Tracking in 4-Dimension

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

Can we provide in one detector, or in combination

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

erc UFSD

The effect of timing information

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

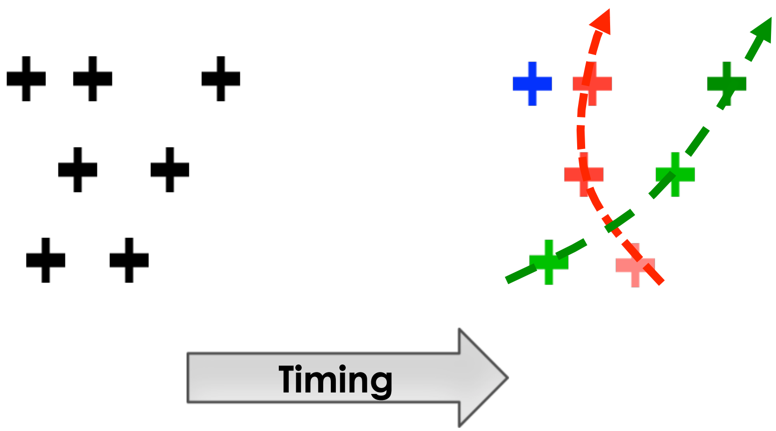
Timing can be available at different levels of the event reconstruction.

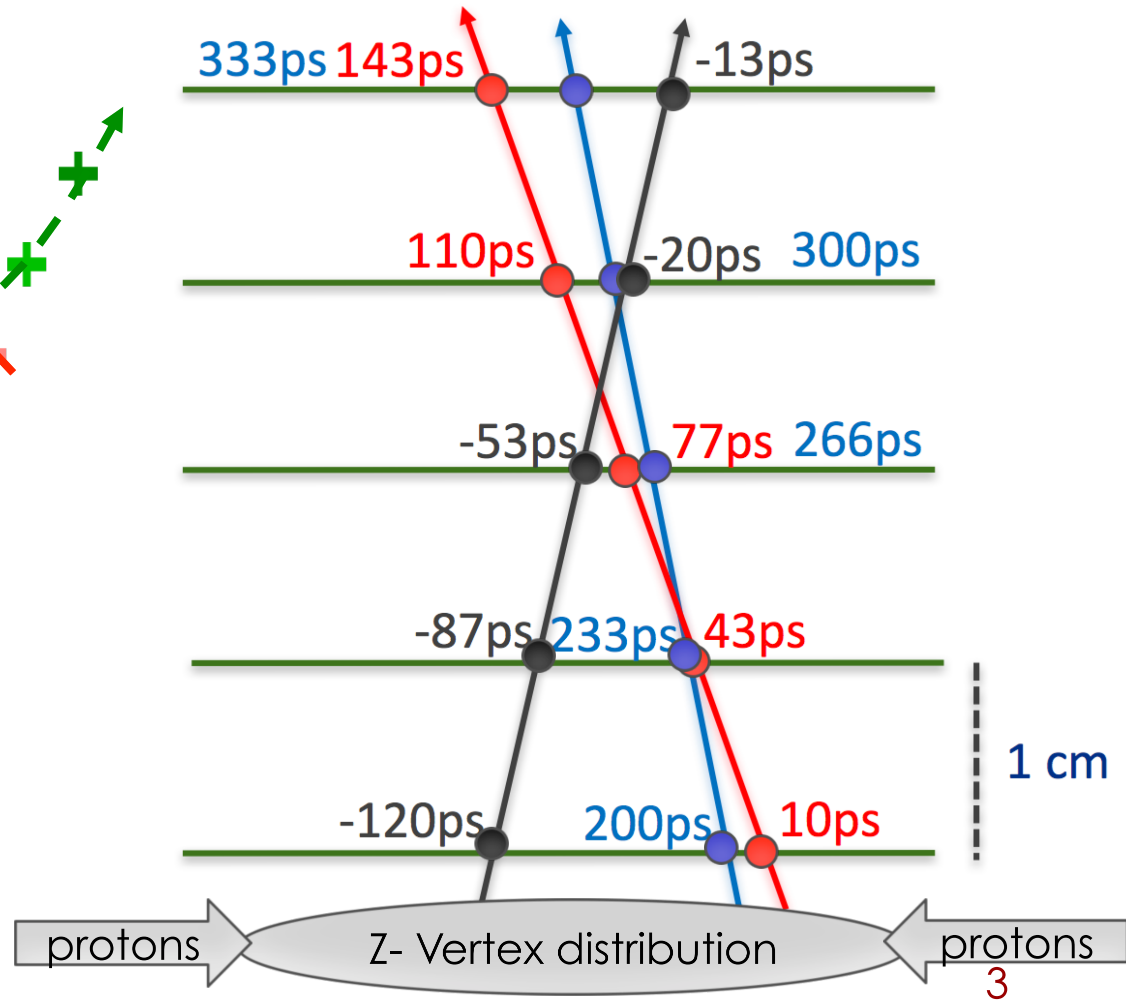
1) Timing at each point along the track
2) Timing in the event reconstruction
3) Timing at the trigger level

Timing at each point along the track

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

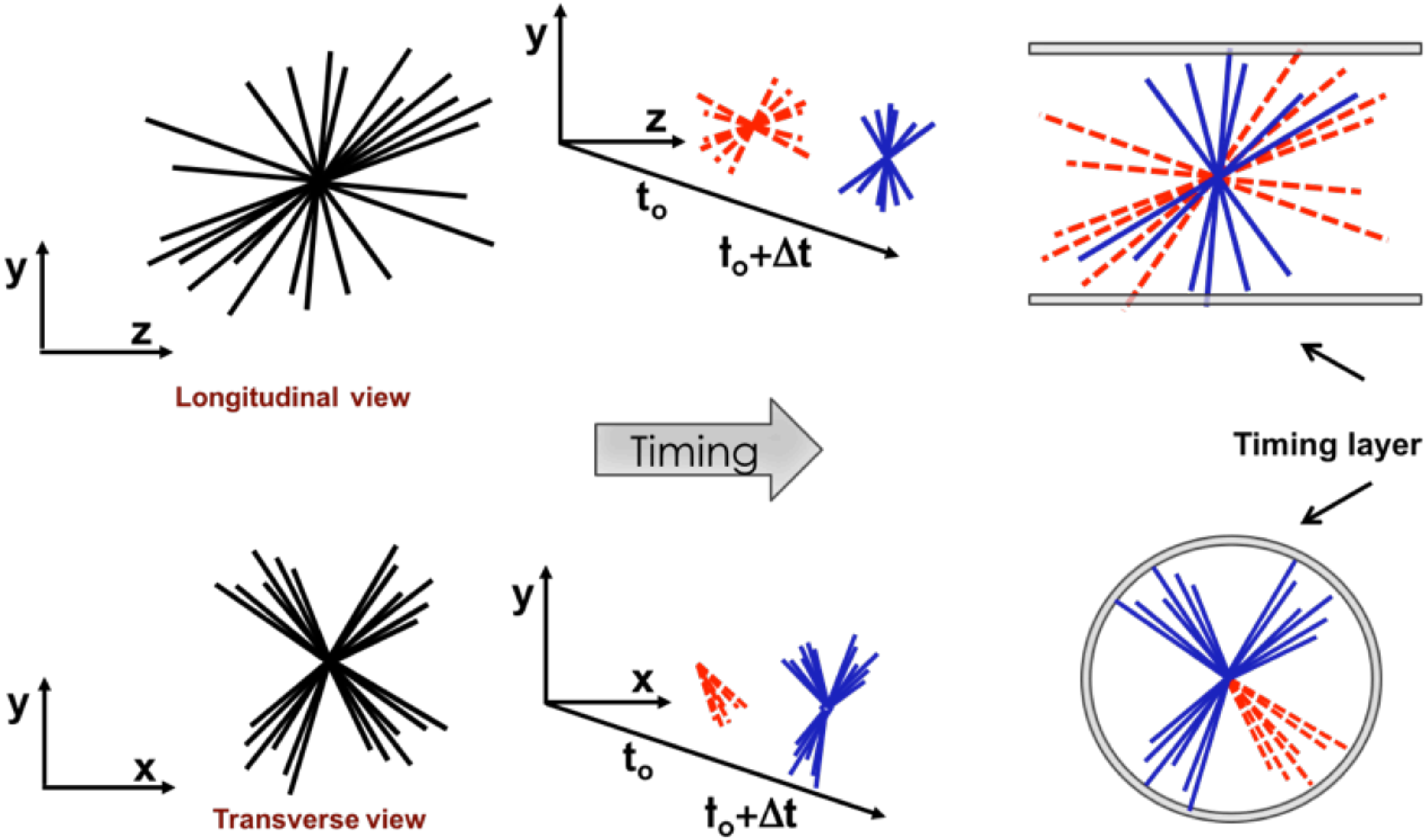
➔ Use only "time compatible points"





