The 4D challenge

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

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

Tracking in 4 Dimensions

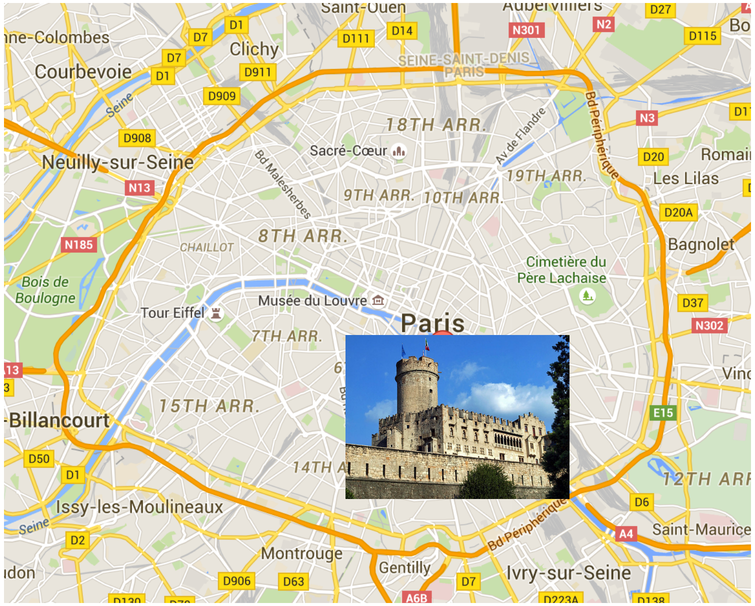
INFN Torino, Univ. Trento, FBK, UCSC Santa Cruz

LGAD R&D:

RD50 Collaboration

LGAD Production:

CNM, Barcelona



Trento @ Paris

The effect of timing information

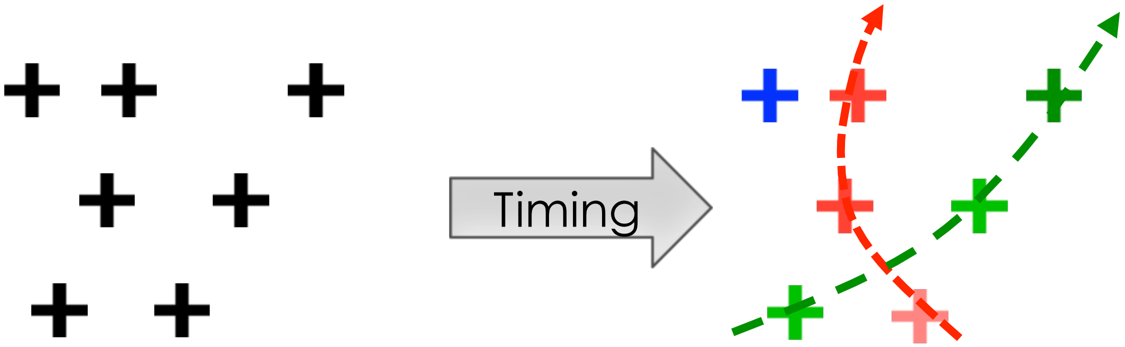
The inclusion of track-timing in the event information has the capability of changing radically how we design experiments.

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

Let me pick 3 situations (colors == time)

1) Timing at each point along the track:

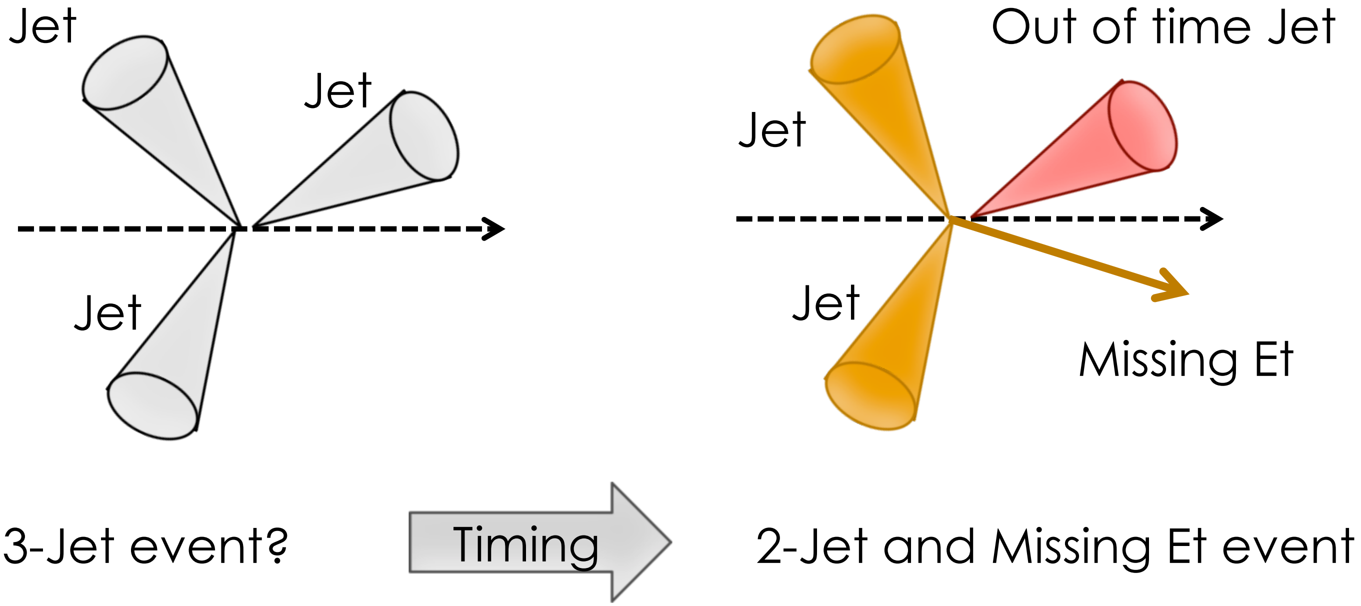
- ➔ Massive simplification of patter recognition, new tracking algorithms will be faster even in very dense environments
- ➔ Use only "time compatible points"



