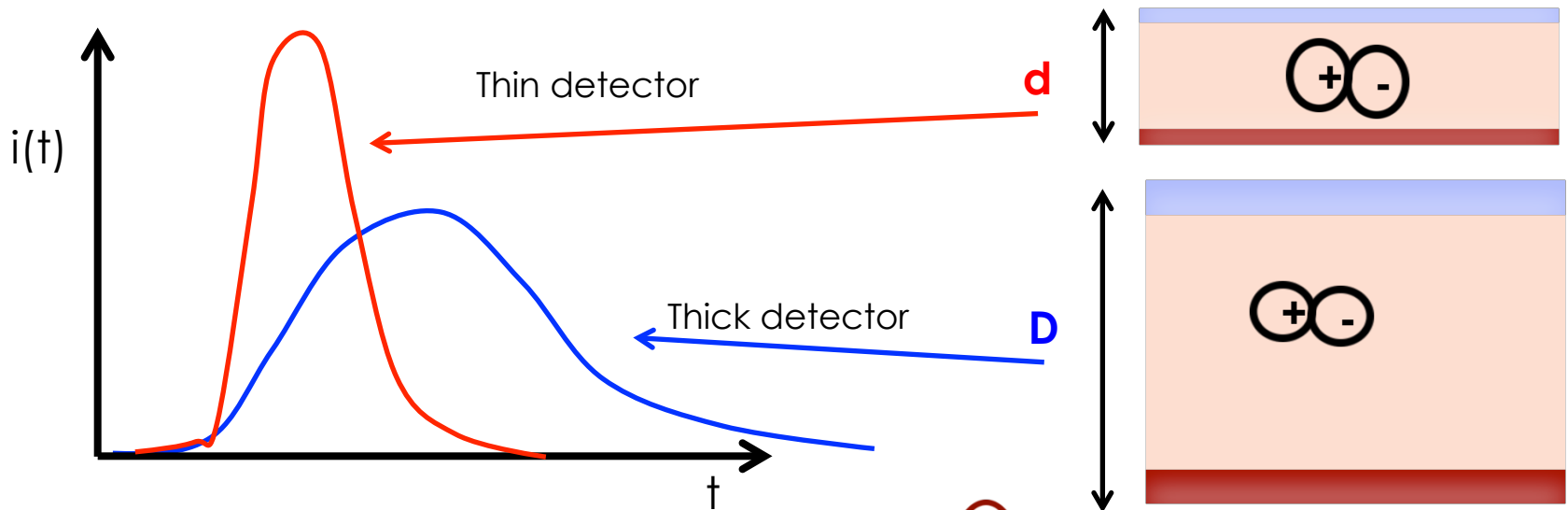
(Simplified model for pad detectors)

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**

$$i \propto qv \left( \frac{1}{d} \right)$$

Weighting field

# Large signals from thick detectors?

(Simplified model for pad detectors)

Thick detectors have higher number of charges:

$$Q_{\text{tot}} \sim 75 q * d$$

However each charge contributes to the initial current as:

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

**The initial current** for a silicon detector does not depend on how thick (d) the sensor is:

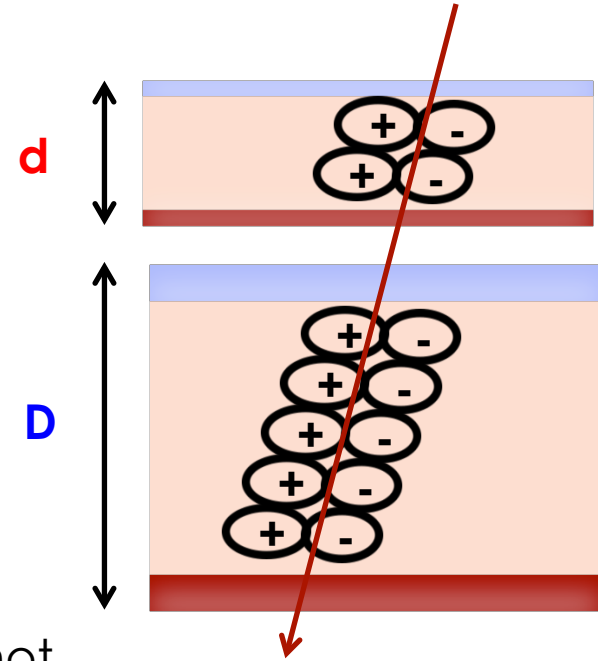
$$i = Nq \frac{k}{d} v = (75dq) \frac{k}{d} v = 75kqv \sim 1 - 2 * 10^{-6} A$$

Number of e/h = 75/micron

Weighting field

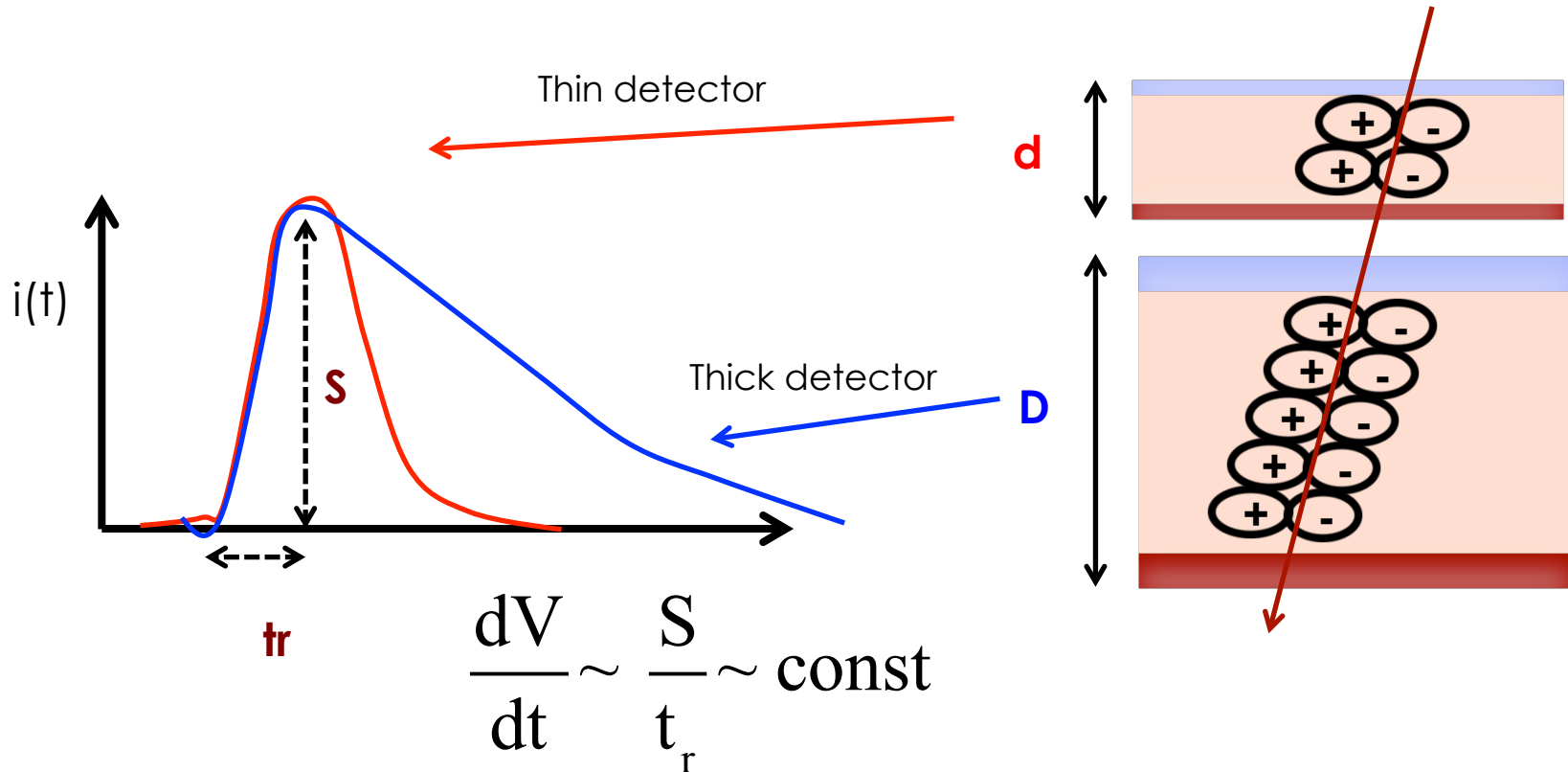
velocity

→ Initial current = constant



# Thin vs Thick detectors

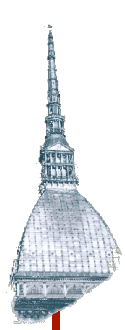
(Simplified model for pad detectors)



Thick detectors have longer signals, not higher signals

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

**To do better, we need to add gain**



# The “Low-Gain Avalanche Detector” project

Is it possible to manufacture a silicon detector that looks like a normal pixel or strip sensor, but with a much larger signal (RD50)?

- 750 e/h pair per micron instead of 75 e/h?
- Finely Segmented
- Radiation hard
- No dead time
- Very low noise (low shot noise)
- No cross talk
- Insensitive to single, low-energy photon

## **Many applications:**

- Low material budget (30 micron == 300 micron)
- Excellent immunity to charge trapping (larger signal, shorter drift path)
- Very good S/N: 5-10 times better than current detectors
- Good timing capability (large signal, short drift time)



# 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:  **$E \sim 300 \text{ kV/cm}$**

Charge multiplication

Gain:

- $\alpha$  = strong E dependance
- $\alpha \sim 0.7 \text{ pair}/\mu\text{m}$  for electrons,
- $\alpha \sim 0.1$  for holes

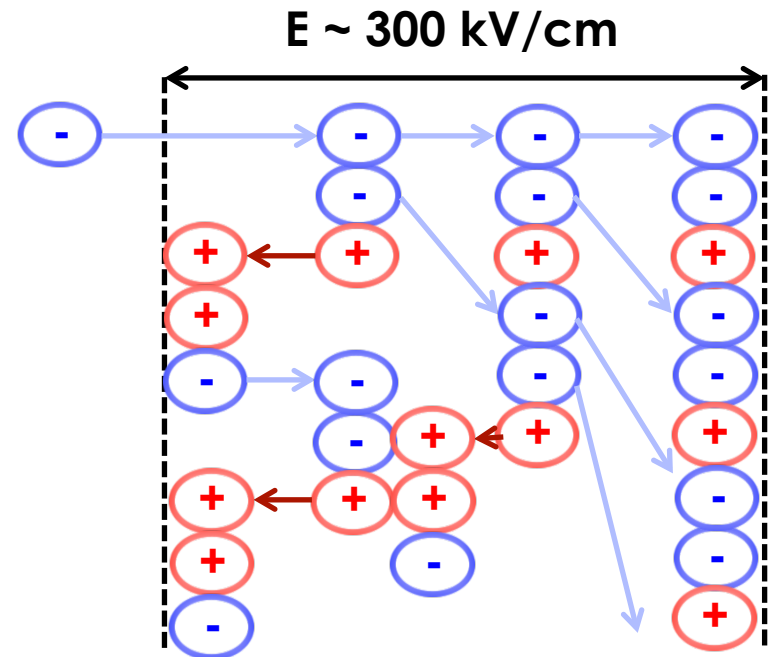
Concurrent multiplication of electrons and holes generate very high gain

**Silicon devices with gain:**

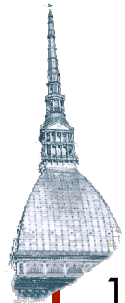
- **APD: gain 50-500**
- **SiPM: gain  $\sim 10^4$**

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

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

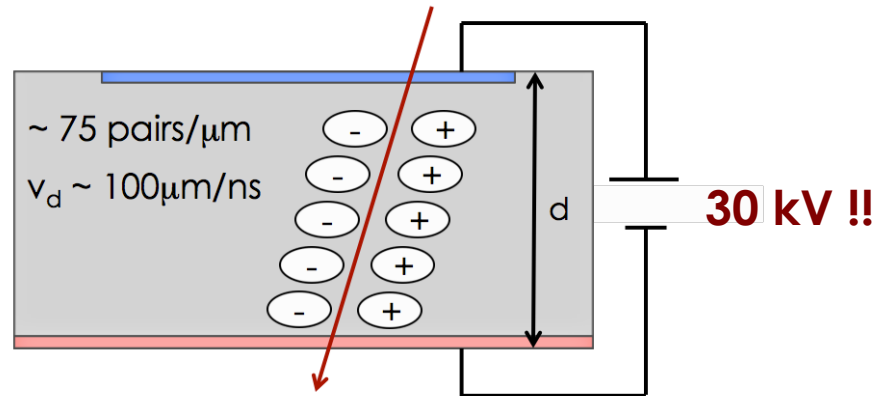


# How can we achieve $E \sim 300\text{kV/cm}$ ?



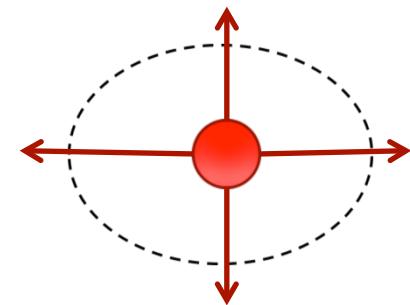
1) Use external bias: assuming a 300 micron silicon detector, we need  $V_{\text{bias}} = 30\text{ kV}$

**Not possible**



2) Use Gauss Theorem:

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



$$E = 300\text{ kV/cm} \rightarrow q \sim 10^{16} / \text{cm}^3$$

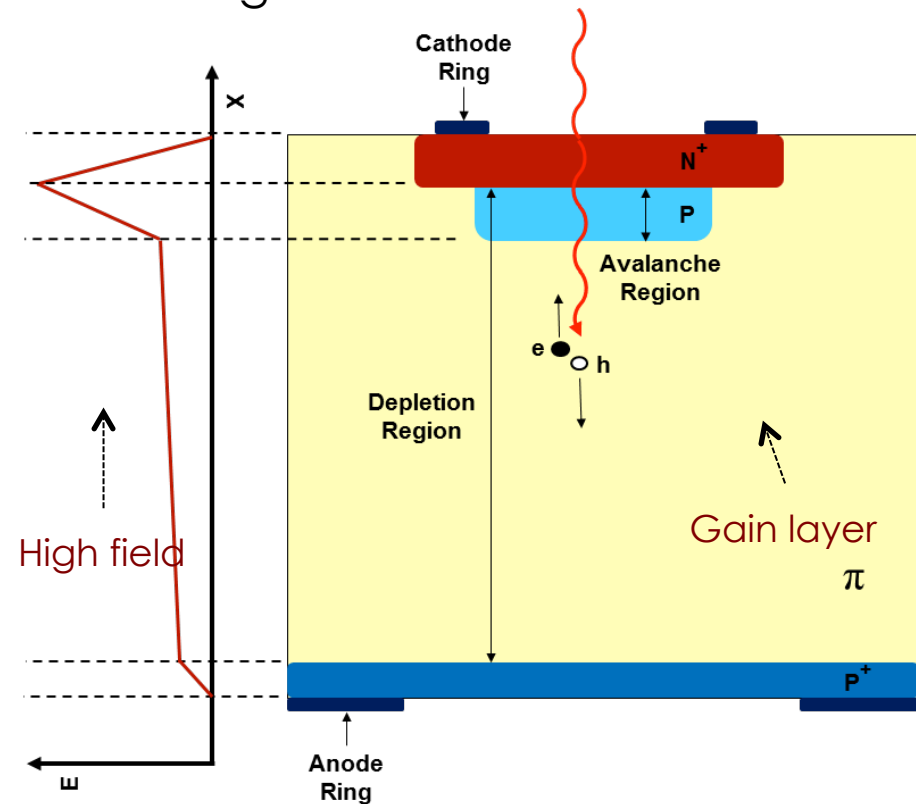
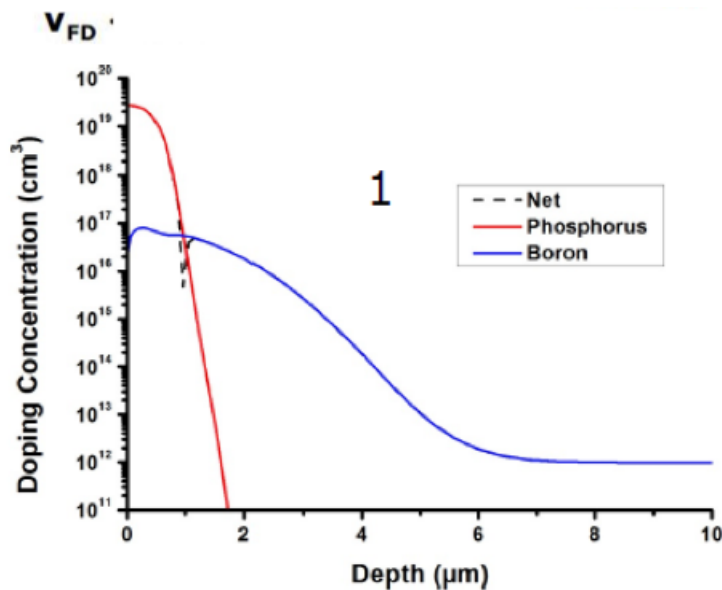
# Low Gain Avalanche Detectors (LGADs)

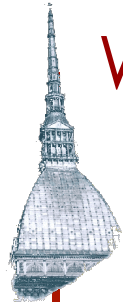
The LGAD sensors, as proposed and manufactured by CNM

(National Center for Micro-electronics, Barcelona):

**High field obtained by adding an extra doping layer**

$E \sim 300$  kV/cm, closed to breakdown voltage





# Why low gain? Can we use APD or SiPM instead?

**My personal conclusion:** I think it's possible to obtain very good timing: APDs, SiPMs have very high gain, so they are excellent in "single shot" timing.