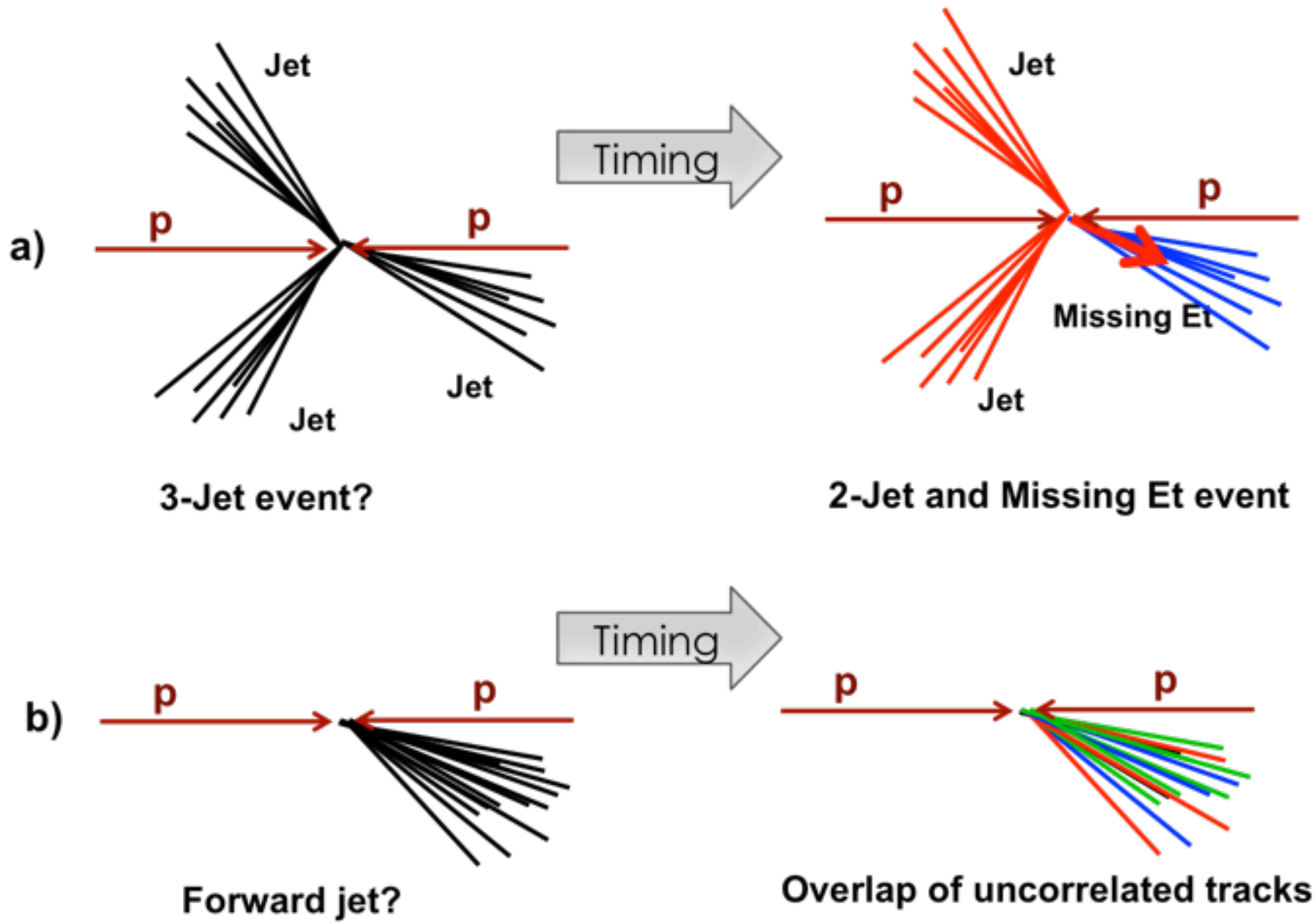
Timing in the event reconstruction

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



Timing in the trigger

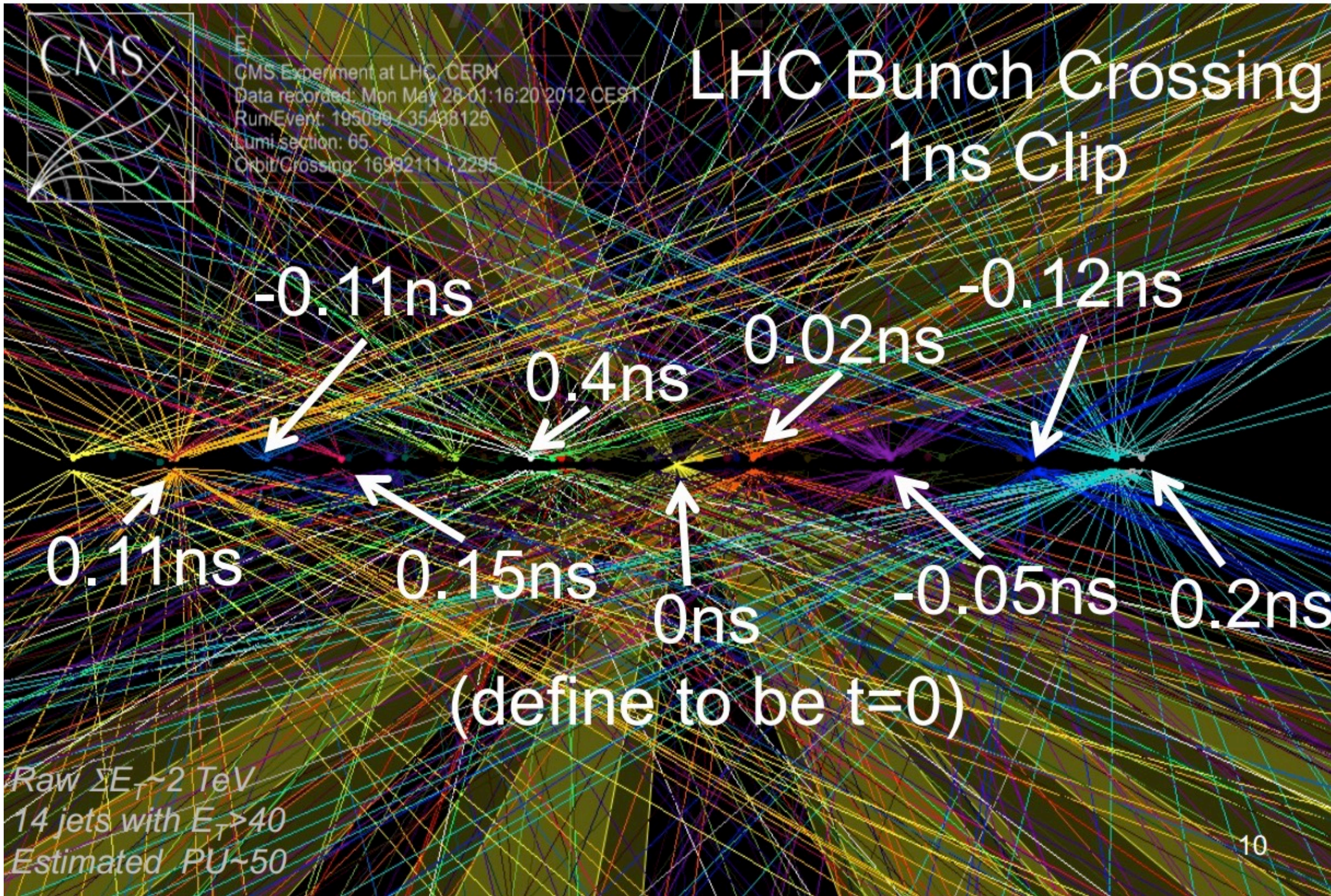
Timing at the trigger decision: it allows reducing the trigger rate, rejecting topologies that look similar, but they are actually different.



Vertexes in space and time

CMS Current situation, pile-up ~ 50:

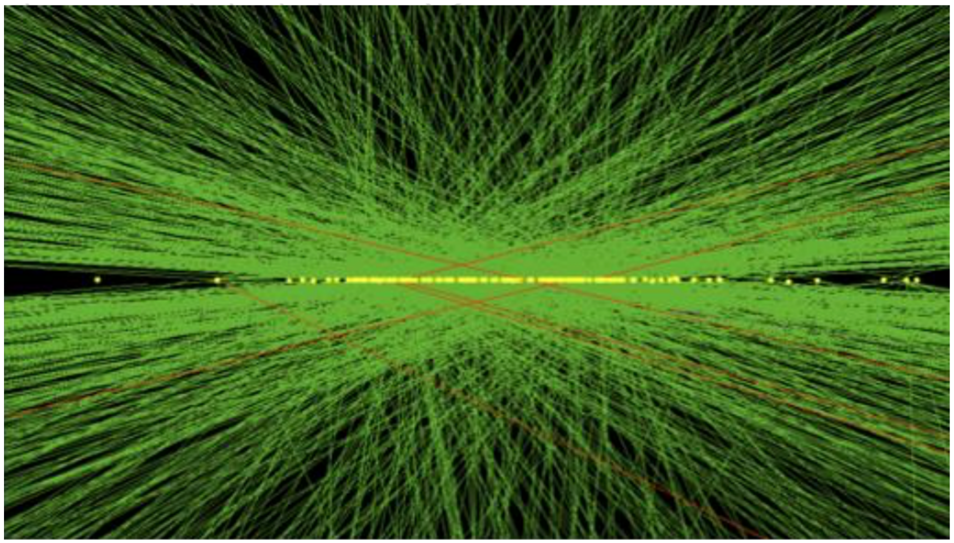
Vertexes do not overlap in space ➔ tracking resolves the vertexes