The effect of timing information

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

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

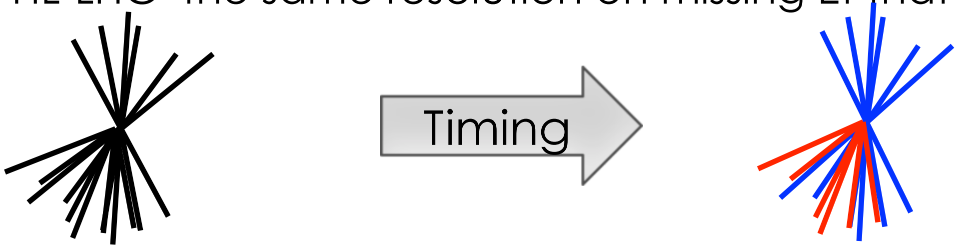


3-Jet event? Timing 2-Jet and Missing Et event

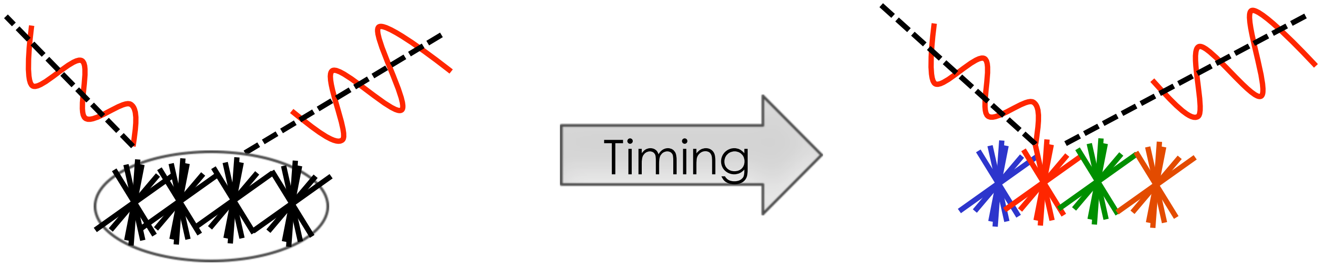
The effect of timing information

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

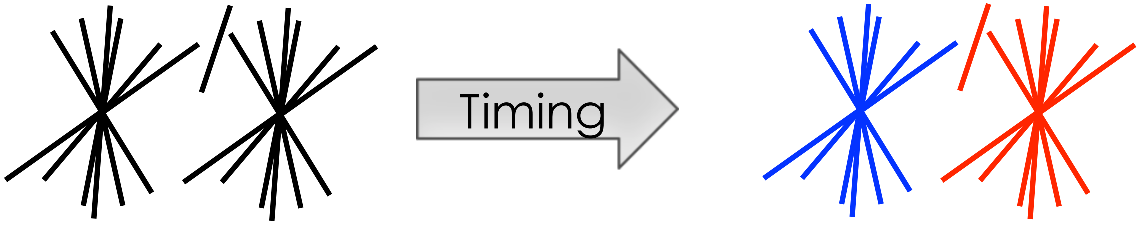
Missing Et: consider overlapping vertexes, one with missing Et: Timing allows obtaining at HL-LHC the same resolution on missing Et that we have now



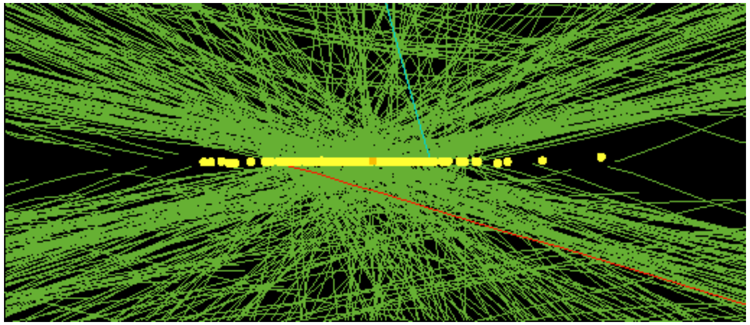
H ➔ γ γ : The timing of the γγ allows to select an area 1 cm) where the vertex is located. The vertex timing allows to select the correct vertex within this area