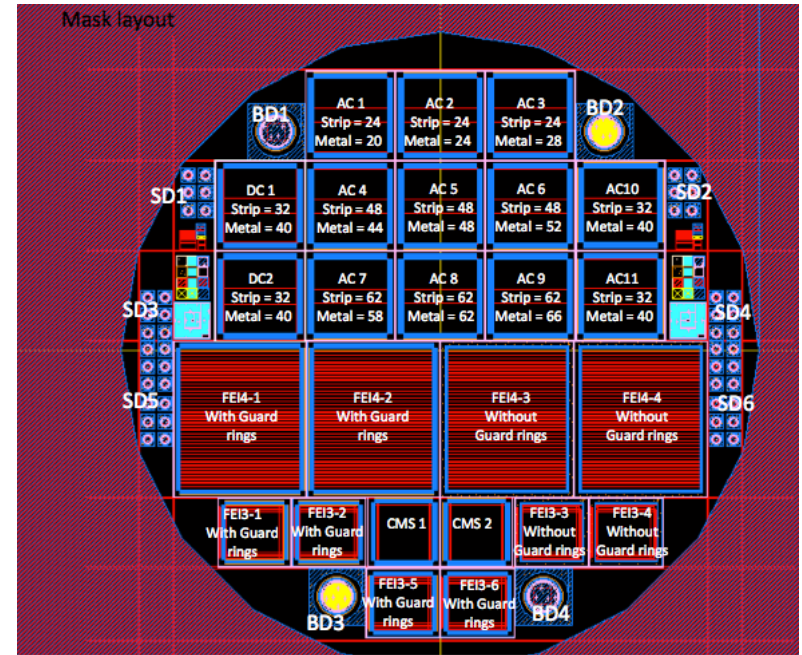
However, we are seeking to obtain something more powerful: a very low noise, finely pixelated device, able to provide excellent timing in any geometry, and also able to work in the presence of many low energy photons without giving fake hits.

These requirements make the use of high gain devices challenging

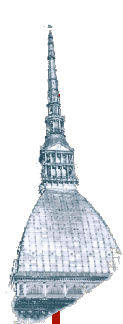
# CNM LGADs mask

CNM, within the RD50 project, manufactured several runs of LGAD, trying a large variety of geometries and designs

**This implant controls the value of the gain**



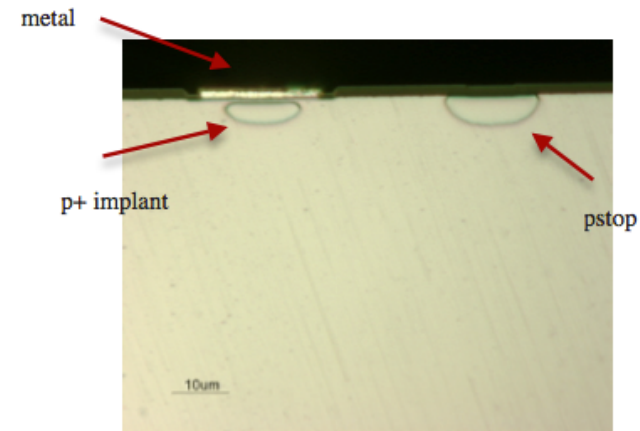
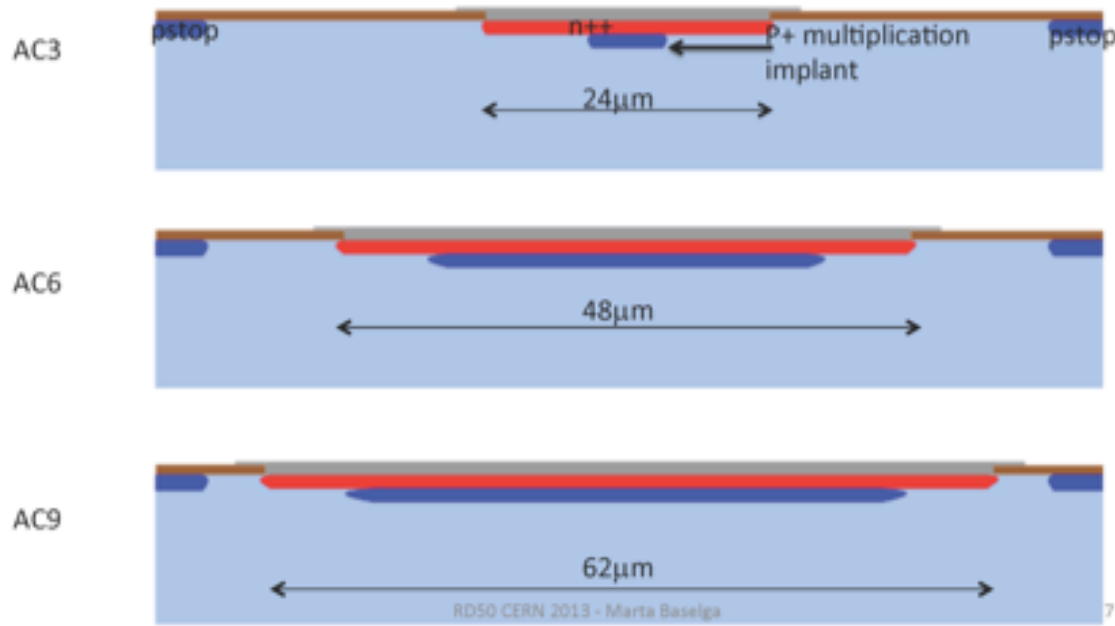
Wafer Number	P-layer Implant (E = 100 keV)	Substrate features	Expected Gain
1-2	$1.6 \times 10^{13} \text{ cm}^{-2}$	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$ ; $<100>$ ; T = $300 \pm 10 \mu\text{m}$ )	2 – 3
3-4	$2.0 \times 10^{13} \text{ cm}^{-2}$	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$ ; $<100>$ ; T = $300 \pm 10 \mu\text{m}$ )	8 – 10
5-6	$2.2 \times 10^{13} \text{ cm}^{-2}$	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$ ; $<100>$ ; T = $300 \pm 10 \mu\text{m}$ )	15
7	(---) PiN Wafer	HRP 300 (FZ; $\rho > 10 \text{ K}\Omega \cdot \text{cm}$ ; $<100>$ ; T = $300 \pm 10 \mu\text{m}$ )	No Gain

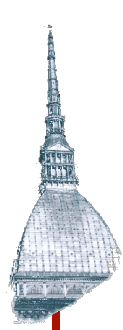


# LGADs Pads, Pixels and Strips

The LGAD approach can be extended to any silicon structure, not just pads.

This is an example of LGAD strips





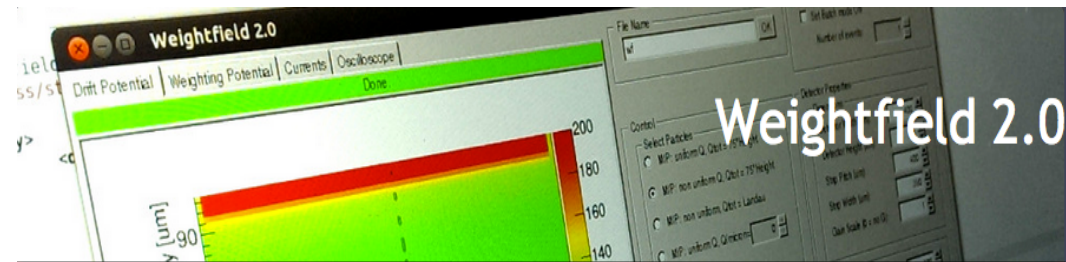
# Sensor: Simulation

We developed a full sensor simulation to optimize the sensor design

WeightField2, F. Cenna, N. Cartiglia 9<sup>th</sup> 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



# WeightField2: a program to simulate silicon detectors

The screenshot displays the WeightField 2.6 software interface. The main window is titled "Weightfield 2.6" and contains several panels:

- Control Panel:** Precision (1=best, 10=fastest): 10; Sampling (GigaSample): 100; File Name: ON wf; Batch: ON # of events: 1.
- Select Particles Panel:** MIP: non uniform, Qtot = Landau (selected); MIP: uniform Q, Q/micron = 75; alpha from top (E = 5 MeV); alpha from bottom (E = 5 MeV); Set range (Max = 30 um): 10.
- Detector Properties Panel:** Type: Si (selected); Strips: n-type (selected); Bulk: p-type (selected); Dimensions: # of strips (1,3,5,...): 3; Detector Height (um): 285; Strip Pitch (um): 300; Strip Width (um): 290; Gain Scale (1 = no G): 1; Force Fixed Gain: OFF; h/e Gain ratio: 0; Gain layer recess (um): 0; Voltage: Bias Voltage (V): 800; Depletion Voltage (V): 40.
- Electronics Panel:** ON (checked); Detector Cap (pF): 1; Oscilloscope BW (GHz): 2.5; Shaper T\_r - T\_f (ns): 3.5; Shaper Trans Imp. (mV/IQ): 4; Shaper Noise & Vth (mV): 1; PreAmp input Imp. (Ohm): 50.
- Main Plot:** A 2D color map showing the drift potential distribution. The x-axis is labeled "x [um]" and ranges from 0 to 900. The y-axis is labeled "y [um]" and ranges from 0 to 250. A vertical dashed line is drawn at approximately x = 450 um.
- Plotting at:** On Strips (selected), Between Strips; 465; Draw; Field: |Ey|, |Ex|.
- Drift Potential V [V] Plot:** A graph showing the drift potential as a function of y [um]. The x-axis is y [um] (0 to 300) and the y-axis is V [V] (0 to 1000). The plot shows a linear relationship.
- Drift Field E (kV/cm) Plot:** A graph showing the drift field as a function of y [um]. The x-axis is y [um] (0 to 300) and the y-axis is E (kV/cm) (0 to 35). The plot shows a nearly constant field around 28 kV/cm.



# WeightField2: output currents

Control

Precision (1=best, 10=fastest):

Sampling (GigaSample):

File Name  
 ON

Batch  
 ON # of events:

Select Particles

MIP: uniform Q, Qtot = 75\*Height

MIP: non uniform Q, Qtot = 75\*Height

MIP: non uniform, Qtot = Landau

MIP: uniform Q, Q/micron=

alpha from top (E = 5 MeV)

alpha from bottom (E = 5 MeV)

Set range (Max = 30 um):

Plot Settings

Draw Electric Field

No 1D Plots  No 1D & 2D

Currents

Switch B-Field on and set to (T):

Diffusion

Temperature (K):

Detector Properties

Type  
 Si  Diamond  Free

Strips  
 n-type  p-type

Bulk  
 n-type  p-type

Dimensions

# of strips (1,3,5,...):

Detector Height (um):

Strip Pitch (um):

Strip Width (um):

Gain Scale (1 = no G):

Force Fixed Gain:  ON

h/e Gain ratio:

Gain layer recess (um):

Voltage

Bias Voltage (V):

Depletion Voltage (V):

Electronics

ON

Detector Cap (pF):

Oscilloscope BW (GHz):

Shaper T\_r - T\_f (ns):

Shaper Trans Imp. (mV/IQ):

Shaper Noise & Vth (mV):

PreAmp input Imp. (Ohm):

Particle hits Detector at:  Angle (deg):

Charge Collection

e- charges (e): 14657	h+ charges (e): 9751	e- + h+ charges (e): 24408
Gain e- charges (e): 0	Gain h+ charges (e): 0	Gain e- + h+ charges (e): 0
Total e- charges (e): 14657	Total h+ charges (e): 9751	Total Charges (e): 24408

Lorentz Drift

e- Lorentz Angle (degree):	0.00	h+ Lorentz Angle (degree):	0.00
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# WeightField2: response of the read-out electronics

The figure displays four plots related to the detector response:

- CSA:** A green plot showing Amplitude (mV) vs Time (s) with a peak of approximately 15.5 mV at 5 ns.
- Shaper Rising edge derivative:** A blue plot showing  $\sigma V_{out}$  (mV/ns) vs Time (s) with a peak of approximately 6.5 mV/ns at 1.5 ns.
- Charge:** A red plot showing Charge (fC) vs Time (s) with a saturation value of approximately 3.8 fC.
- Cividec broadband (50 Ohm and 40db):** A red plot showing Amplitude (mV) vs Time (s) with a peak of approximately 9 mV at 0.5 ns.

Weightfield 2.6

Control

Precision (1=best, 10=fastest):

Sampling (GigaSample):

File Name  
 ON

Batch  
 ON # of events:

Select Particles

MIP: uniform Q, Qtot = 75\*Height

MIP: non uniform Q, Qtot = 75\*Height

MIP: non uniform, Qtot = Landau

MIP: uniform Q, Q/micron =

alpha from top (E = 5 MeV)

alpha from bottom (E = 5 MeV)

Set range (Max = 30 um):

Plot Settings

Draw Electric Field

No 1D Plots  No 1D & 2D

Currents

Switch B-Field on and set to (T):

Diffusion

Temperature (K):

Set Calculate Potentials

Calculate Currents Stop Exit

Detector Properties

Type  
 Si  Diamond  Free

Strips  
 n-type  p-type

Bulk  
 n-type  p-type

Dimensions

# of strips (1,3,5..):

Detector Height (um):

Strip Pitch (um):

Strip Width (um):

Gain Scale (1 = no G):

Force Fixed Gain:  ON

h/e Gain ratio:

Gain layer recess (um):

Voltage

Bias Voltage (V):

Depletion Voltage (V):

Electronics

ON

Detector Cap (pF):

Oscilloscope BW (GHz):

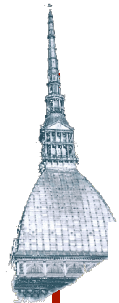
Shaper T\_r - T\_f (ns):

Shaper Trans Imp. (mV/fC):

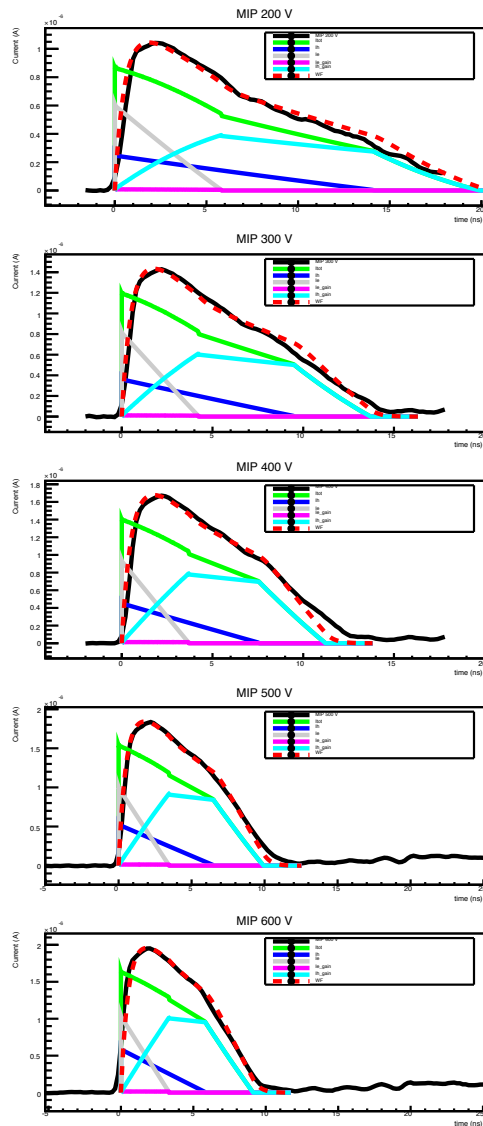
Shaper Noise & Vth (mV):

PreAmp input Imp. (Ohm):