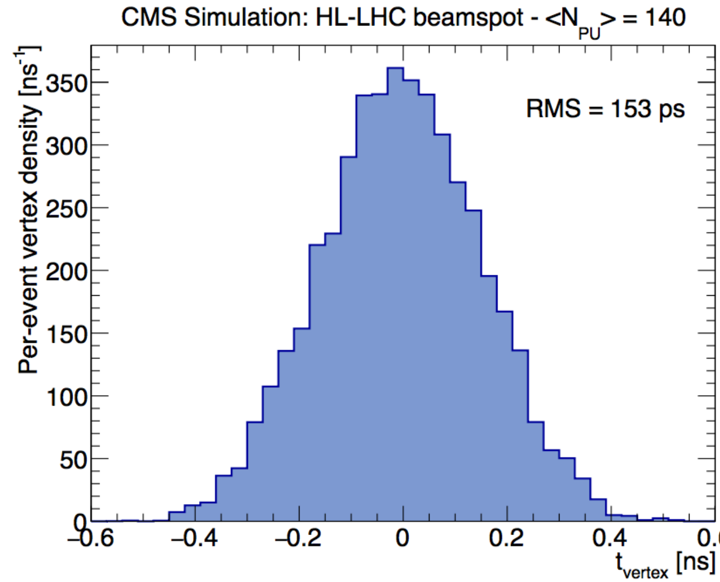


Vertexes in space and time

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

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



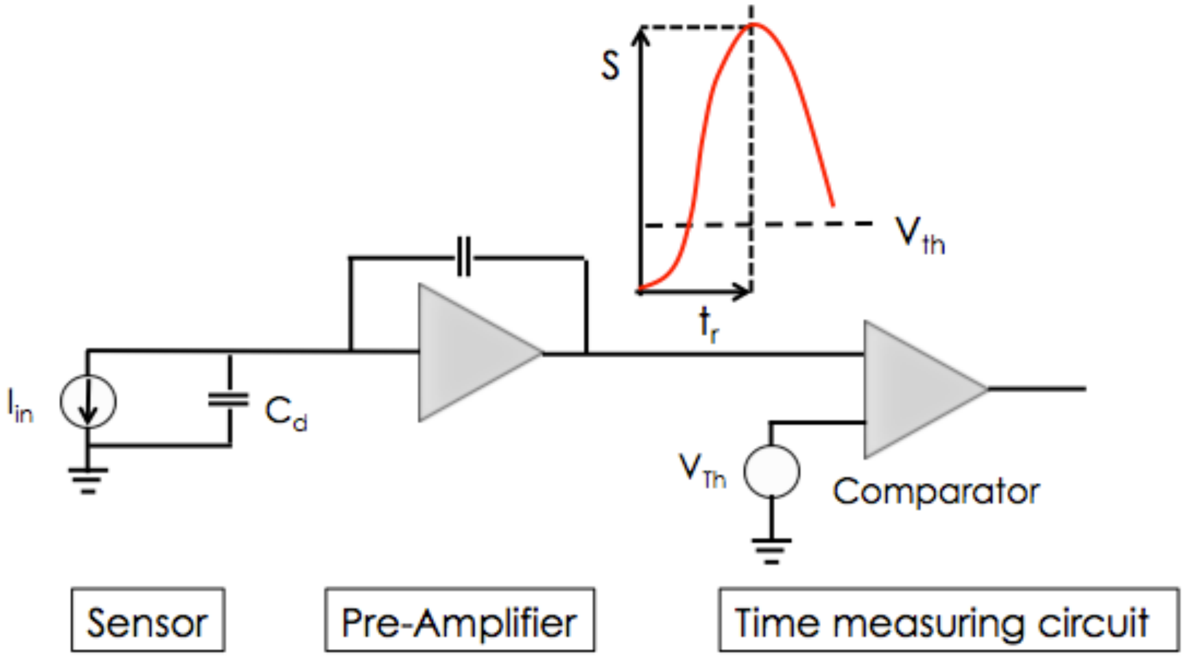


There are between 15-20% of tracking vertexes (longitudinal resolution ~ 200 micron) that are actually composed by 2 or more interactions

➔ Loss of events ➔ loss of luminosity

Silicon time-tagging detector

(a simplified view)



Time is set when the signal crosses the comparator threshold

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

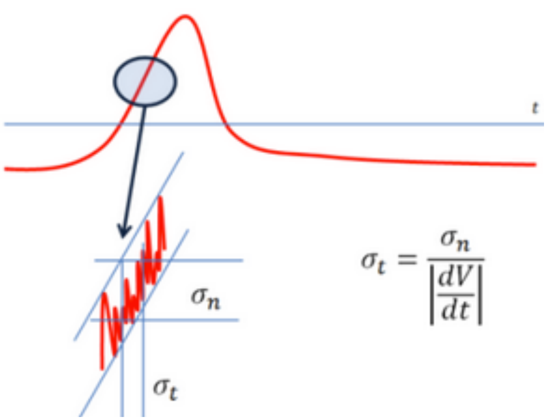
Strong interplay between sensor and electronics

Time resolution

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

Usual "Jitter" term

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

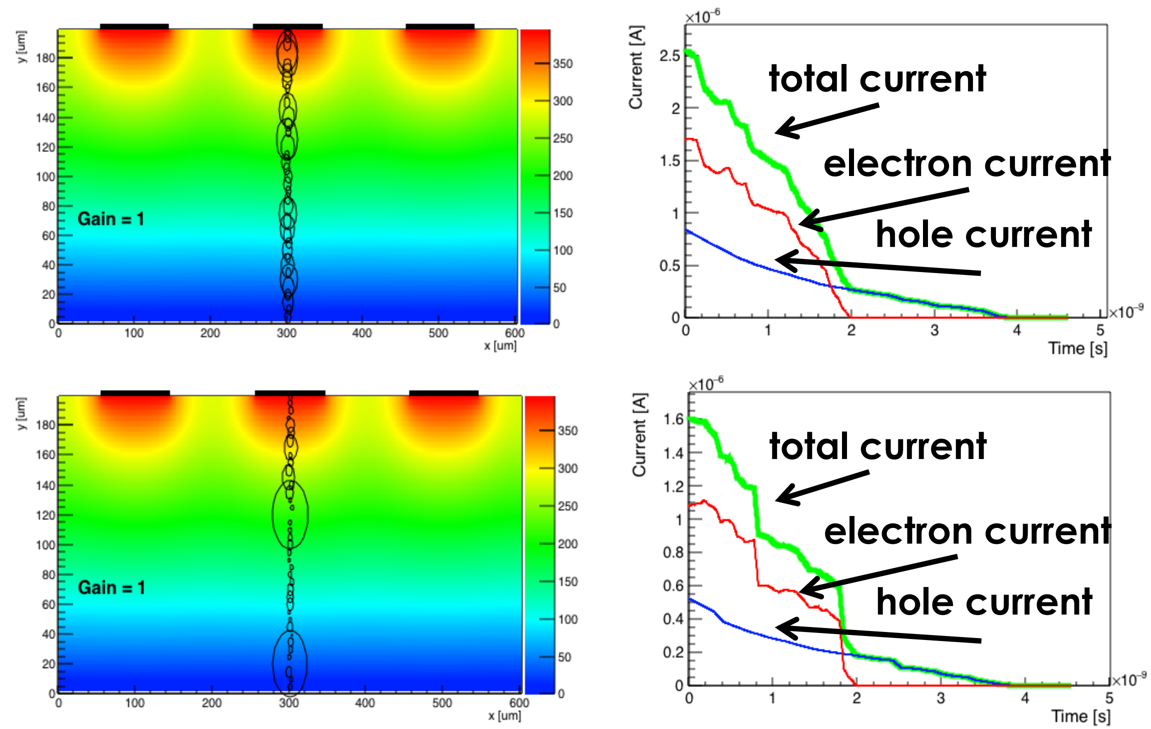


$$\sigma_t = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|}$$

Need large dV/dt

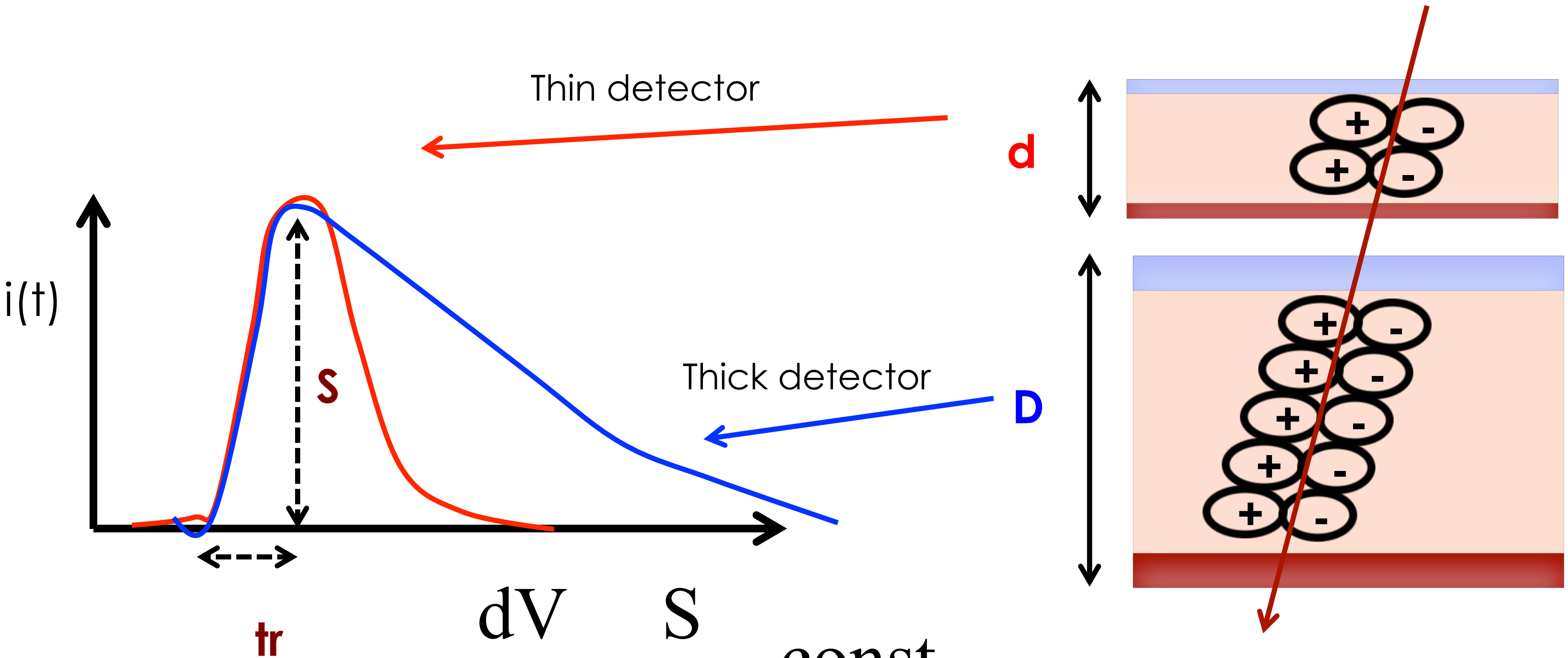
Time walk: Amplitude variation, corrected in electronics