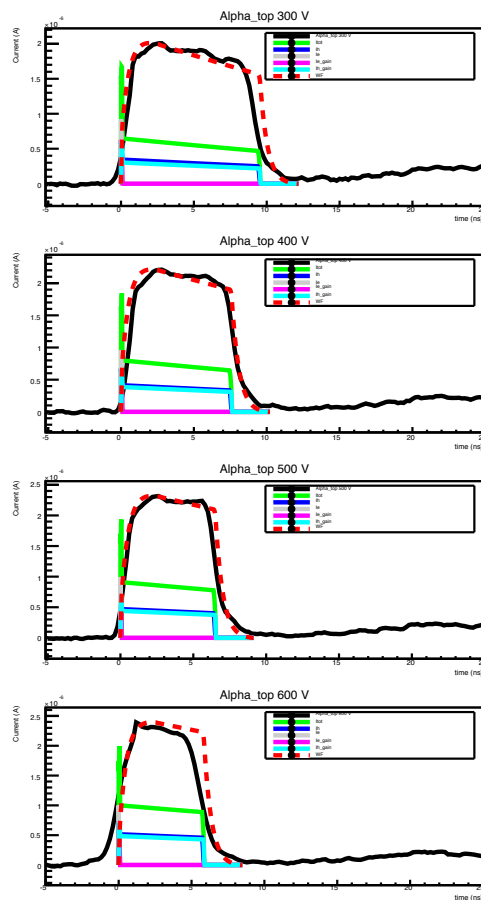
# Comparison Data Simulation



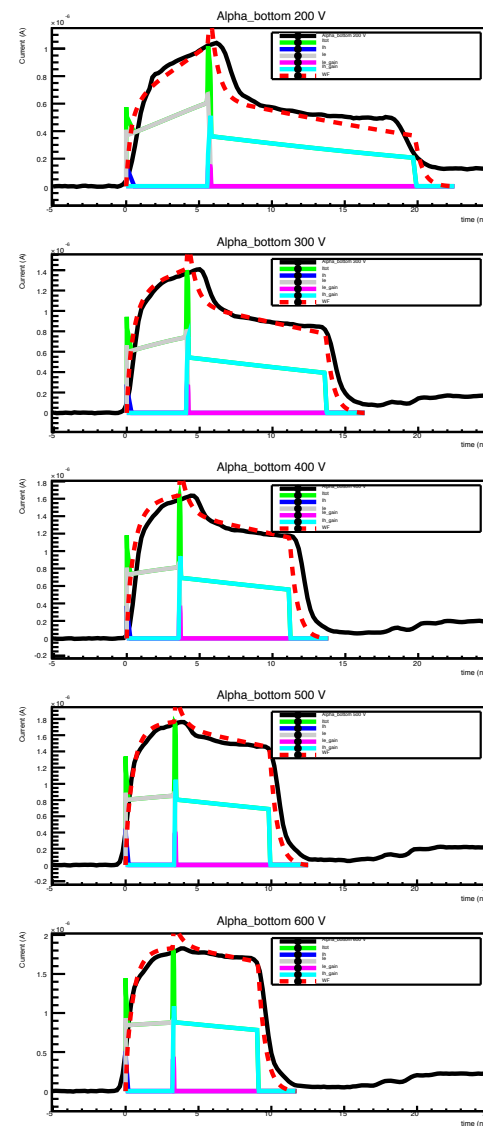
## MIP



## Alpha from Top



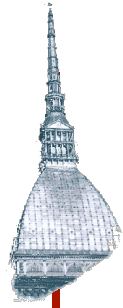
## Alpha from bottom



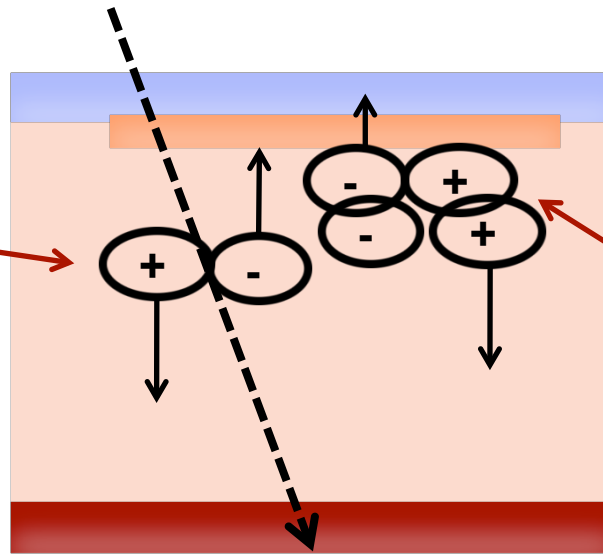
## V bias



# How gain shapes the signal



Initial electron, holes

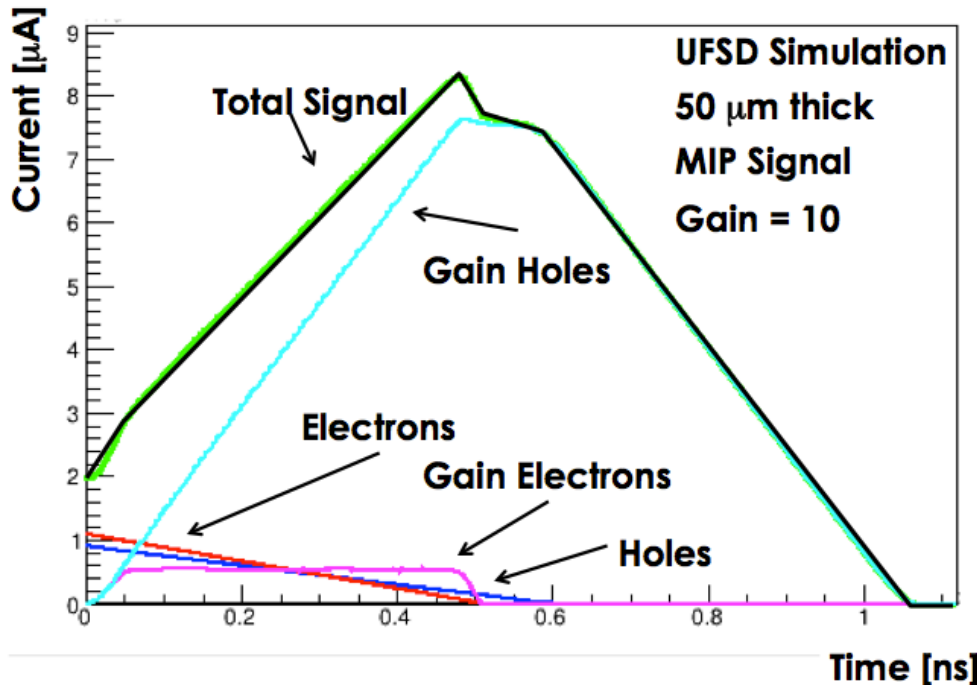


**Gain electron:**

absorbed immediately

**Gain holes:**

long drift home



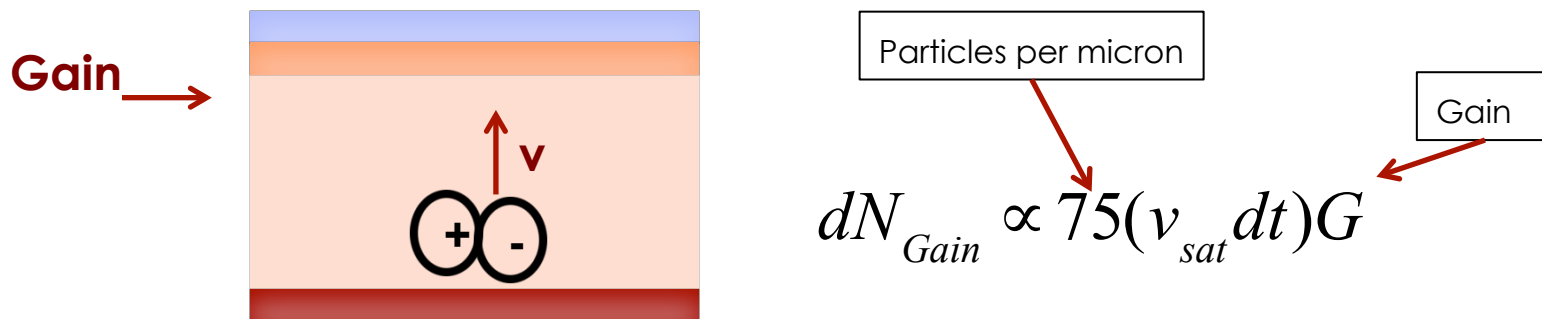
Electrons multiply and produce additional electrons and holes.

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

➔ **No holes multiplications**

# Interplay of gain and detector thickness

**The rate of particles** produced by the gain does not depend on  $d$  (assuming saturated velocity  $v_{sat}$ )



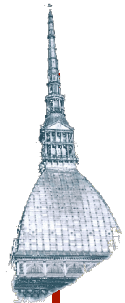
→ **Constant rate of production**

However the initial value of the **gain current depends on  $d$**  (via the weighing field)

$$di_{gain} \propto dN_{Gain} qv_{sat} \left(\frac{k}{d}\right) \Rightarrow \text{Gain current} \sim 1/d$$

A given value of gain has much more effect on thin detectors

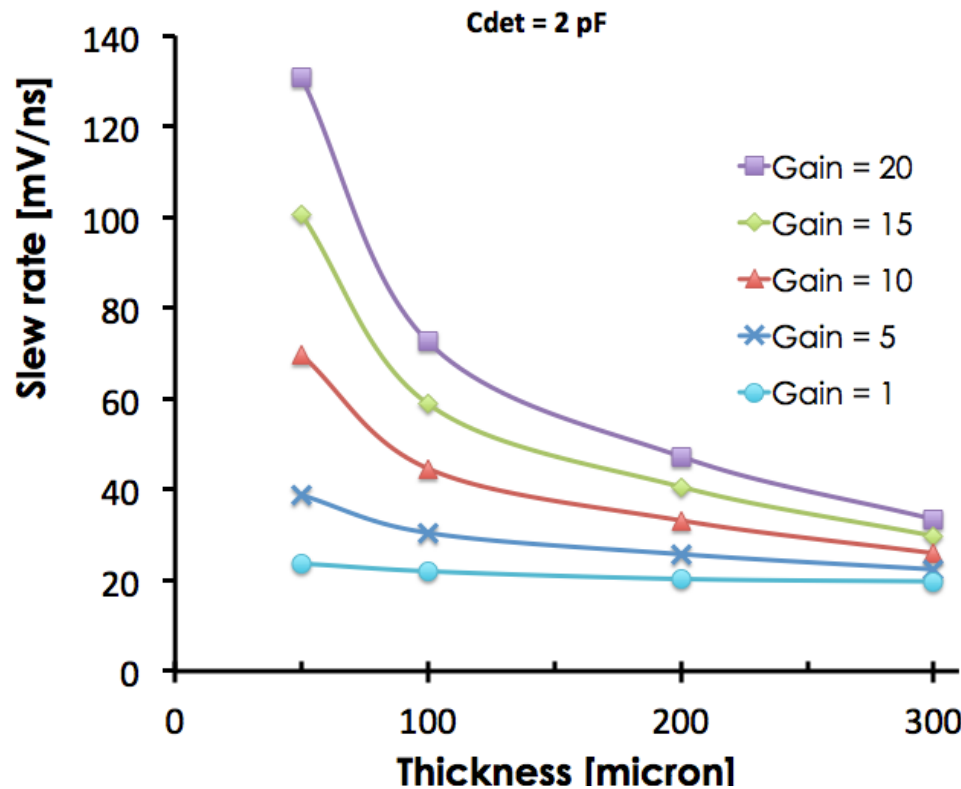
# Gain current vs Initial current



$$\frac{di_{gain}}{i} \propto \frac{dN_{Gain} q v_{sat} \frac{k}{d}}{k q v_{sat}} = \frac{75(v_{sat} dt) G q v_{sat} \frac{k}{d}}{k q v_{sat}} \propto \frac{G}{d} dt$$

!!!

→ Go thin!!



(Real life is a bit more complicated, but the conclusions are the same)

Full simulation

(assuming 2 pF detector capacitance)

**300 micron:**

~ 2-3 improvement with gain = 20

**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)

# First Measurements and future plans

## **LGAD laboratory measurements**

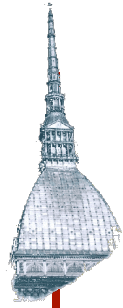
- Doping concentration
- Gain
- Time resolution measured with laser signals

## **LGAD Testbeam measurements**

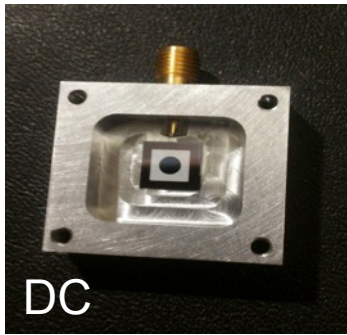
- Landau shape at different gains
- Time resolution measured with MIPs



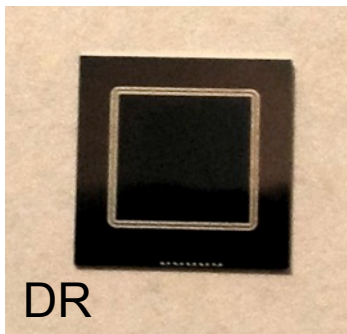
# LGAD Sensors in Torino



**Thickness:**  
300  $\mu\text{m}$



DC



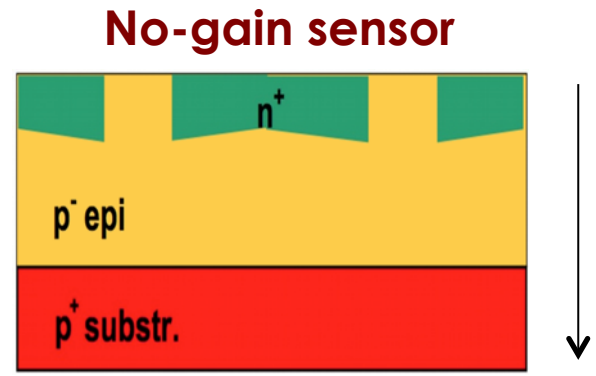
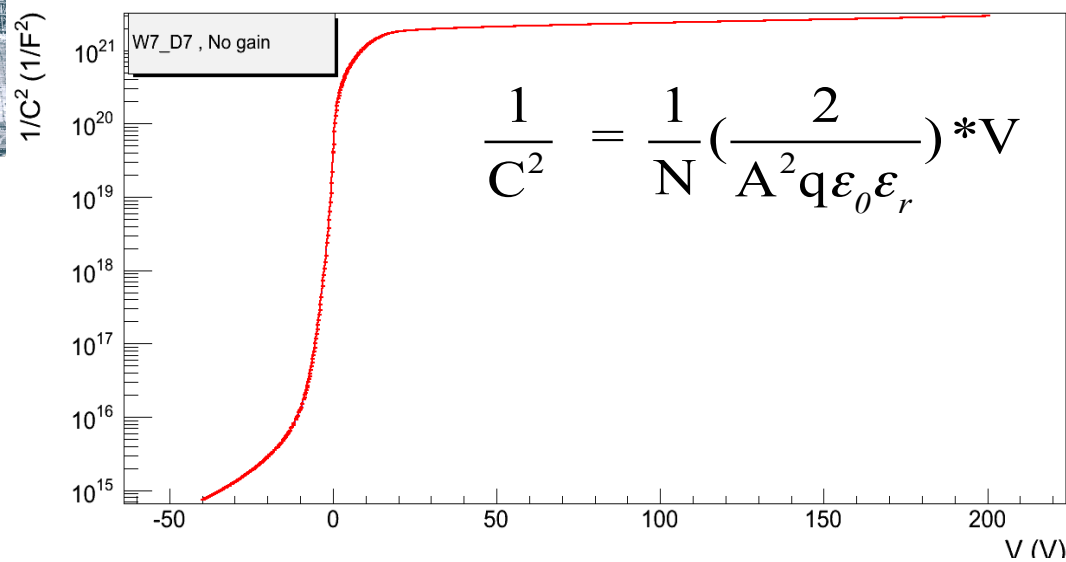
DR

Run	Sensor	P-Layer Implant (E=100 KeV)	Gain	$V_{\text{break}}$	Metal Layer
6474	W8_B4	?	~ 10	> 500 V	DR
6474	W8_C6	?	~ 10	> 500 V	DC
6474	W9_B6	No implant	No Gain	> 500 V	DR
7062	W1_F3	$1.6 \times 10^{13} \text{ cm}^{-2}$	~ 1-2	> 500 V	DR
7062	W3_H5	$2.0 \times 10^{13} \text{ cm}^{-2}$	~ 10	> 500 V	DR
7062	W7_D7	No implant	No Gain	> 500 V	DR

# Doping profile from CV measurement - I



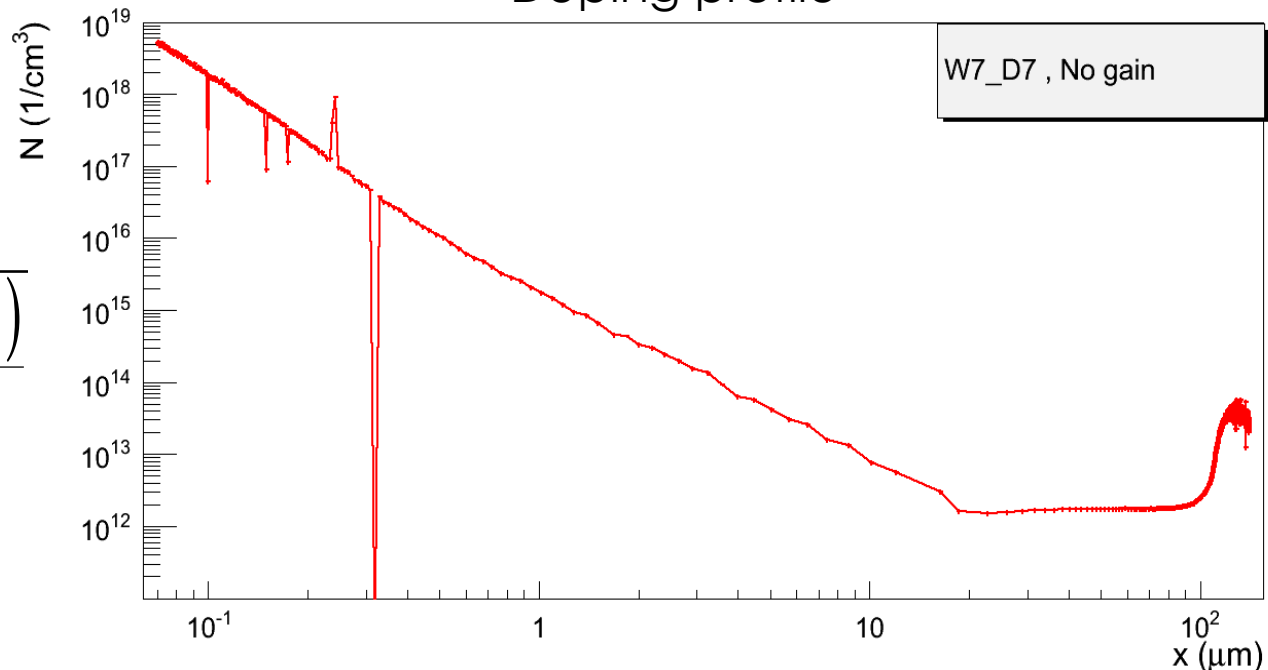
Nicolò Cartiglia, INFN, Torino - UFSD - LBNL