Shape variations: non homogeneous energy



dV/dt in Thin and Thick silicon 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

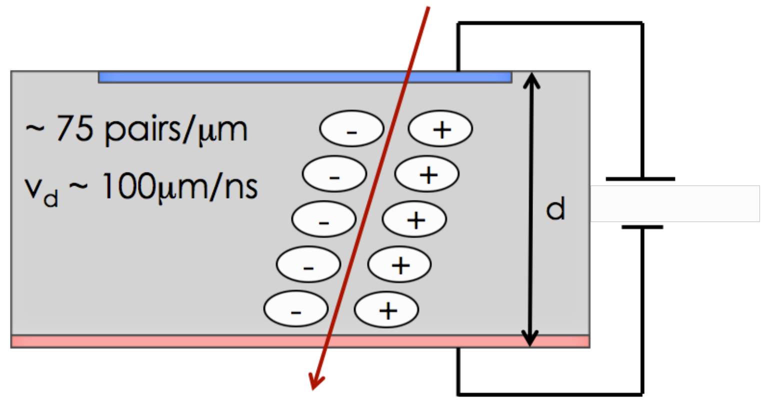
Best result : NA62, 150 ps on a 300 x 300 micron pixels

How can we do better?

➔ Add internal gain

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

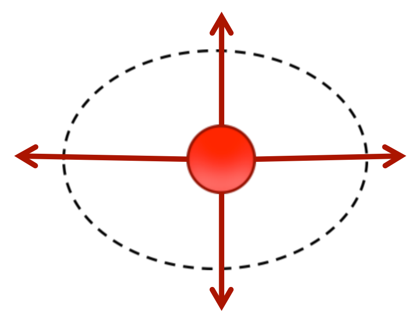
1) Use external bias: assuming a 50 micron silicon detector, we need $\mathbf{V_{bias} = \sim 600 - 700\ kV}$



Difficult to achieve

2) Use Gauss Theorem:

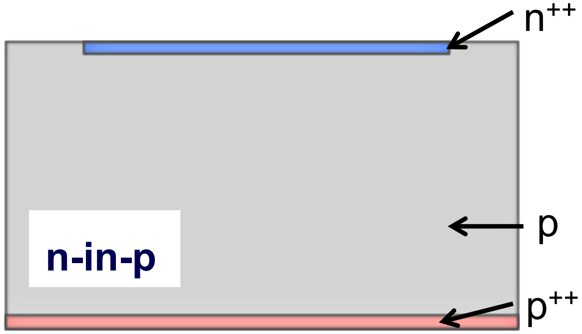
$$\sum q = 2\pi r * E$$



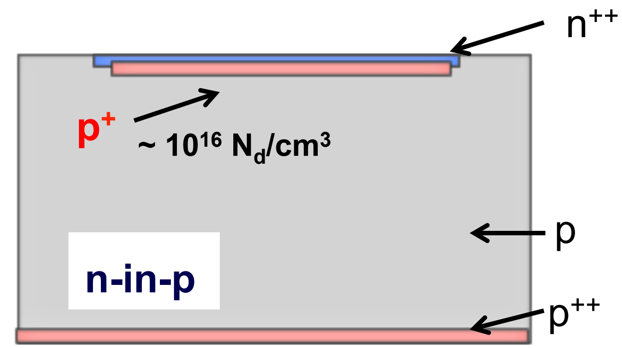
E = 300 kV/cm ➔ q ~ 10^{16} /cm^3

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

LGAD - Ultra-Fast Silicon Detector



Traditional silicon detector

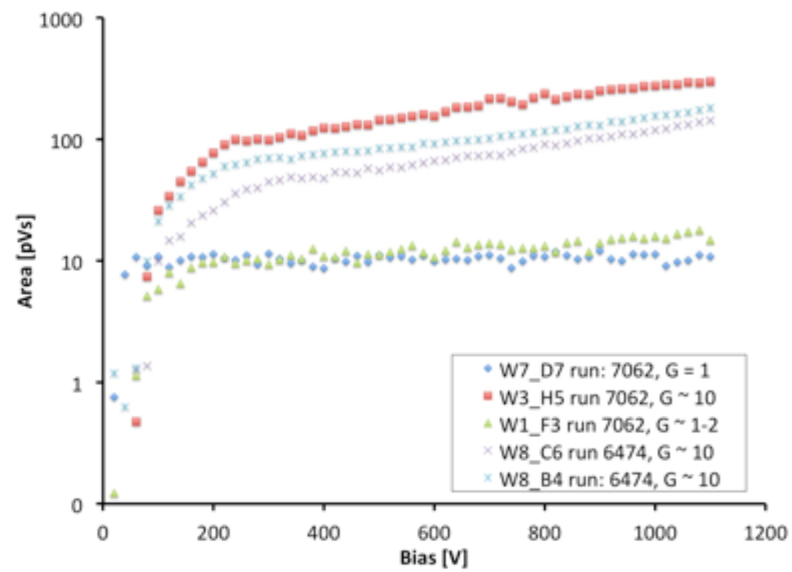


Low gain avalanche detectors

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.

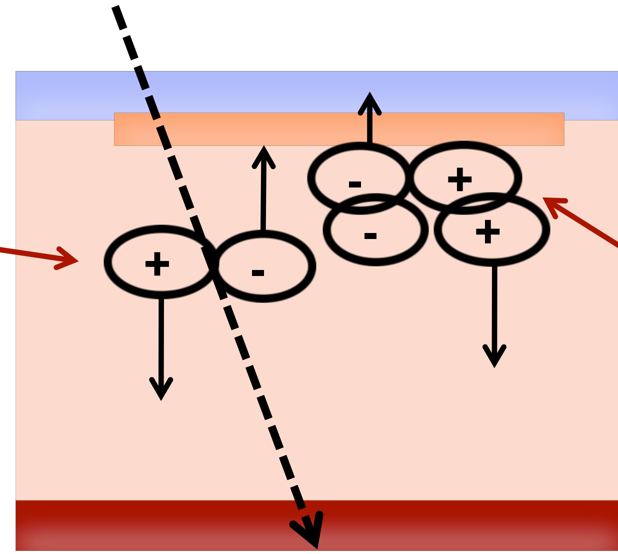
Gain changes very smoothly with bias voltage.

Easy to set the value of gain requested.