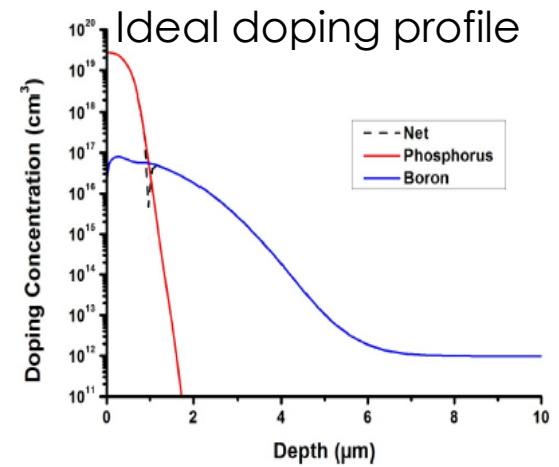
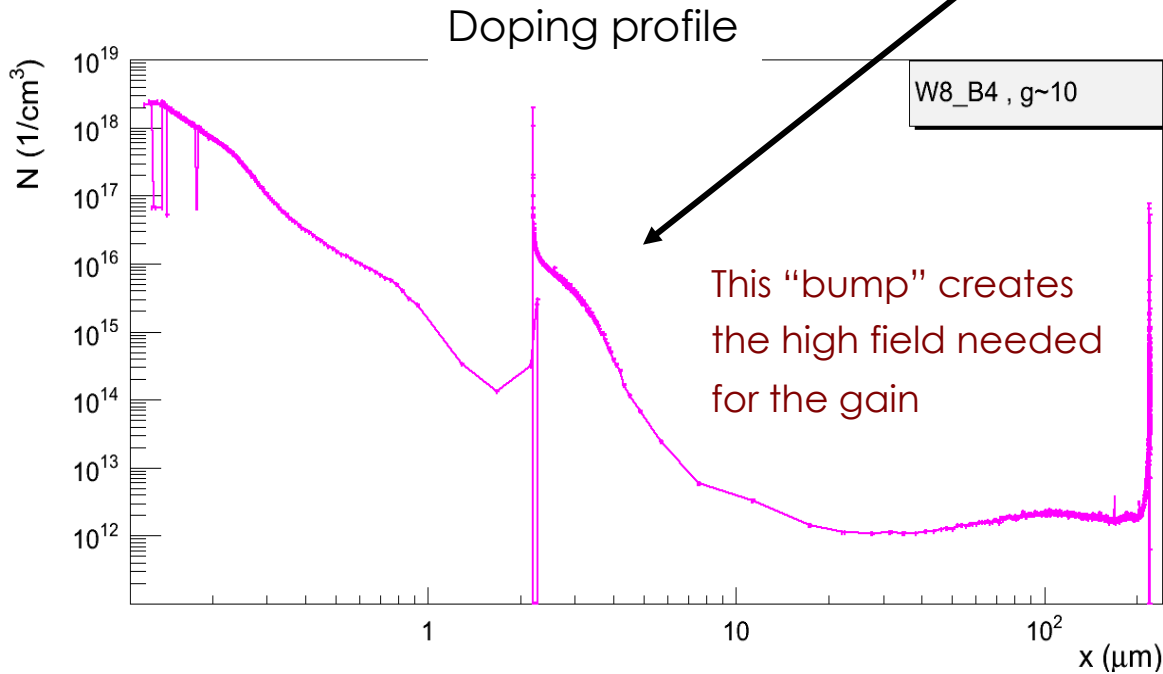
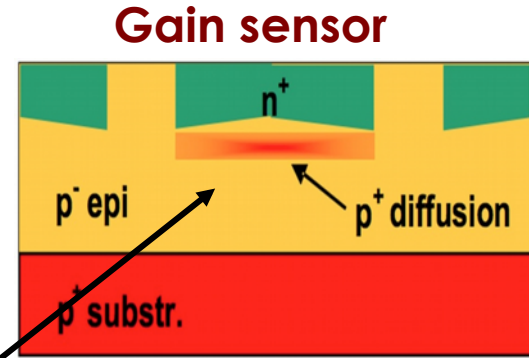
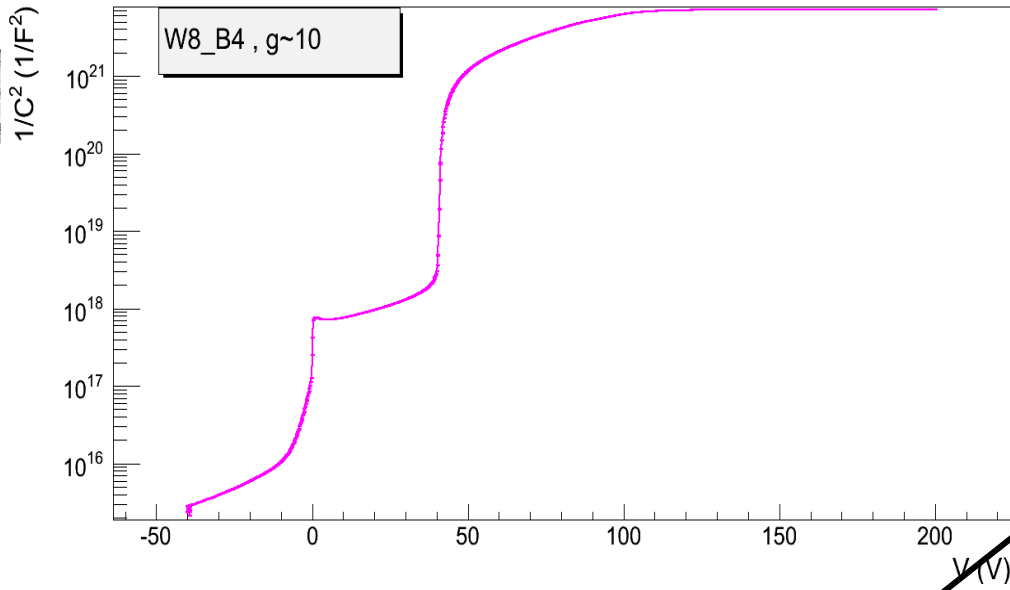
Doping profile

$$N = \frac{2}{q \epsilon_0 \epsilon_r A^2} \frac{d(1/C^2)}{dV}$$

Doping

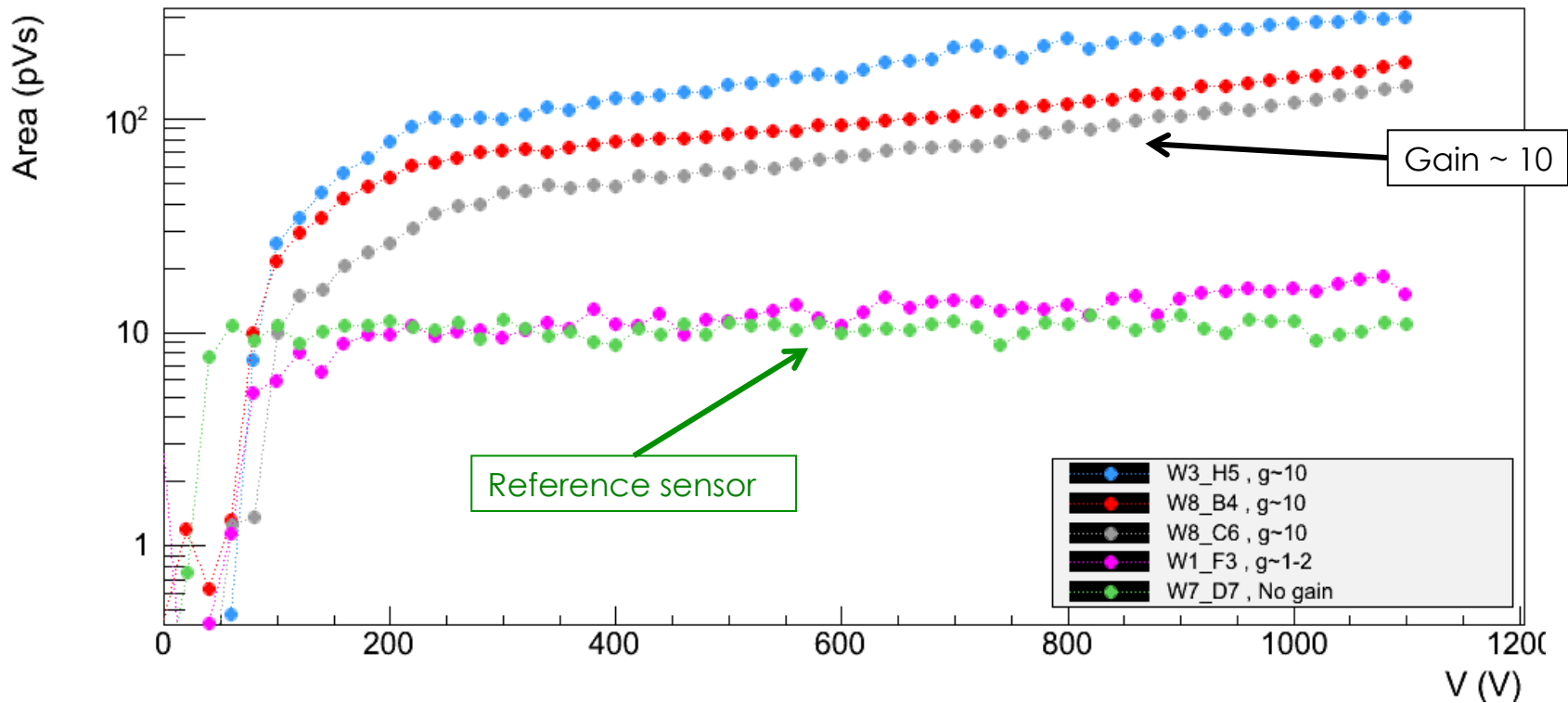


# Doping profile from CV measurement - II



# Signal amplitude

Using laser signals we are able to measure the different responses of LGAD and traditional sensors

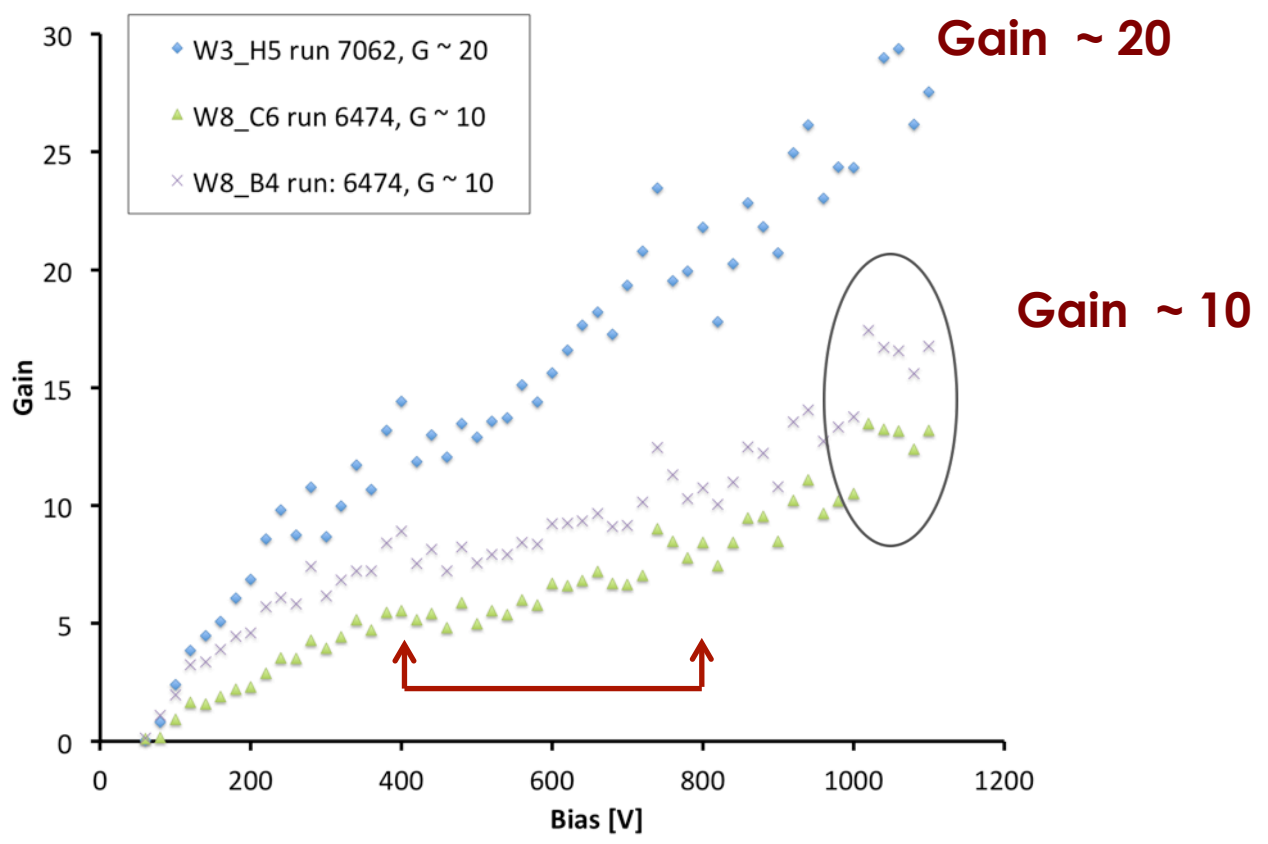


# Gain

The gain is estimated as the ratio of the output signals of LGAD detectors to that of traditional one

**The gain increases linearly with  $V_{bias}$  (not exponentially!)**

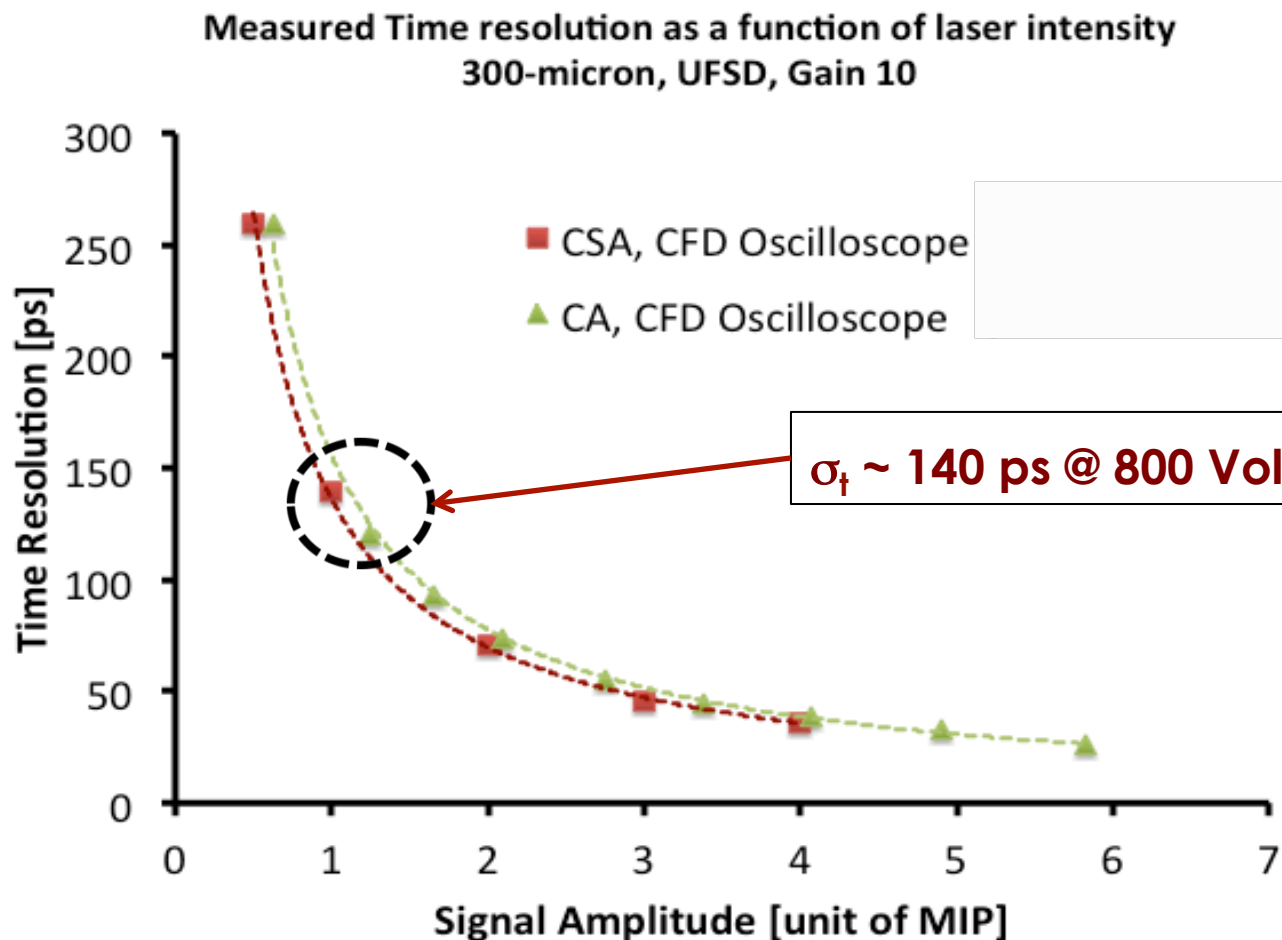
$$\frac{\text{Gain @ 800V}}{\text{Gain @ 400V}} \sim 2$$



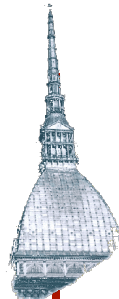
# Laser Measurements on CNM LGAD

We use a 1064 nm picosecond laser to emulate the signal of a MIP particle (without Landau Fluctuations)

The signal output is read out by either a Charge sensitive amplifier or a Current Amplifier (Cividec)

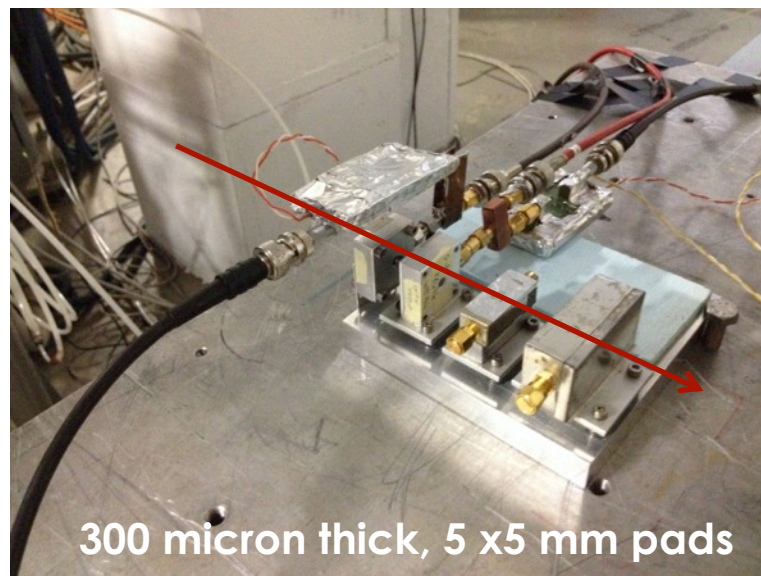


# Testbeam Measurements on CNM LGAD

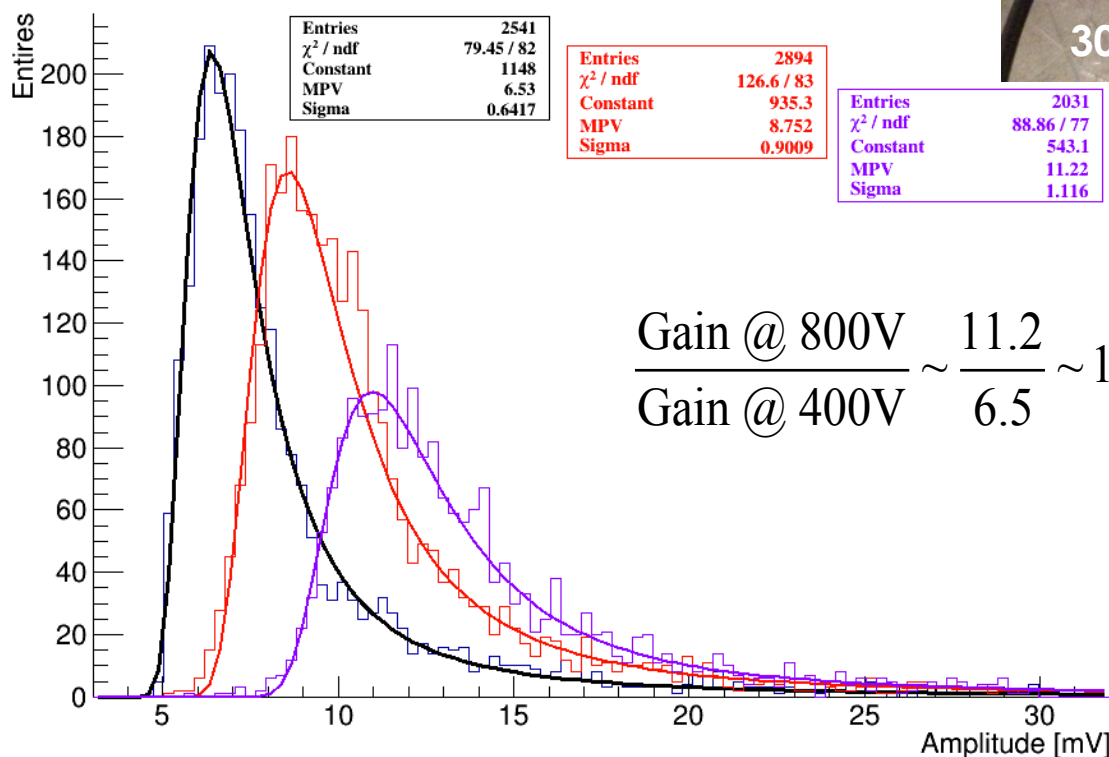


In collaboration with Roma2, we went to Frascati for a testbeam using 500 MeV electrons

As measured in the lab, the gain ~ doubles going from 400 -> 800 Volt.



300 micron thick, 5 x5 mm pads



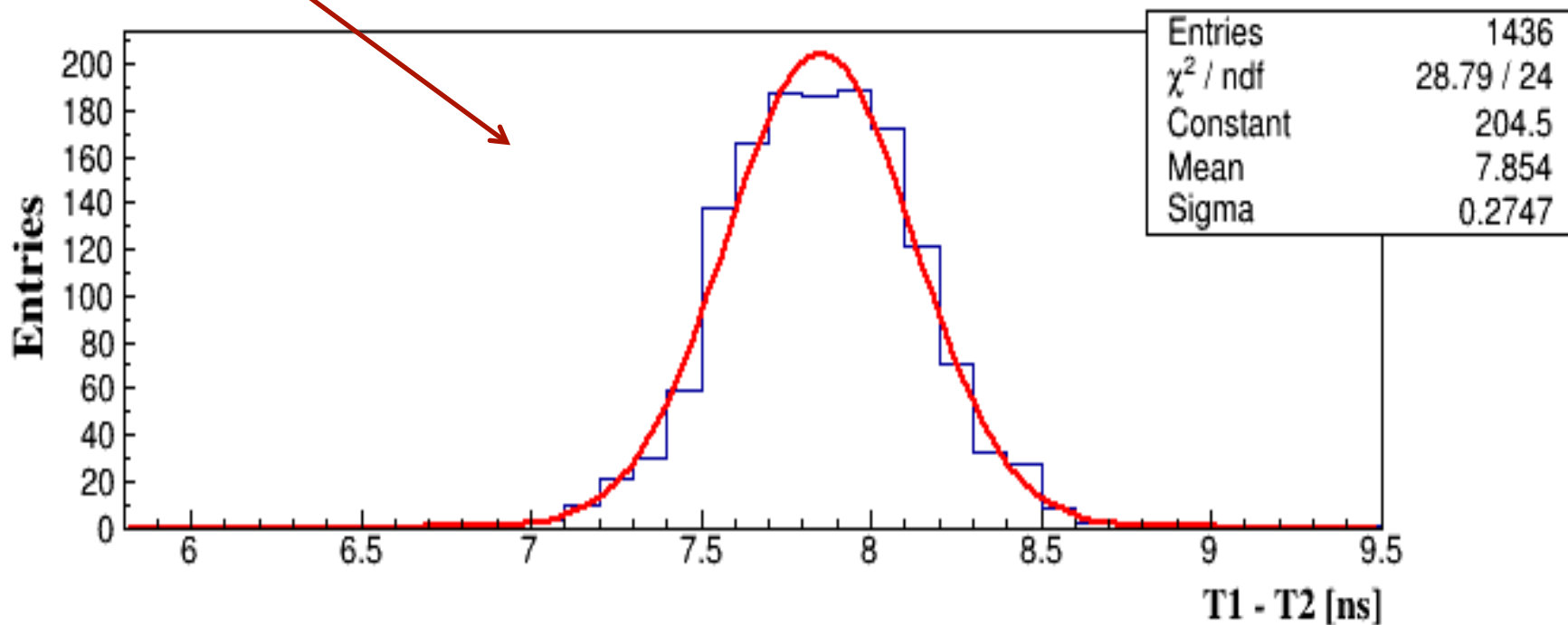
The gain mechanism preserves the Landau amplitude distribution of the output signals

# Testbeam Measurements on CNM LGAD

Time difference between two LGAD detectors crossed by a MIP

Tested different types of electronics (Rome2 SiGe, Cividec),  
**Not yet optimized for these detectors**

$\sigma_t \sim 190 \text{ ps @ 800 Volts}$

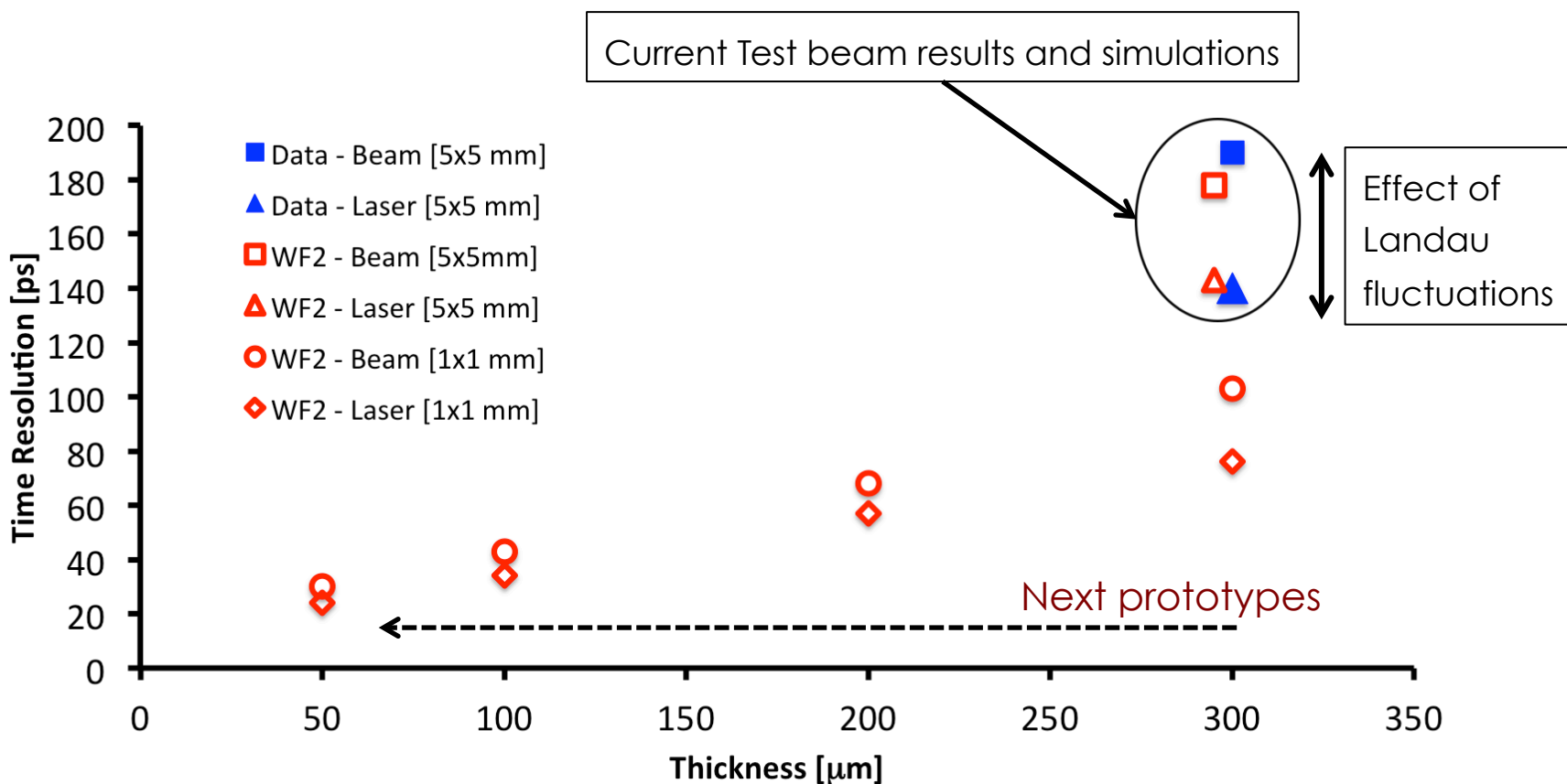




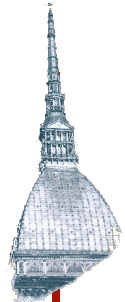
# Present results and future productions

With WF2, we can reproduce very well the laser and testbeam results.

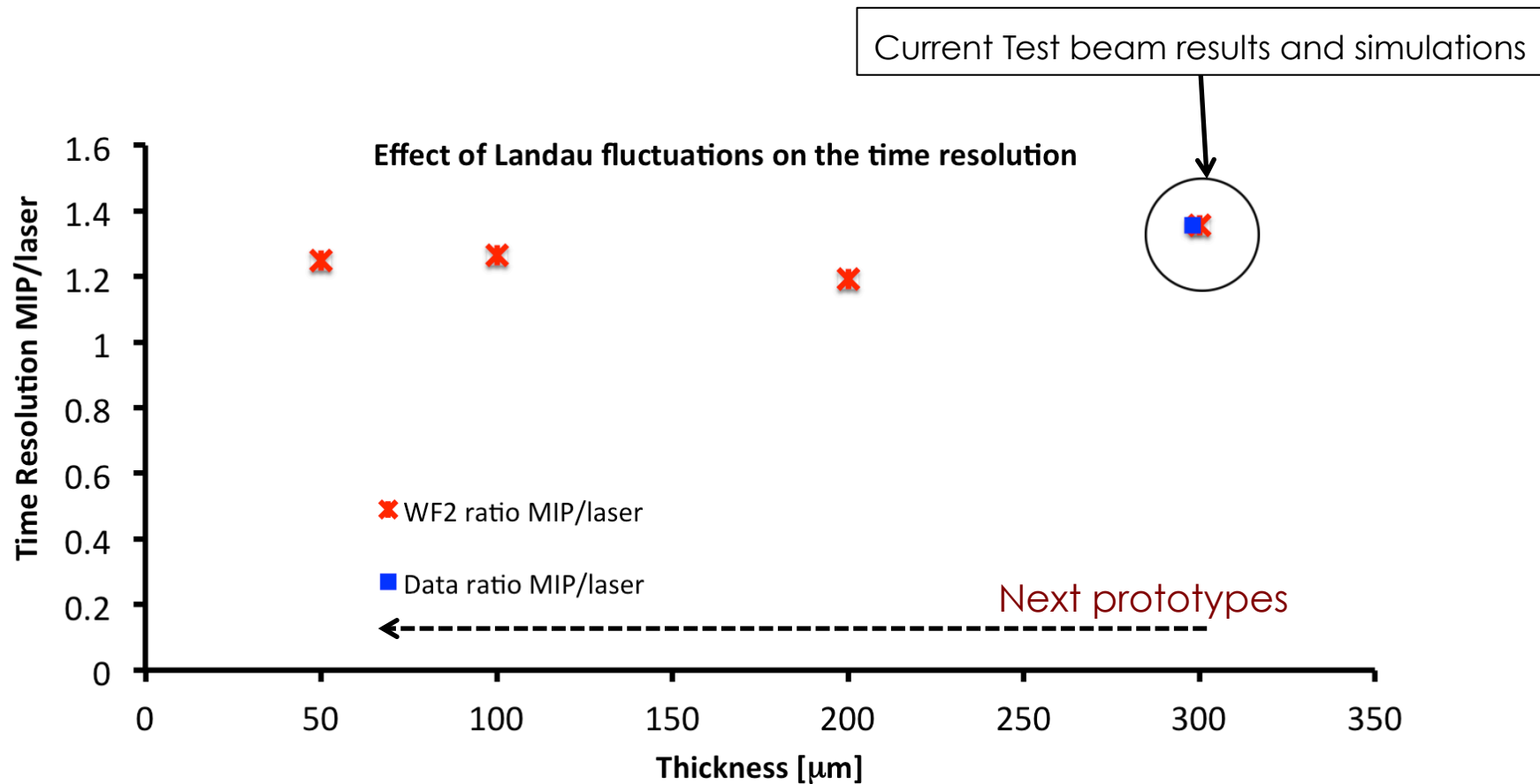
Assuming the same electronics, and 1 mm<sup>2</sup> LGAD pad with gain 10, we can predict the timing capabilities of the next sets of sensors.