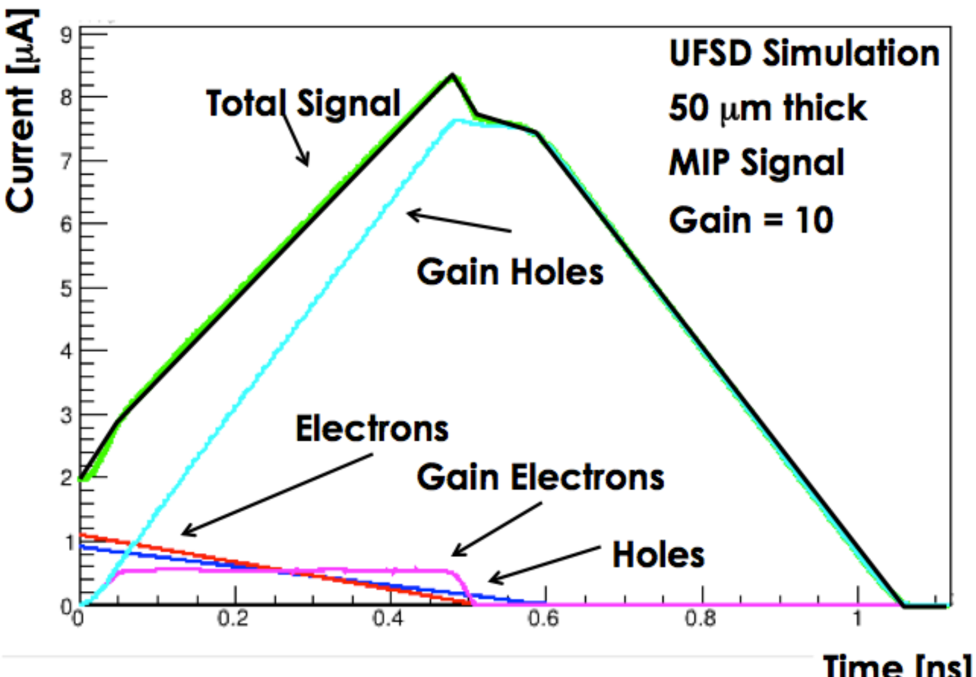


How gain shapes the signal

Initial electron, holes



Gain electron: absorbed immediately
Gain holes: long drift home

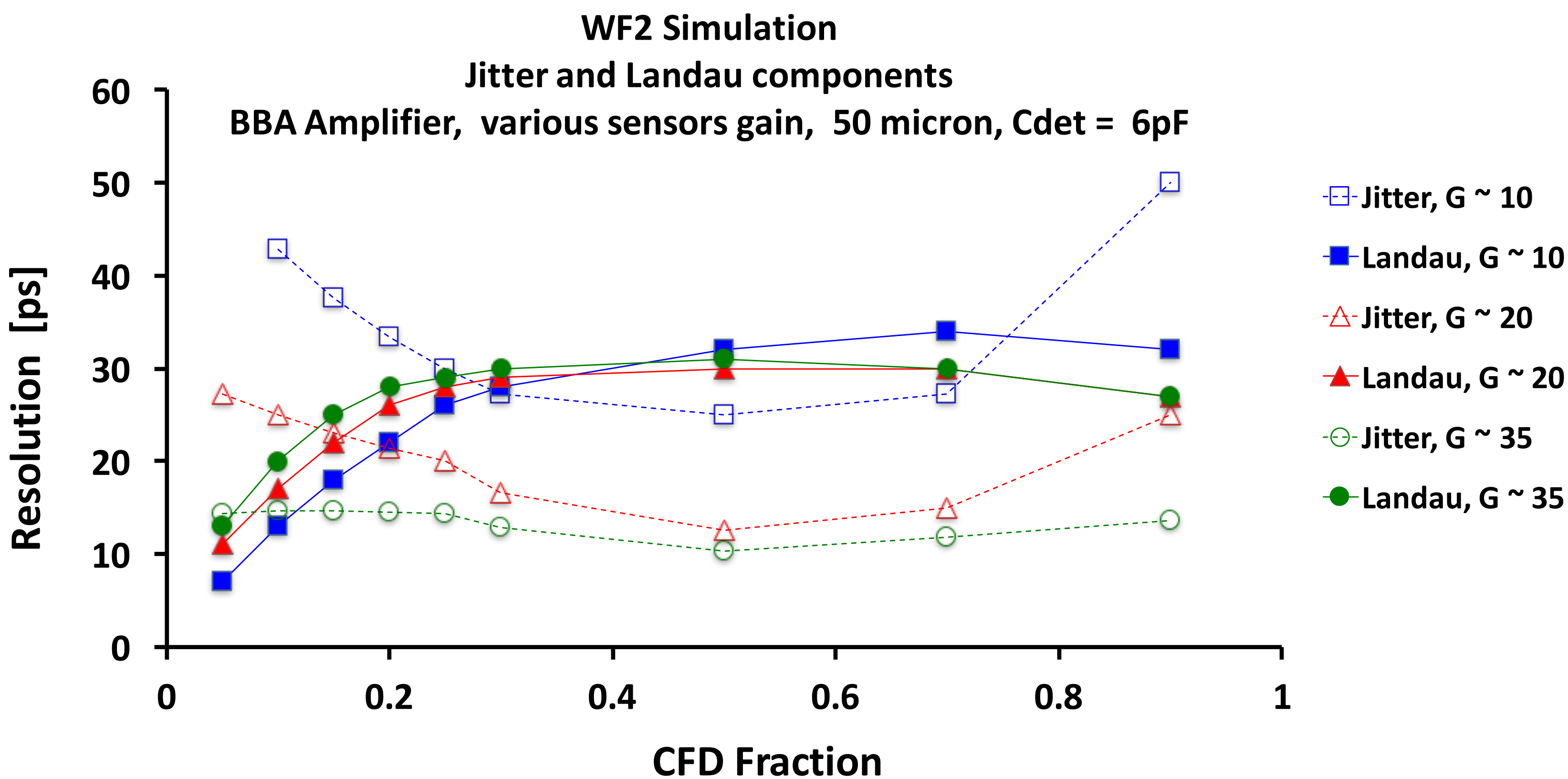


Electrons multiply and produce additional electrons and holes.

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

➔ **No holes multiplications**

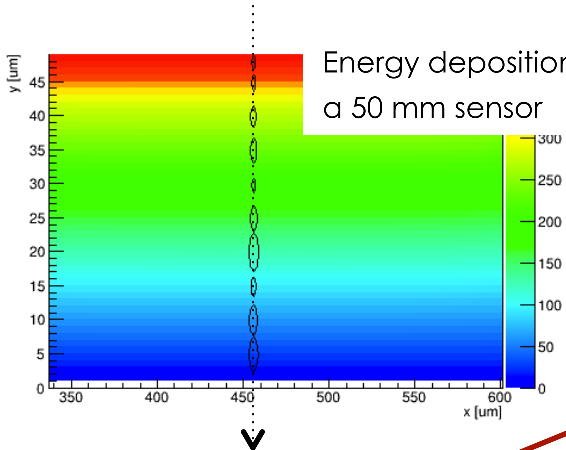
How precise can we be with 50-micron thick sensors?



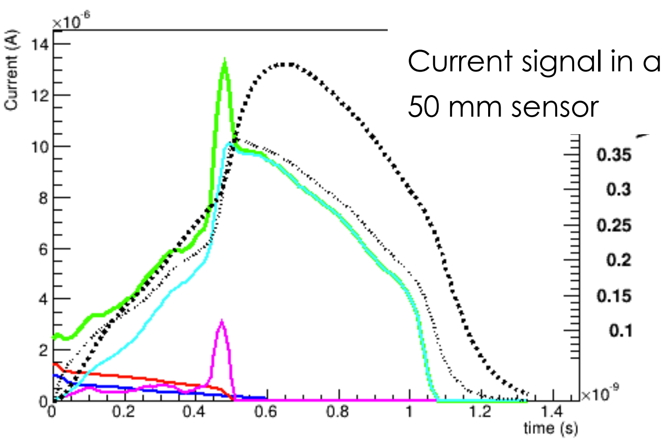
Two main contributions: **Jitter** and **charge non uniformity**

- **Jitter** (empty symbols) can be lowered with gain
- **Charge non uniformity** (solid symbol) limits the ultimate precision

What is the best pre-amp choice?

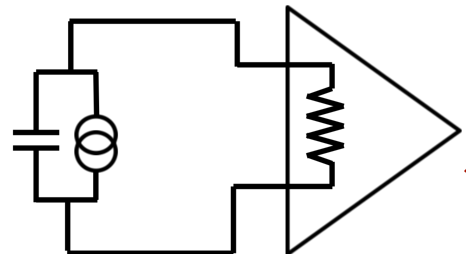


Energy deposition in a 50 mm sensor

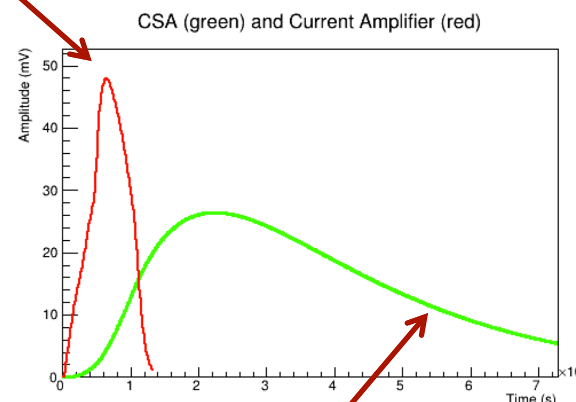


Current signal in a 50 mm sensor

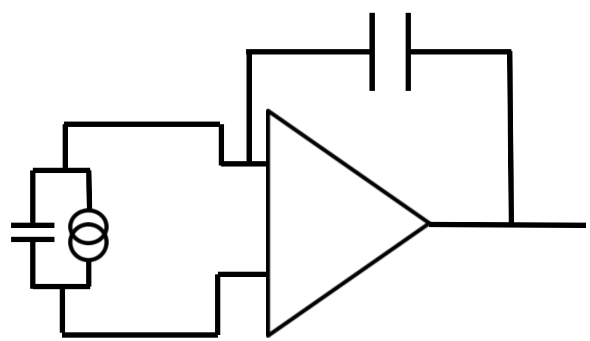
Current Amplifier



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



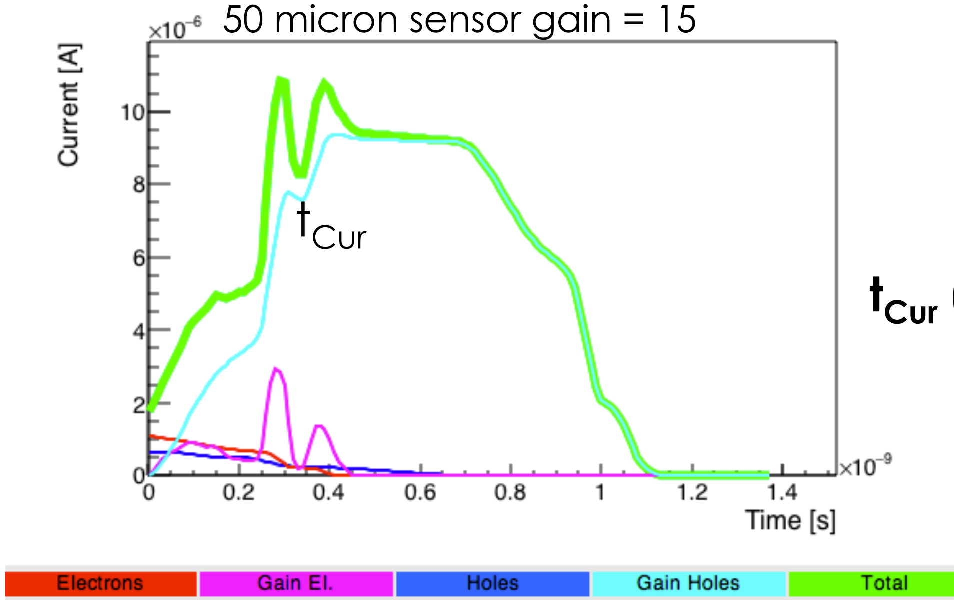
Integrating Amplifier

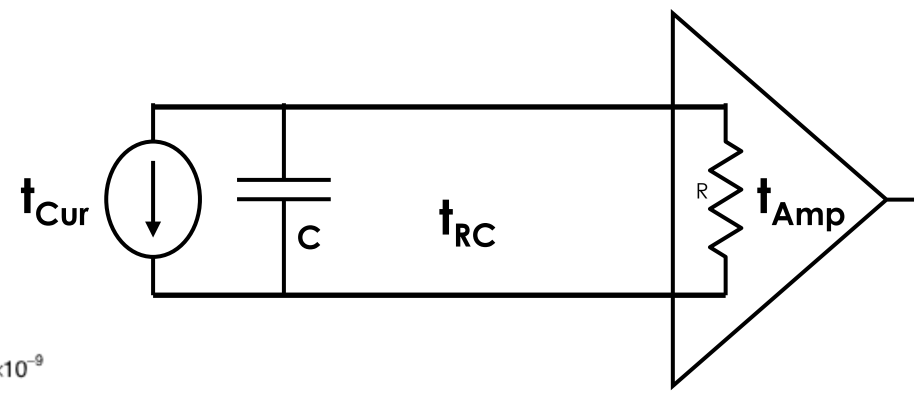


- Slower slew rate
- Lower noise
- Signal smoothing
- Less power

The players: signal, noise and slope

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





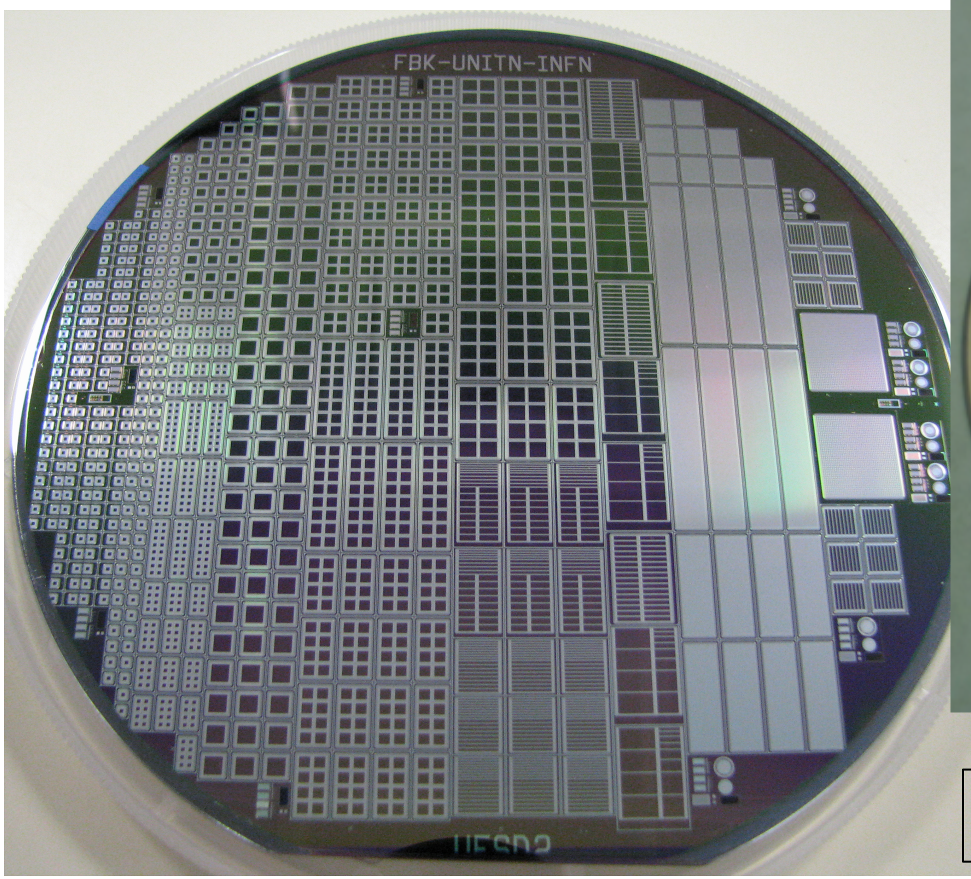
The current rise time (t_{Cur}) | The RC circuit (t_{RC}) | Amplifier rise time (t_{Amp})

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})

Sensors: FBK & CNM

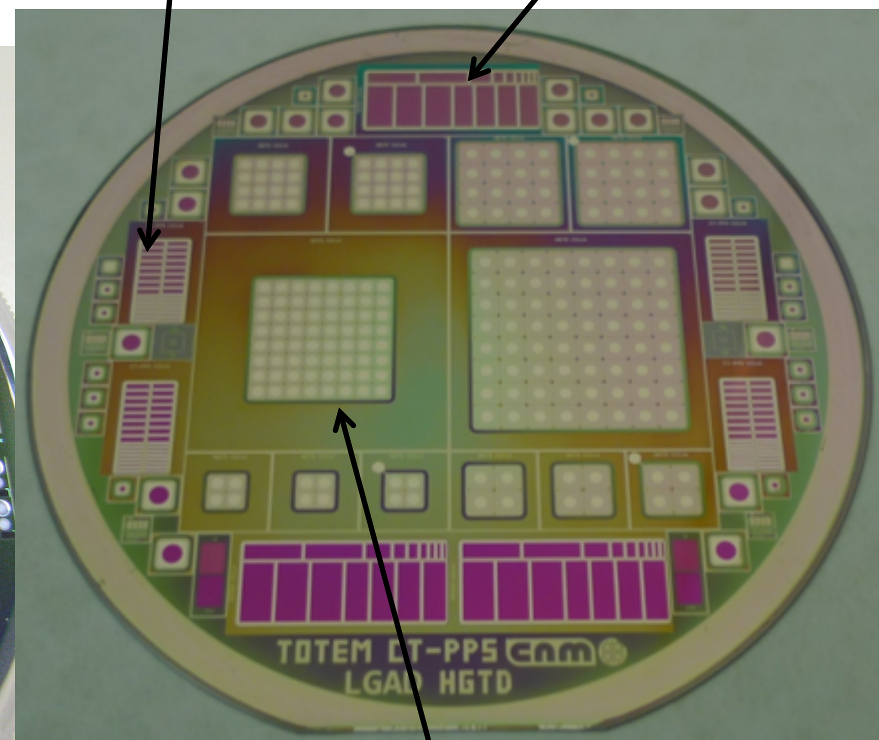
FBK 50-micron production
Very successful, good gain and overall behavior
Gain layer: Boron, Gallium, Boron+Carbon, Gallium+Carbon



CNM 75-micron
CNM 50-micron production

x4 CT-PPS

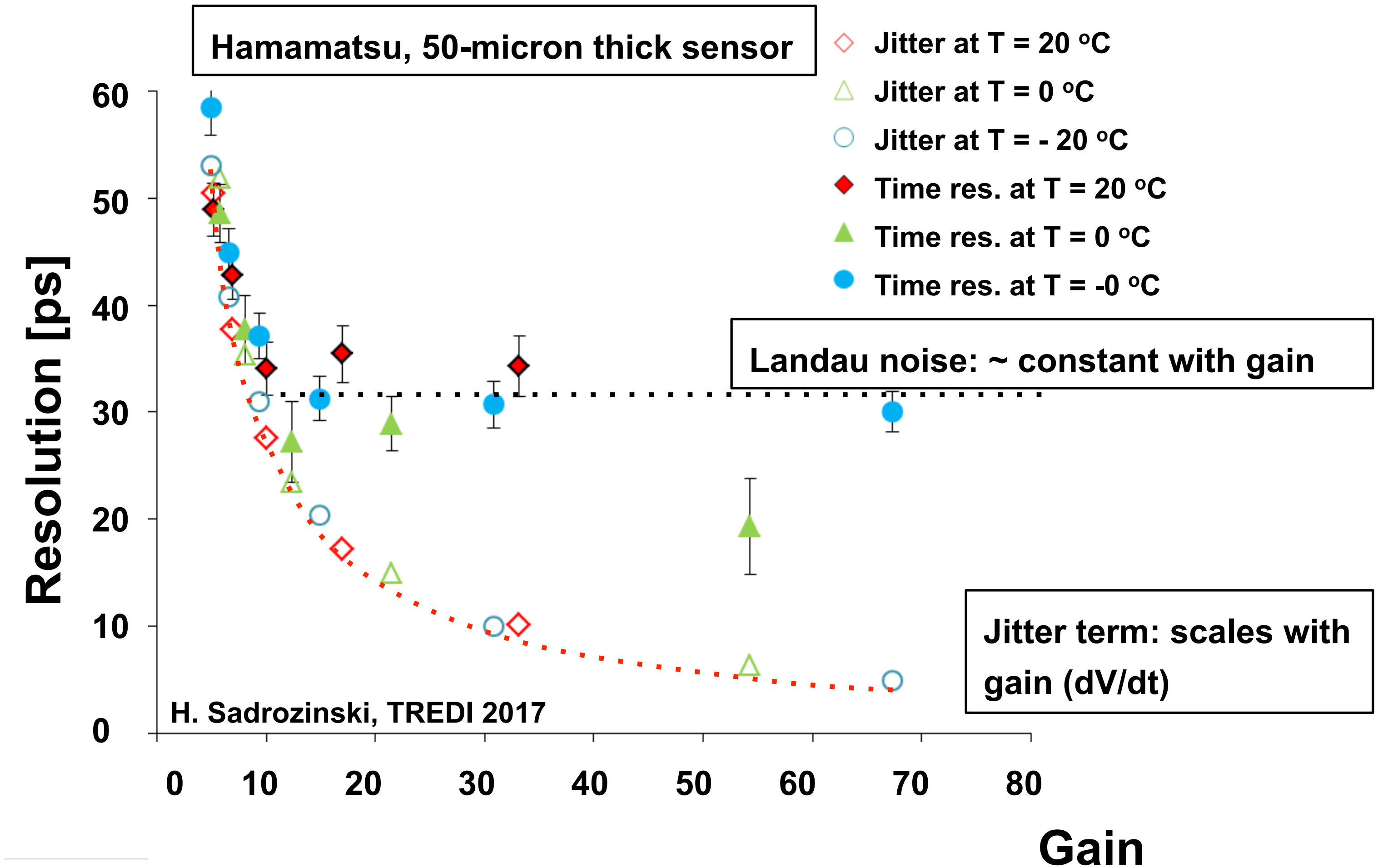
x3 TOTEM



ATLAS High Granularity Timing Det.