# Effect of Landau Fluctuations on the time resolution



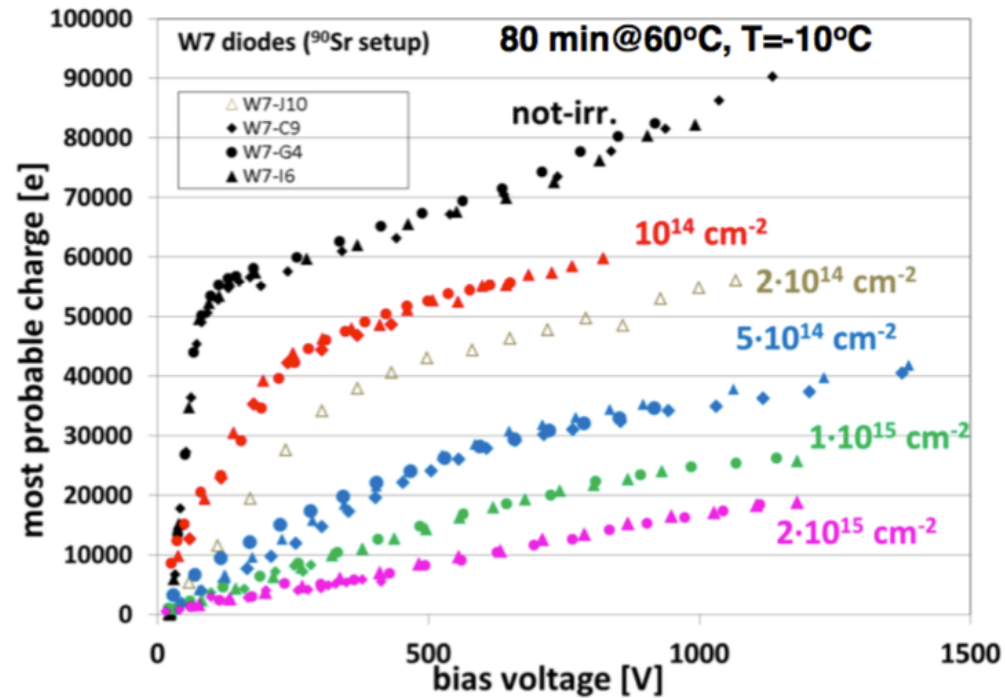
The effect of Landau fluctuations in a MIP signal are degrading the time resolution by roughly 30 % with respect of a laser signal



# Irradiation tests

The gain decreases with irradiations:  
**at  $10^{14}$  n/cm<sup>2</sup> is 20% lower**

→ **Due to boron disappearance**



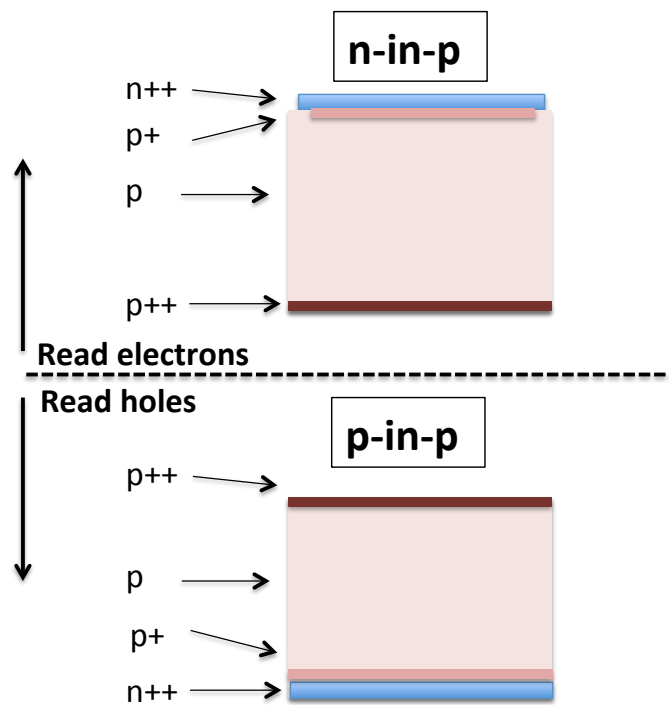
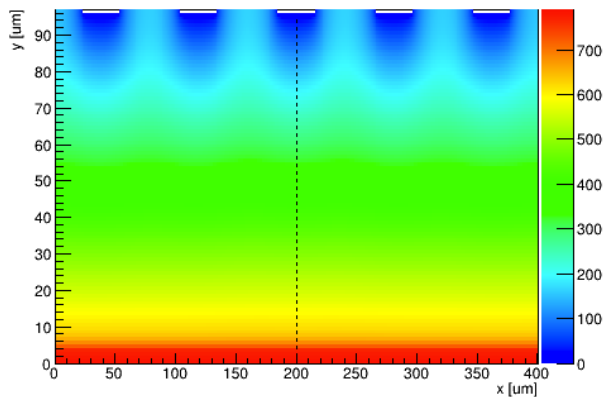
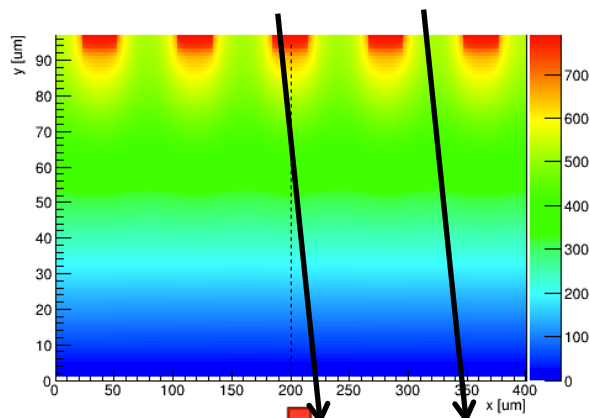
**What-to-do next:**

Planned new irradiation runs (neutrons, protons), new sensor geometries

**Use Gallium instead of Boron for gain layer** (in production now)

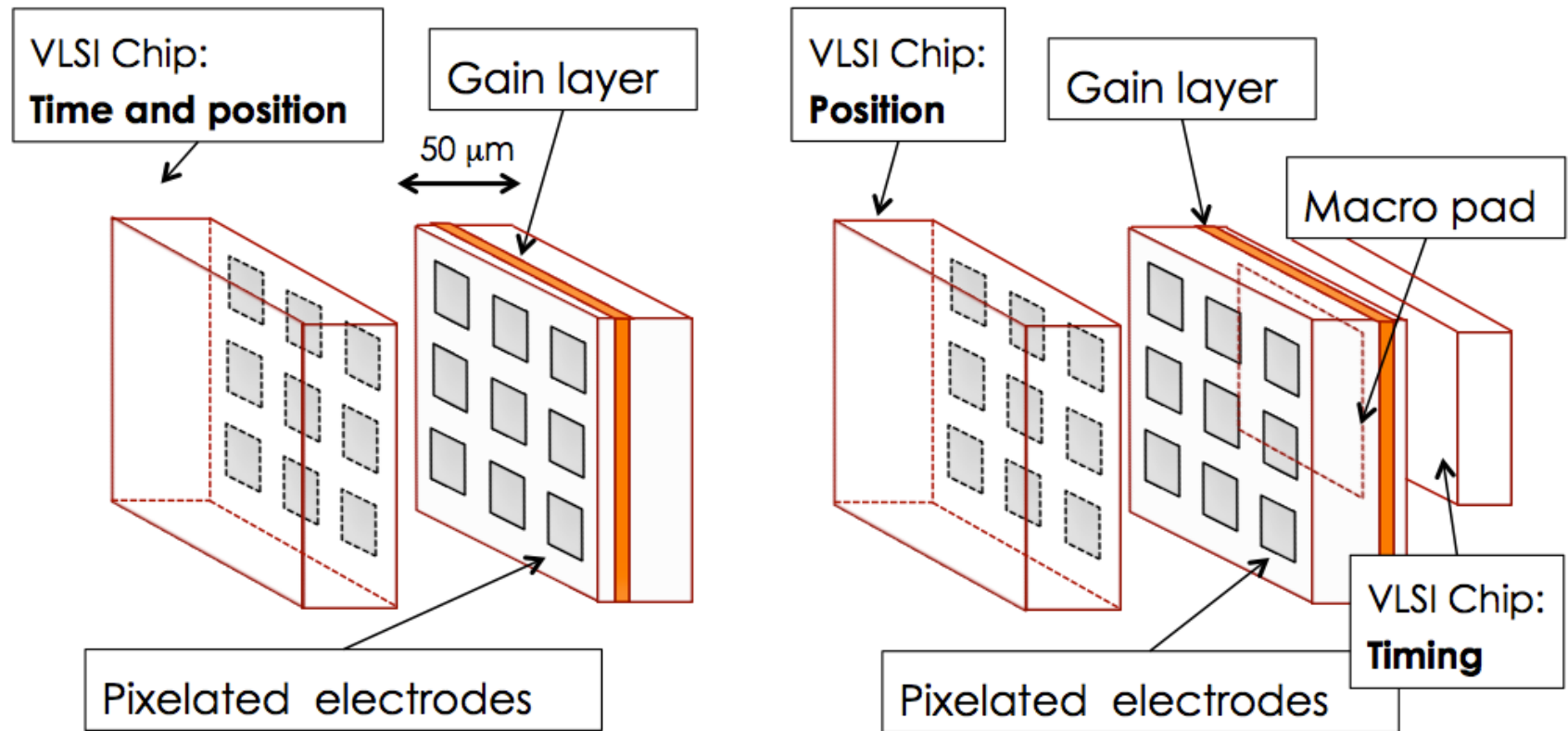
# Gain in finely segmented sensors

Segmentation makes the effect of gain more difficult to predict, and most likely very dependent on the hit position



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

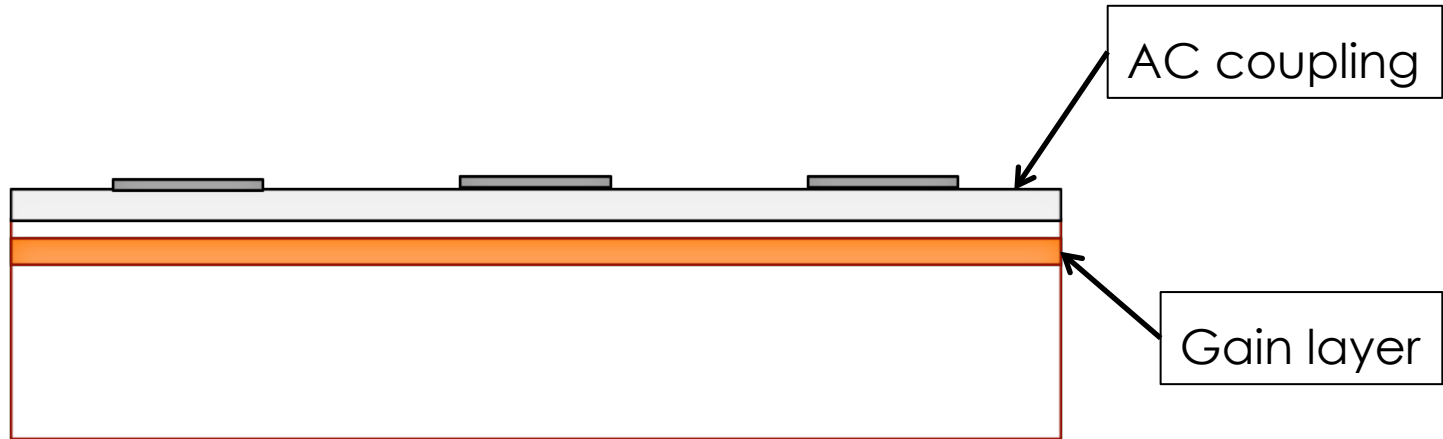
# Splitting gain and position measurements



The ultimate time resolution will be obtained with a custom ASIC. However we might split the position and the time measurements

# Using AC coupling to achieve segmentation

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

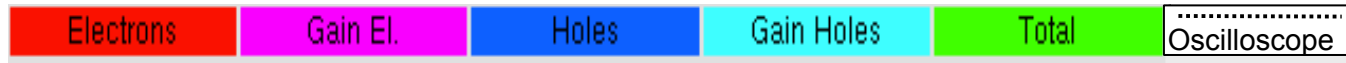
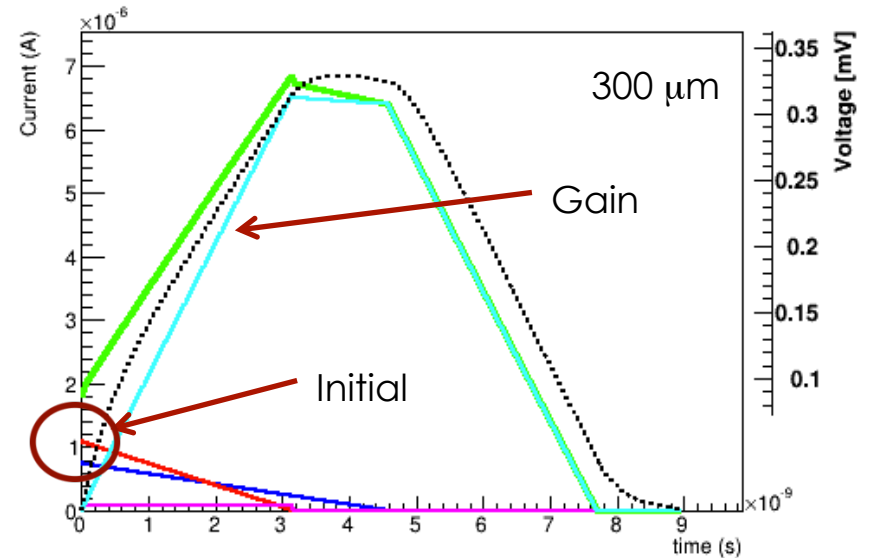
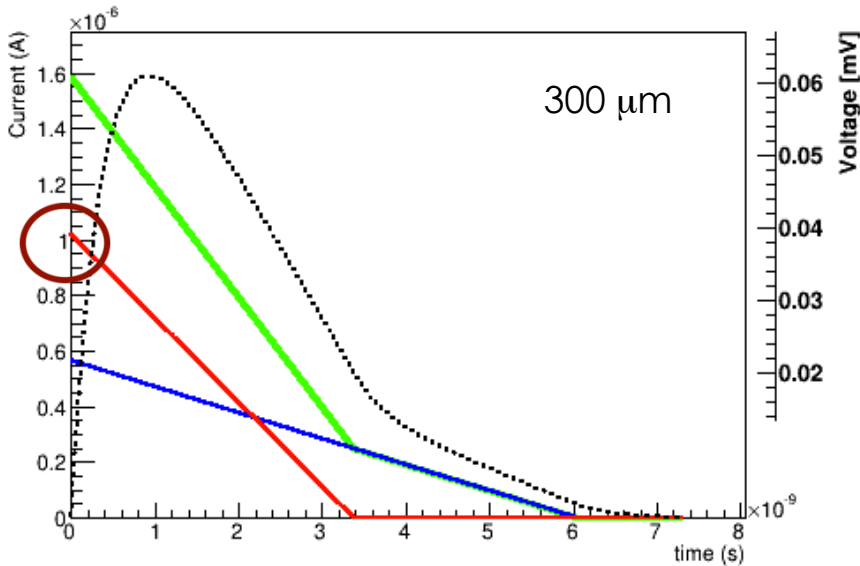
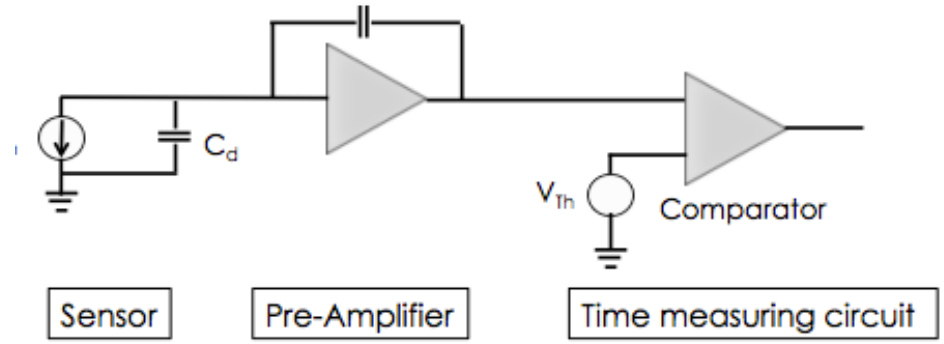


Very uniform field due to large pads,  
Segmentation due to AC coupling pick-up

# Electronics

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

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



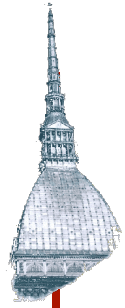
Simulated Weightfield2

**Pads with no gain**

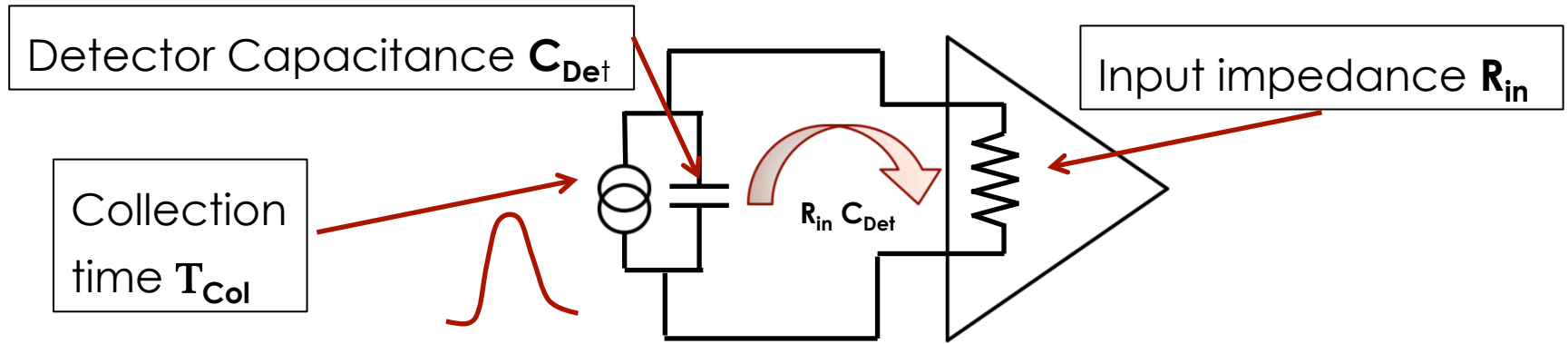
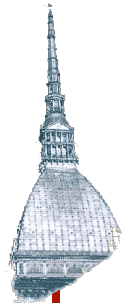
Charges generated uniquely by the incident particle