UFSD time resolution

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



Irradiation effects

Irradiation causes 3 main effects:

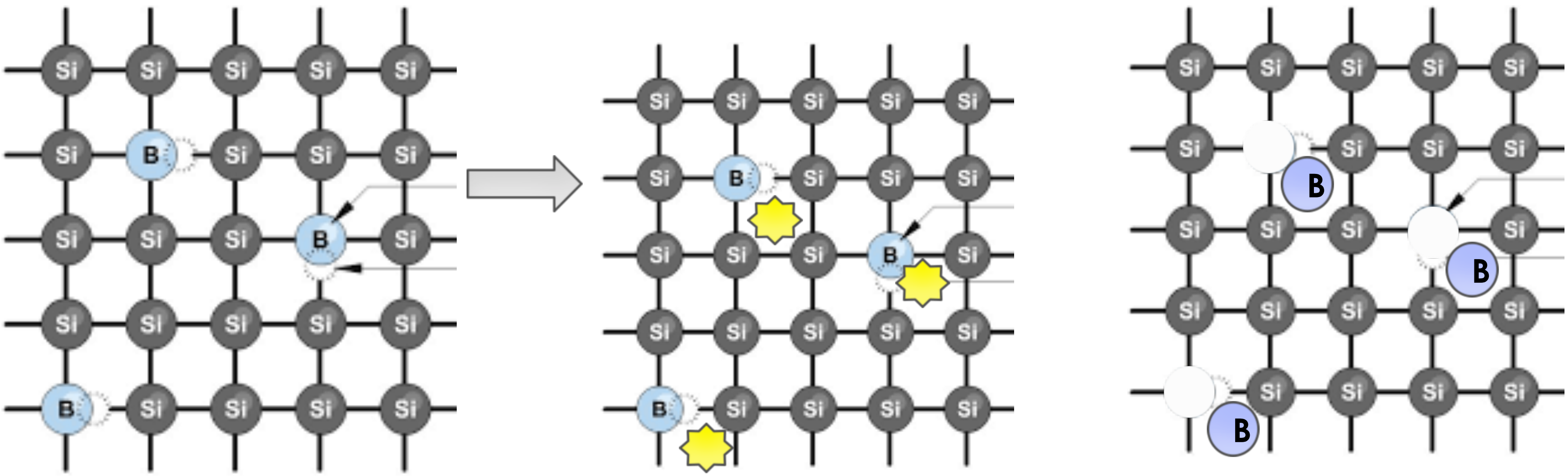
- Decrease of charge collection efficiency due to trapping
  - ➔ Very small in thin sensor
- Increased leakage current, shot noise ➔ back up slides
- Gain layer disappearance ➔ following slides

Radiation issue: Initial acceptor removal

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

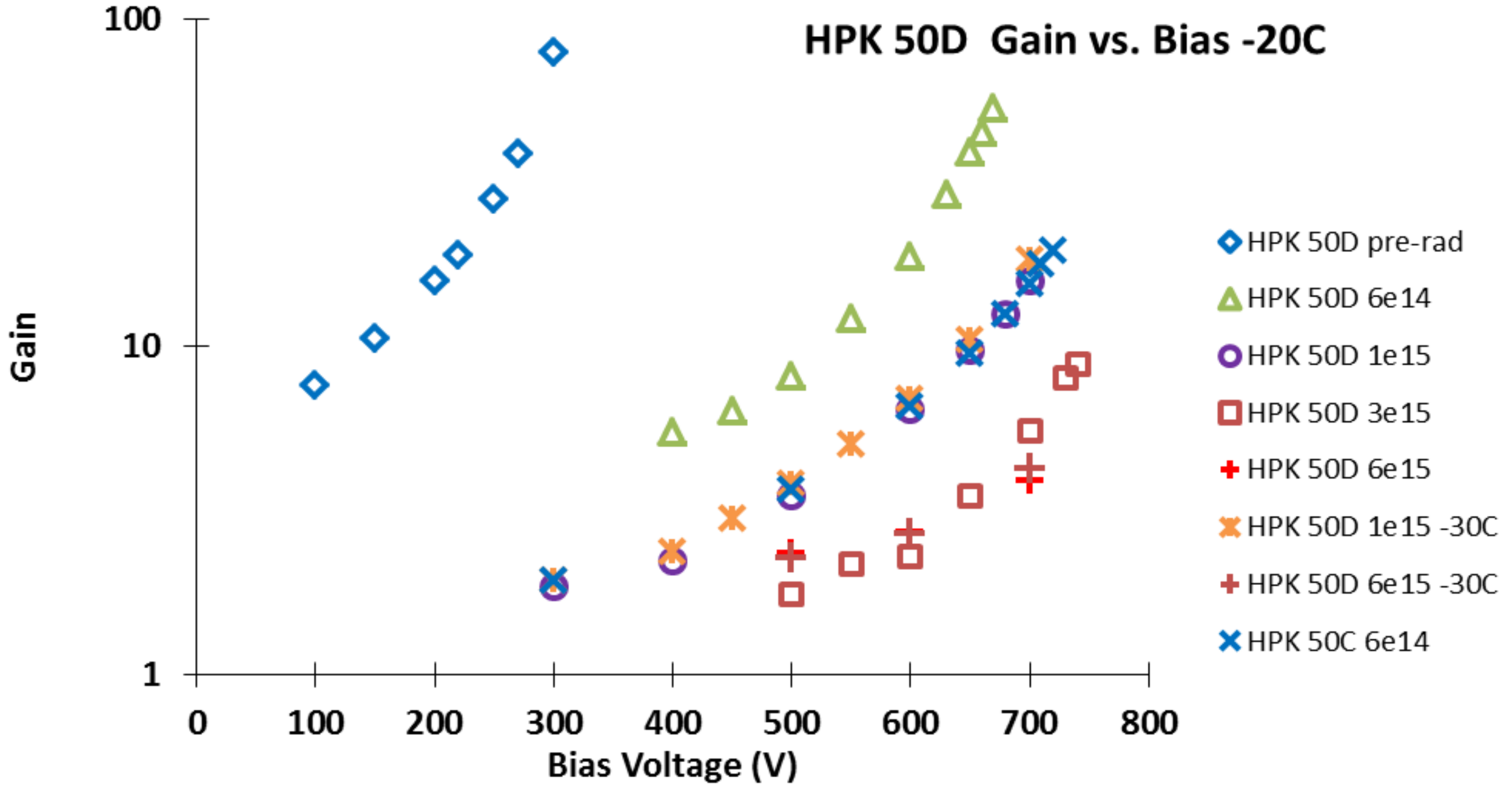
For UFSD this is particularly problematic as it removes the gain layer

Irradiation ➔ Defects ➔ Boron becomes interstitial



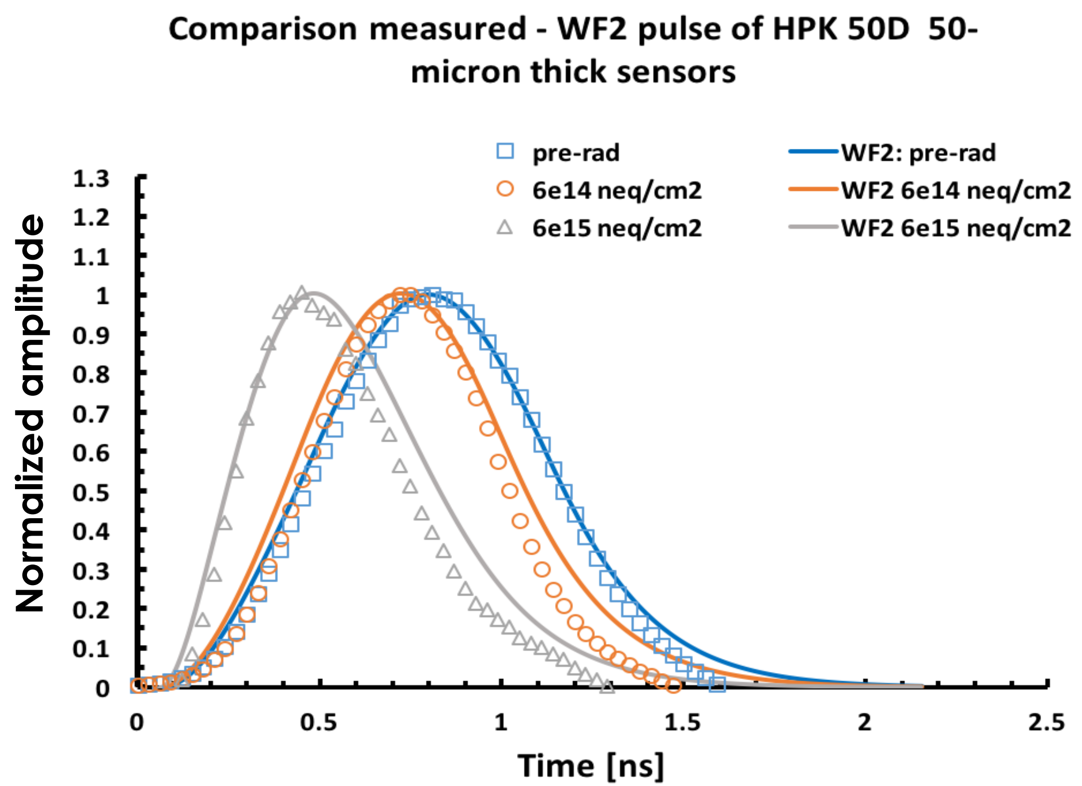
The boron doping is still there, only it has been moves into a different position and it does not contribute to the doping profile, it is inactive

Gain in for irradiated sensors



No unexpected features: the gain layer disappearance is compensated by external bias

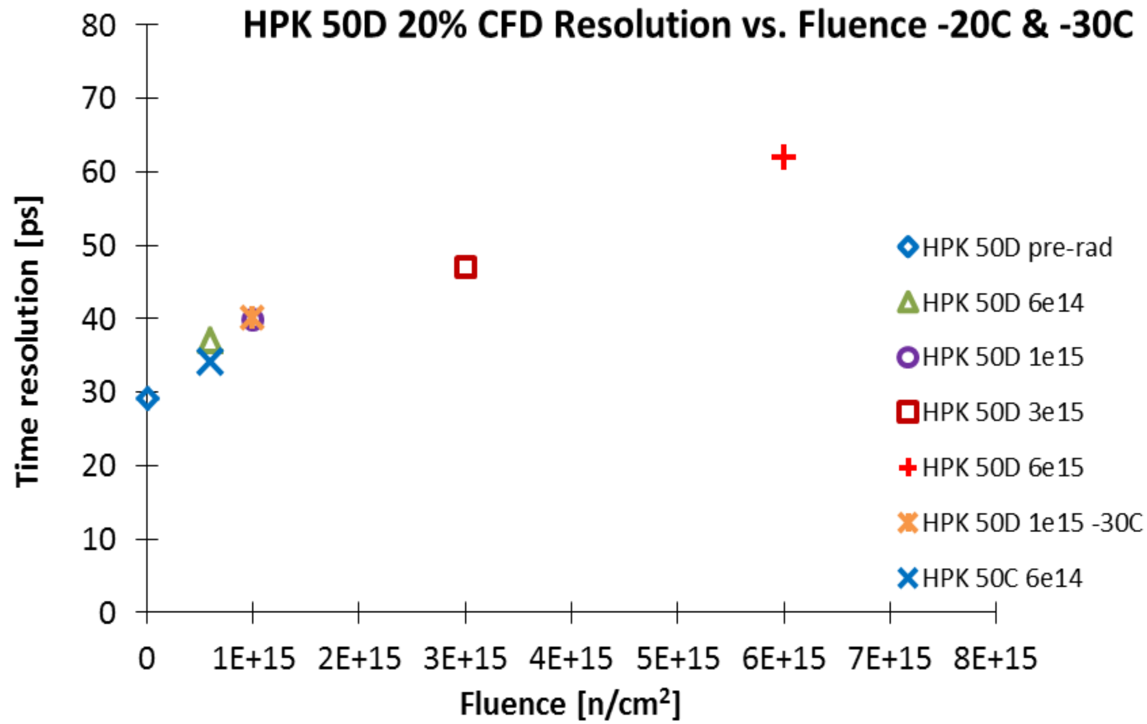
Pulse shape in irradiated UFSD



With irradiation the signal changes: it becomes shorter and steeper

Time resolution of irradiated sensors

Small degradation in time resolution:
~ 30 ps (un-irrad) ➔ ~ 60 ps (5e15 n/cm2)



Can we do better? Probably…
We are now starting to test Gallium, Boron + Carbon and Gallium + Carbon.
By fall 2017 we will know if any of these tricks helps

Note: the above plot is made with a constant CFD threshold (20%).
➔ Better results if we can change it during the sensors' lifetime

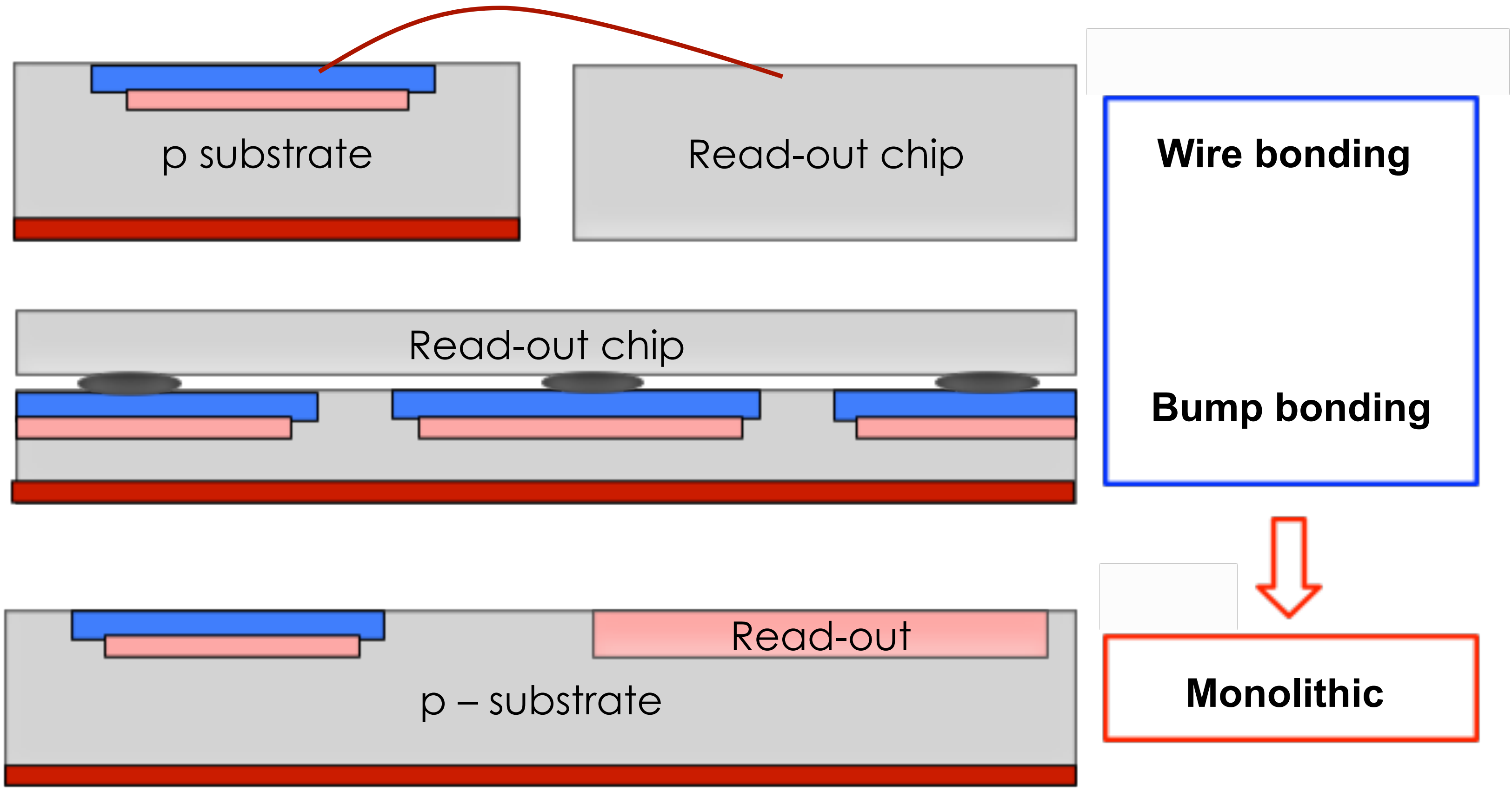
A read-out chip for UFSD sensors

Basic characteristics:

- ➔ Amplifier + comparator + TDC (CFD; ToT+ToA or both)
- ➔ Bump bonded (or similar) to the sensor
- ➔ Input charge range up to 20 fC (gain ~ 40)
- ➔ Measure MIP timing with ~ 20 ps precision (not to spoil UFSD precision)
- ➔ Low power

We have started the R&D on dedicated front-end chip fro track timing

R&D: Can we use Monolithic technology?



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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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Summary

4 Dimensional tracking opens up new opportunities in detector design.

The use of timing at each point in a tracking system allows using much simpler reconstruction algorithm, and allow higher particle densities.

Timing at the track level allows reconstructing the event properties without the effect of pile-up.

4-D tracking can be achieved using special silicon sensors with internal gain, the so called UFSD design based on the LGAD technology

Sensor R&D is very active, funded by a variety of sources.
Very strong collaboration ATLAS-CMS.

Best time resolution is ~ 30 ps (gain ~ 20 with CFD ~ 20%) when new, and ~ 50 ps (gain ~ 7-10 with CFD ~ 50%) at 1e15neq/cm2