**Pads with gain**

Current due to gain holes creates a longer and higher signal

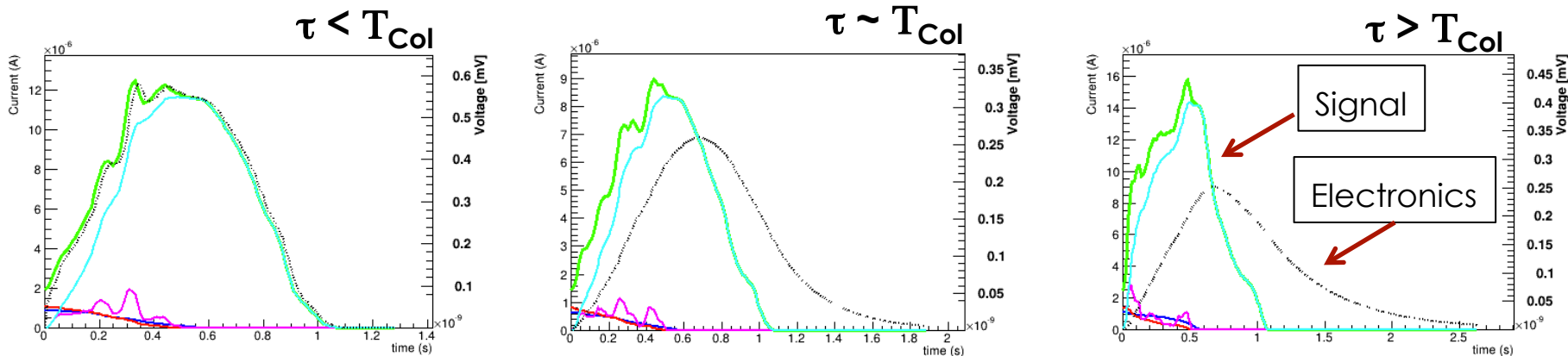


# Interplay of $T_{Col}$ and $\tau = R_{in} C_{Det}$



There are two time constants at play:

- $T_{Col}$ : the signal collection time (or equivalently the rise time)
- $\tau = R_{in} C_{Det}$ : the time needed for the charge to move to the electronics

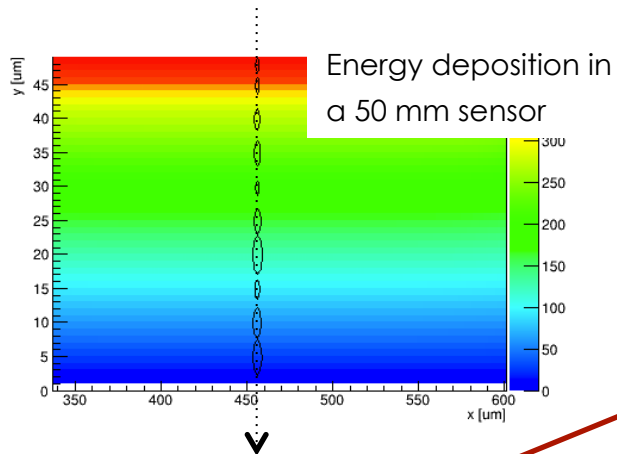
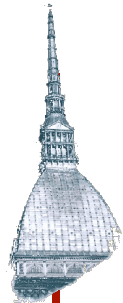


$\tau/T_{Col}$  increases  $\rightarrow$   $dV/dt$  decreases  
 $\rightarrow$  Smoother current

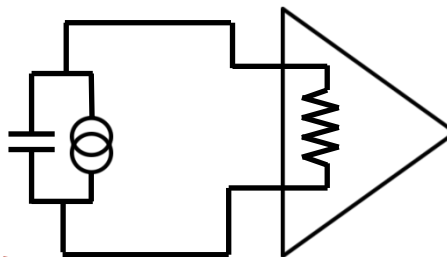
**Need to find the optimum balance**



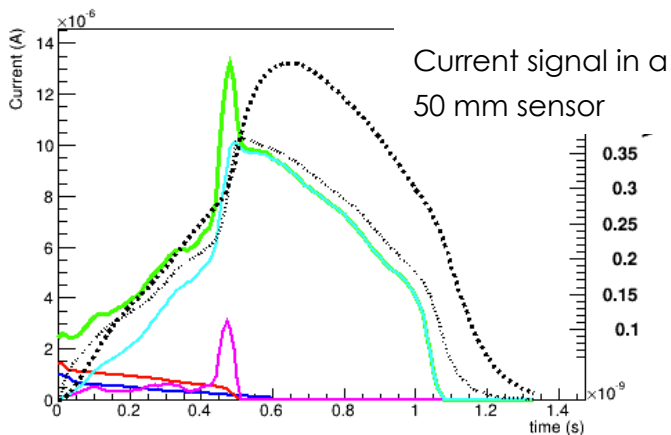
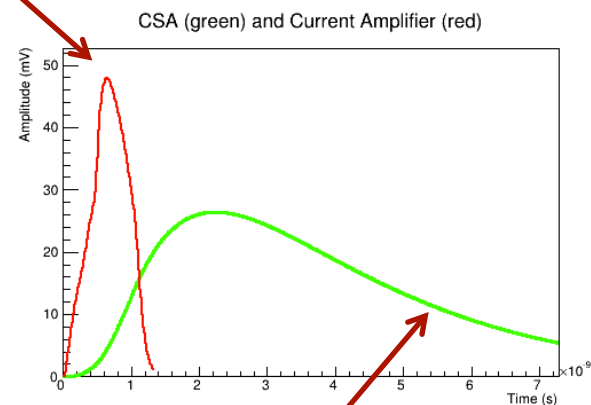
# Electronics: What is the best pre-amp choice?



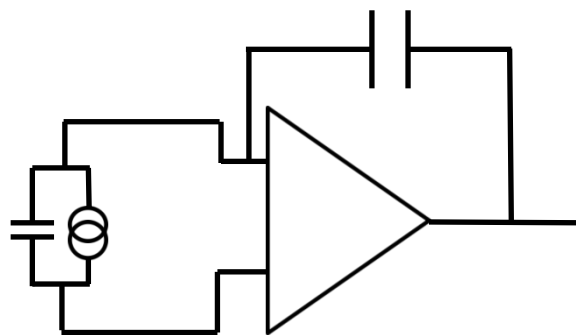
## Current Amplifier



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

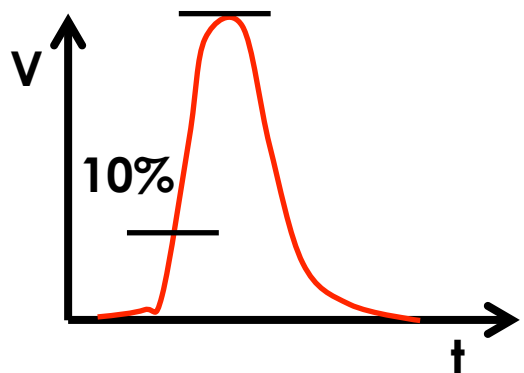


## Integrating Amplifier



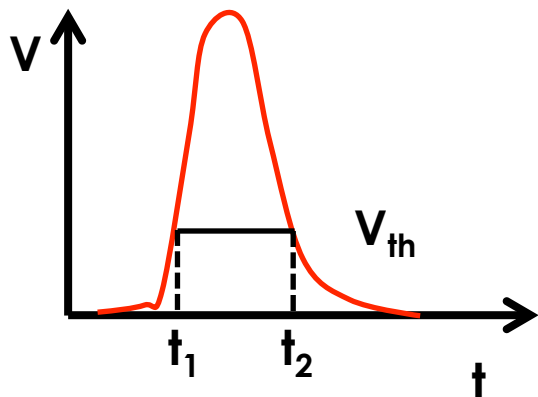
- Slower slew rate
- Quieter
- Integration helps the signal smoothing

# What is the best “time measuring” circuit?



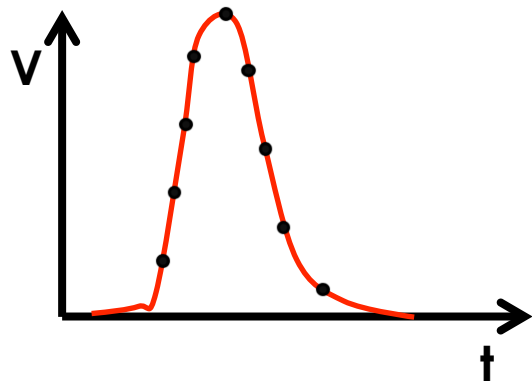
## Constant Fraction Discriminator

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

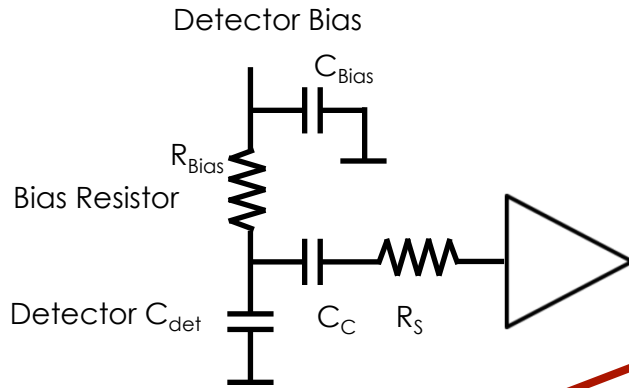


## Multiple sampling

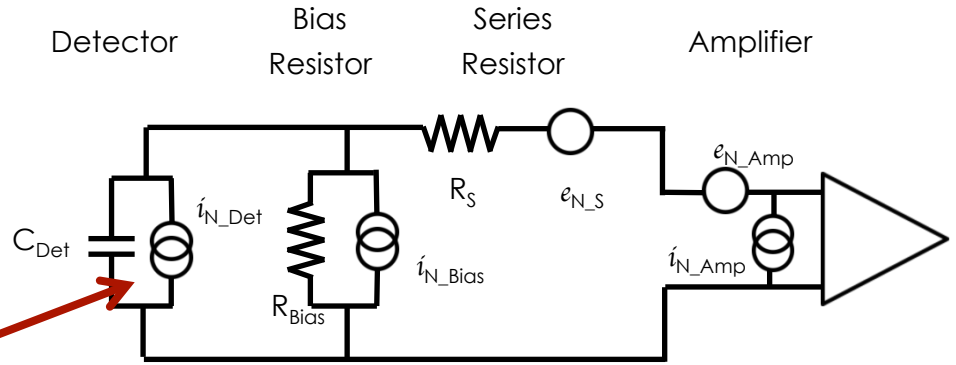
Most accurate method, needs a lot of computing power

# Noise - I

Real life



Noise Model



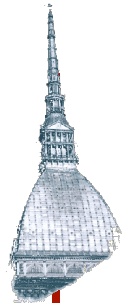
This term, the detector current shot noise, depends on the gain

$$Q_n^2 = (2eI_{Det} + \frac{4kT}{R_{Bias}} + i_{N\_Amp}^2) F T_s + (4kTR_s + e_{N\_Amp}^2) F_v \frac{C_{Det}^2}{T_s} + F_{vf} A_f C_{Det}^2$$

$2eI_{Det} * \text{Gain}$

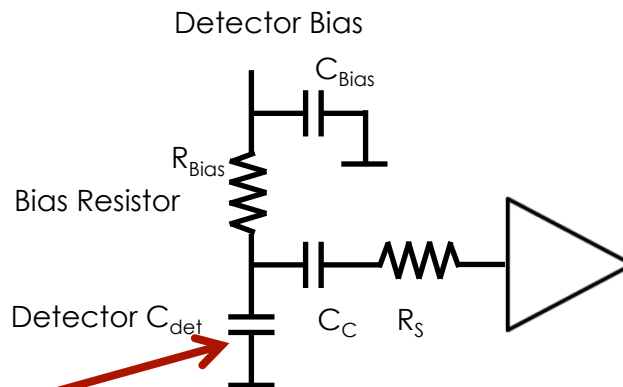
low gain!

This term dominates for short shaping time



# Noise - II

Real life



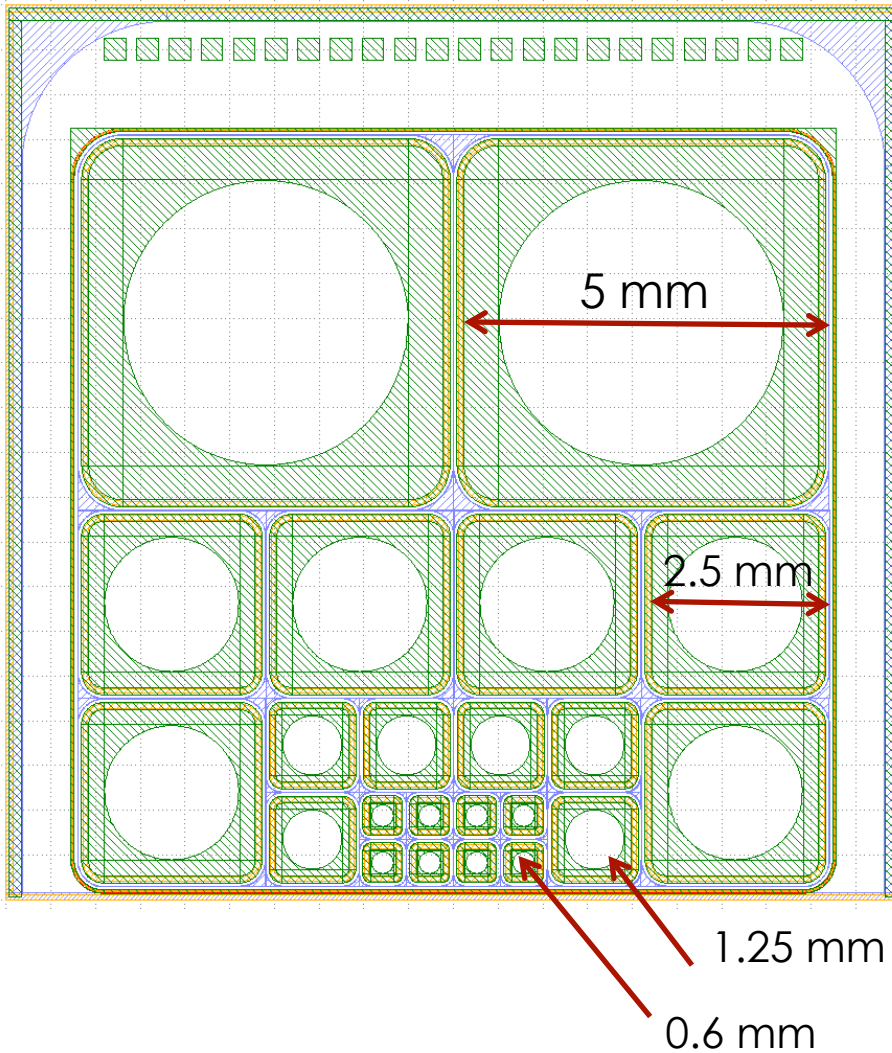
$$ENF = kG + \left(2 - \frac{1}{G}\right)(1 - k)$$

$k$  = ratio h/e gain

**NOISE DUE TO GAIN:**  
**Excess noise factor:**  
**low gain, very small  $k$**

**Low leakage current and low gain ( $\sim 10$ ) together with short shaping time are necessary to keep the noise down.**

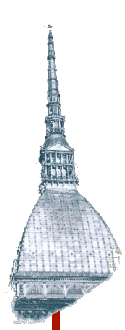
# Next CNM productions



These new productions will allow a detailed exploration of the UFSD timing capabilities, including border effects between pads, and distance from the sensor edge.

## Timescale:

- **Spring 2015:** 200 micron
- **Summer 2015:** 100 micron
- **Summer 2015:** 50 micron



# Next Steps

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1. Wafer Production  
**200 micron** thick sensors by **Spring-2015**  
**100 and 50 micron** thick sensors by **Summer 2015**.
2. Production of UFSD doped with Gallium instead of Boron.
3. Study of reversed-UFSD started for the production of pixelated UFSD sensors (FBK, Trento).
4. UFSD are included in the CMS TDR CT-PPS as a solution for forward proton tagging
5. Use of UFSD in beam monitoring for hadron beam. INFN patent and work on-going
6. Interest in UFSD for 4D tracking at high luminosity
7. Testbeam analyses just started. Results coming soon...

# UFSD – Summary

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## **We are just starting to understand the timing capability of UFSD**

- Low-gain avalanche diodes (LGAD) offer silicon sensors with an enhanced signal amplitude: UFSD are LGAD detectors optimized for timing resolution.
- Several options under studies to obtain concurrently excellent space and time resolutions.
- We developed a program, **Weightfield2** to simulate the behaviors of LGAD and optimized them for fast timing (available at <http://personalpages.to.infn.it/~cartigli/Weightfield2.0/>)

Timescale: 1 year to asses UFSD timing capabilities

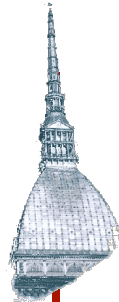






# Additional references

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Several talks at the 22<sup>nd</sup>, 23<sup>rd</sup> and 24<sup>th</sup> RD50 Workshops:

23<sup>rd</sup> RD50: <https://indico.cern.ch/event/265941/other-view?view=standard>

22<sup>nd</sup> RD50: [http://panda.unm.edu/RD50\\_Workshop/](http://panda.unm.edu/RD50_Workshop/)

9<sup>th</sup> Trento Workshop, Genova, Feb 2014.

F. Cenna “**Simulation of Ultra-Fast Silicon Detectors**”

N. Cartiglia “**Timing capabilities of Ultra-Fast Silicon Detector**”

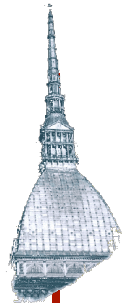
Papers:

[1] N. Cartiglia, Ultra-Fast Silicon Detector, 13th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD13), 2014 JINST 9 C02001, <http://arxiv.org/abs/1312.1080>

[2] H.F.-W. Sadrozinski, N. Cartiglia et al., Sensors for ultra-fast silicon detectors, Proceedings "Hiroshima" Symposium HSTD9, DOI: 10.1016/j.nima.2014.05.006 (2014).

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## Backup



# The "Low-Gain Avalanche Detector" project

Is it possible to manufacture a silicon detector that looks like a normal pixel or strip sensor, but with a much larger signal (RD50)?

- 730 e/h pair per micron instead of 73 e/h
- Finely segmented
- Radiation hard
- No dead time
- Very low noise (low shot noise)
- No cross talk

### Low-Gain Avalanche Detectors (LGAD)

S. Ely, V. Fairley, Z. Dattaway, H. Grates, Z. Liang, C. Parker, K. F.W. Sadrizinski (Senior Member), T. Sai, A. Seiden, A. Stone, A. Zaitsevskiy, SCIPP, UC Santa Cruz, USA  
 M. Szelega, P. Fernández-Martínez, D. Flores, V. Greco, S. Hidalgo, G. Pellegrini, D. Quinn, IMBICM-CBIC, Barcelona, Spain  
 C. Cavallari, S. González, J. Longo, J. López-Pascual, Barcelona, Spain  
 M. Fernández García, J. González Sánchez, N. Jovanović Echeverría, I. Vila, IFCA (CSIC-UC), Switzerland, Spain  
 P. Figini, G. Galluzzi, M. Mühl, H. Neugebauer, CERN, Switzerland  
 G. Kramberger, V. Conzo, I. Mandić, M. Mair, M. Završnik, Institut Jozef Stefan, Ljubljana, Slovenia  
 N. Cartiglia, F. Cirrera, A. Picozzi, F. Ravera, INFN Torino, Italy  
 G.-F. Dalla Bernardina (Senior Member), L. Fanfani, University of Trento and INFN-INFN, Italy  
 M. Passadore, G. Zanone, C. Zucchetti, INFN, Trento, Italy

<h4>Introduction and Motivation</h4> <p>Relevant for the wide spread use of Silicon Detectors in HEP, Astrophysics, Medicine</p> <ul style="list-style-type: none"> <li>• Population demand</li> <li>• Good efficiency, Signal to Noise SN</li> <li>• High radiation sensitivity (up to 10<sup>16</sup> protons/cm<sup>2</sup>)</li> <li>• High resolution (in the calculation of drift velocity)</li> <li>• Superior Silicon Detectors performance by increasing the SN with internal gain</li> </ul> <p><b>Potential applications:</b></p> <ul style="list-style-type: none"> <li>• Low Gain Silicon Detectors (LGAD)</li> <li>• Fast sensors for Time of Flight TSP</li> <li>• Radiation-resistant sensors</li> </ul>	<h4>Low-Gain Avalanche Detectors (LGADs)</h4> <p>LGADs exploit avalanche phenomenon of reverse biased p-n junction</p> <p>Internal gain ~100 is optimized for high line rate collection, reduced leakage, low noise</p> <p><b>Electrical Characterization</b></p> <p>On a few series, inhomogeneous regions are observed with TEC, noise, full depletion, and leakage current dependence of the multiplication factor</p> <p><b>Inhomogeneity &amp; Instability (Run 7082)</b></p> <p>On a few series, inhomogeneous regions are observed with TEC, noise, full depletion, and leakage current dependence of the multiplication factor</p> <p>Stability at high bias voltages visible in OC, V<sub>OC</sub>, I<sub>OC</sub> vs V<sub>OC</sub> for different series</p>	<h4>LGAD Design</h4> <p>Central area (gain region, multiplication layer) contains electric field, sufficient high to activate mechanism of space-charge multiplication</p> <p><b>Applied Edge Termination</b></p> <p>Lightly doped N-type deep diffusion (LTD) and addition of a field stop</p> <p>Allows high electric field in the central region above breakdown voltage V<sub>BD</sub> (up to V<sub>OC</sub> (doped))</p> <p><b>Polysilicon</b></p> <p>Polysilicon counteracts inversion and sets off current gain</p> <p>Based guard ring around the detection region connects the surface component of the current</p>	<h4>Three critical regions of the LGAD design</h4> <p>Central area (gain region, multiplication layer) contains electric field, sufficient high to activate mechanism of space-charge multiplication</p> <p><b>Applied Edge Termination</b></p> <p>Lightly doped N-type deep diffusion (LTD) and addition of a field stop</p> <p>Allows high electric field in the central region above breakdown voltage V<sub>BD</sub> (up to V<sub>OC</sub> (doped))</p> <p><b>Polysilicon</b></p> <p>Polysilicon counteracts inversion and sets off current gain</p> <p>Based guard ring around the detection region connects the surface component of the current</p>
<h4>Fabrication of LGADs at CNM</h4> <p>1.2 μm pitch</p> <p>1.2 μm pitch</p> <p>1.2 μm pitch</p> <p>1.2 μm pitch</p>	<h4>Electrical Characterization</h4> <p>Current - Voltage (IV)</p> <p>Breakdown Voltage ~ 1100V</p> <p>Gain vs. Voltage</p> <p>Gain vs. Voltage</p> <p>Gain vs. Voltage</p>	<h4>Optimization of the Gain Region</h4> <p>Doping profile of the P-type multiplication layer determines both Gain and Breakdown</p> <p>Higher Boron Doping → Higher Gain</p> <p>Higher Boron Doping → Higher Gain</p>	<h4>Gain Sensitivity to Boron Doping: β MIP's</h4> <p>Boron implant dose is varied from water to water (Run 8074)</p> <p>Gain vs. Boron Doping</p> <p>Gain vs. Boron Doping</p>
<h4>Gain Testing of LGAD's</h4> <p>Direct measurement of signal gain agreement</p> <p>Gain vs. Voltage</p> <p>Gain vs. Voltage</p>	<h4>Gain in thin LGAD</h4> <p>Gain in 10 μm 100 nm deep LGAD (8072)</p> <p>Gain vs. Voltage</p> <p>Gain vs. Voltage</p>	<h4>Segmented LGADs</h4> <p>300 μm FZ (8072) low p-doped pixels</p> <p>Gain vs. Voltage</p> <p>Gain vs. Voltage</p>	<h4>Segmented LGAD R&amp;D</h4> <p>Gain of LGAD pad detectors is well-developed</p> <p>Gain vs. Voltage</p> <p>Gain vs. Voltage</p>
<h4>Mitigation of Radiation Damage</h4> <p>Large fraction of radiation damage LGADs has seen</p> <p>Damage to the gain region is observed as increase of leakage current and depletion voltage</p> <p>Damage to the multiplication layer</p> <p>Damage to the Base layer in the multiplication layer</p>	<h4>Conclusions</h4> <p>LGADs show uniform gain for pads across series with same p-doping</p> <p>Mitigation of radiation damage planned in 2024</p> <p>This technology, fast timing, proposed for LGAD for segmented LGAD</p>	<h4>Time Resolution</h4> <p>Time resolution is very sensitive to the detector</p> <p>Time resolution is very sensitive to the detector</p> <p>Time resolution is very sensitive to the detector</p>	<h4>Acknowledgments</h4> <p>Part of this work has been performed in the framework of the INFN INFN-UBD project</p> <p>Part of this work has been performed in the framework of the INFN INFN-UBD project</p>



# How can we progress? Need simulation

We developed a full simulation program to optimize the sensor design, WeightField2, (<http://cern.ch/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

Weightfield2: a fast simulator for silicon and diamond detectors

N. Cartiglia<sup>1</sup>, F. Cenna<sup>1</sup>, M. Friedl<sup>2</sup>, B. Kolbinger<sup>3</sup>, A. Seiden<sup>3</sup>, H.F.W. Sadrozinski<sup>4</sup>, Andriy Zatskerlyany<sup>5</sup>, Anton Zatskerlyany<sup>5</sup>  
<sup>1</sup>INFN Torino, <sup>2</sup>INFN Genova, <sup>3</sup>University of California, Santa Cruz, <sup>4</sup>INFN Padua, <sup>5</sup>INFN Trieste  
 Contact: cartiglia@to.infn.it Poster N11-8

<p><b>Goal</b></p> <p>The aim of this project is to create a fast simulator of the signal generated by an impinging particle in silicon and diamond detectors. The program should be fast, and easy to use and it should provide an accurate assessment of the detector response.</p>	<p><b>Methods</b></p> <p>The program is written in C++ and uses the HEP programs ROOT and GEANT4. It computes the electric and weighting fields for any given geometry and it uses Ramo's theorem to calculate the induced output current signal.</p>	<p><b>Findings</b></p> <p>WF2 is able to compute the detector response for a variety of impinging particles and sensor geometries. Its predictions have been validated using laboratory measurements, testbeam data, and TCAD simulations obtaining very good agreements.</p>
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**The Weightfield2 Graphical User Interface**

**Results**

**References**

[1] ...

[2] ...

**Acknowledgements**

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[2] ...

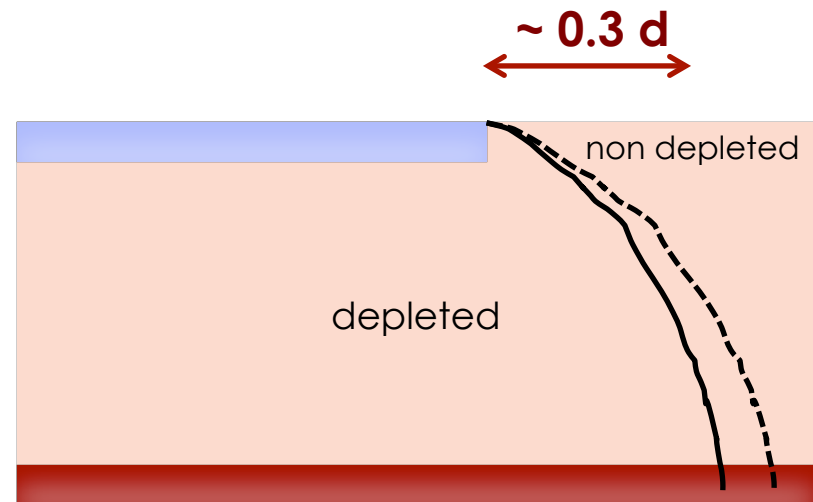
# Sensor thickness and slim edge

**Rule:** when the depletion volume reaches the edge, you have electrical breakdown.

It's customary to assume that the field extends on the side by  $\sim 1/3$  of the thickness.

**edge =  $k \cdot$  thickness**

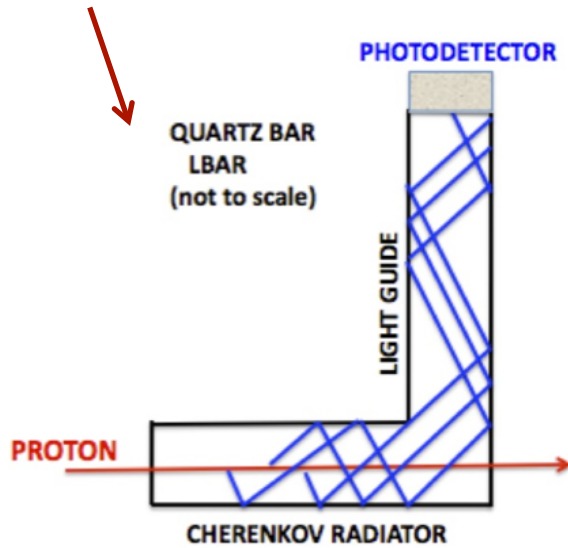
- $k = 1$  very safe
- $k = 0.5$  quite safe
- $K = 0.3$  limit



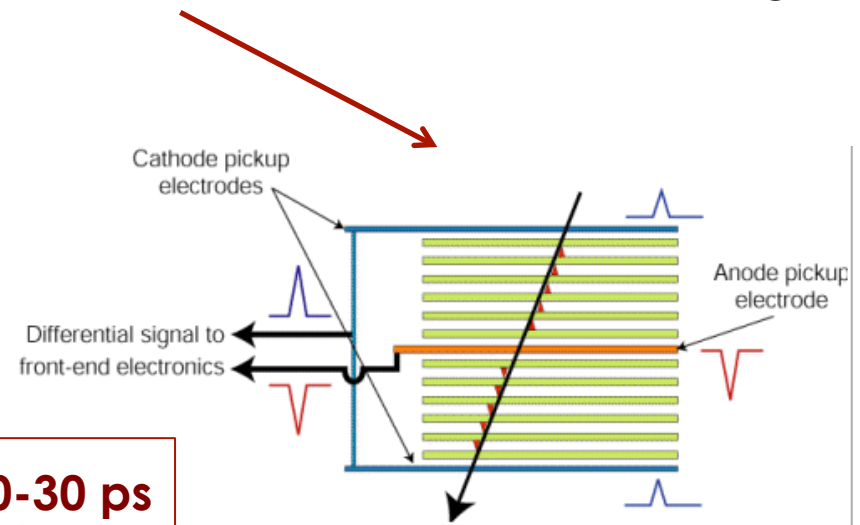
**By construction, thin detectors ( $\sim 100$  micron) might have therefore slim edge**

# State-of-the-art Timing Detectors

Timing detectors exploit very fast physics processes such as **Cherenkov light** emission or **electronic avalanches** to create prompt signals



**CMS/ATLAS**



**ALICE**

$\sigma_t \sim 20-30 \text{ ps}$   
 $\sigma_x \sim 1-2 \text{ mm}$

- These detectors measure time very accurately but locate particles with the precision of  $\sim 1 \text{ mm}$
- Good timing is obtain by using a gain mechanism, either in the detector or in the electronics

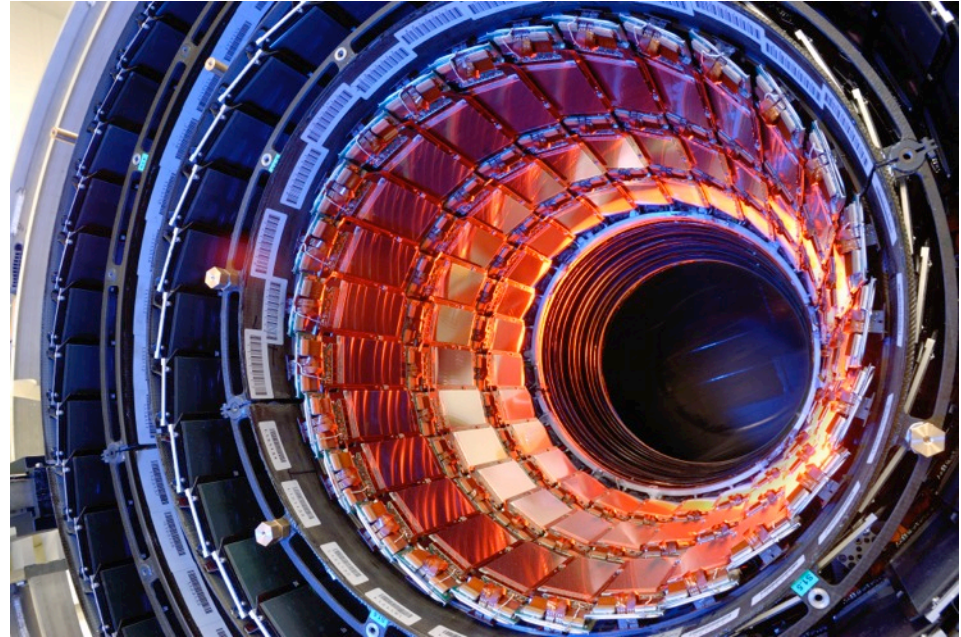


# State-of-the-art Position Detectors

Extremely good position detectors are currently in use in every major high energy physics experiment:

- Millions of channels
- Very reliable
- Very radiation hard

The timing capability is however limited to  $\sim 100\text{-}150$  ps (NA62 @CERN)



$$\sigma_t \sim 100\text{-}150 \text{ ps}$$

$$\sigma_x \sim 20\text{-}30 \text{ } \mu\text{m}$$