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

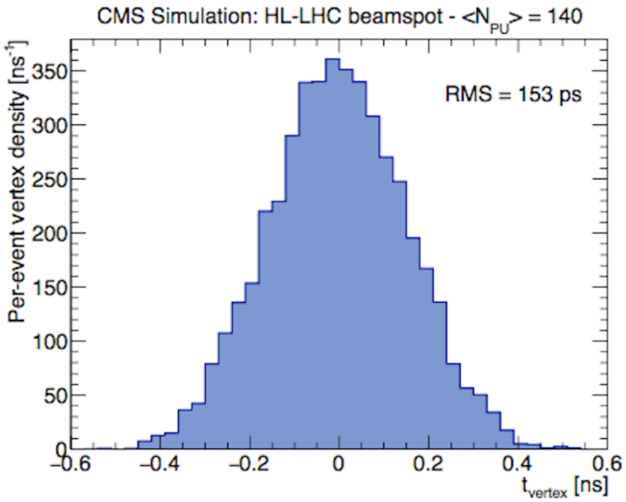


Is timing really necessary?



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

150-200 events/bunch crossing



According to CMS simulations:

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

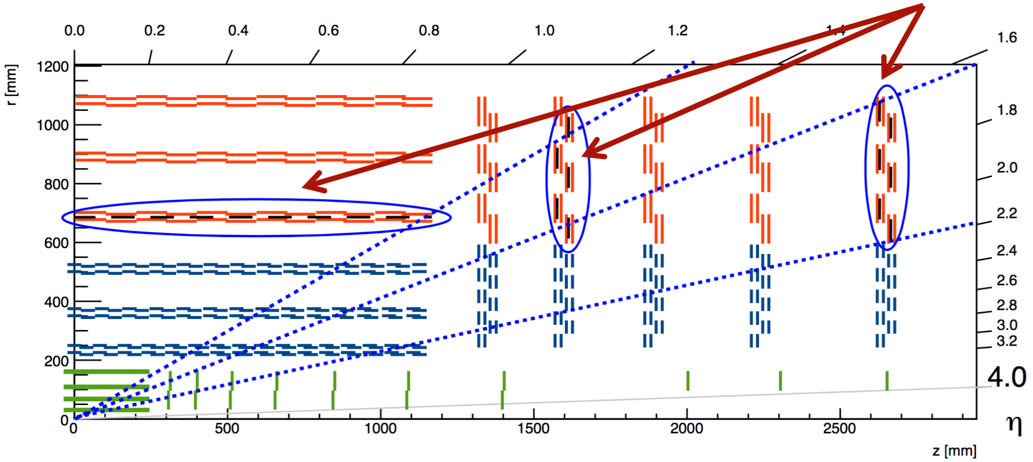
At HL-LHC: Timing is equivalent to additional luminosity

In other experiments (NA62, PADME…):

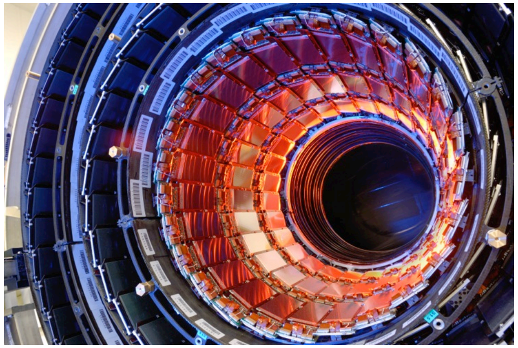
Timing is key to background rejection

Where do we place a track-timing detector?

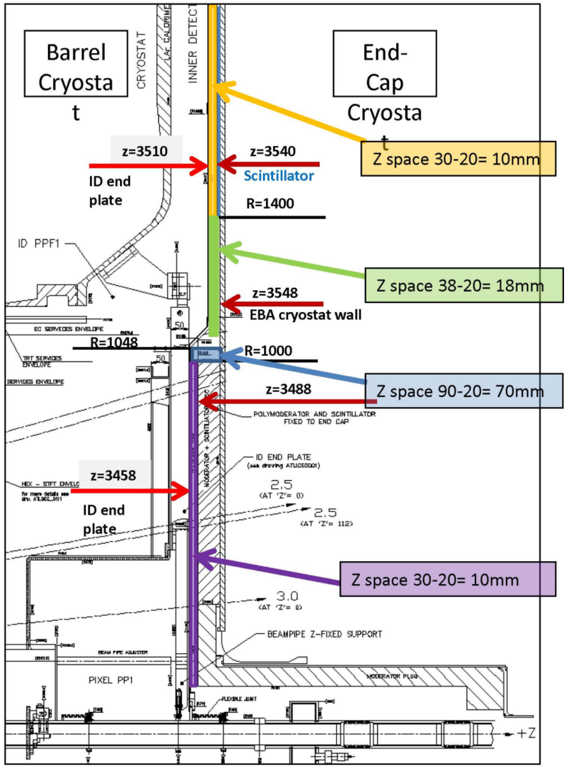
Some (all?) layers in a silicon tracker can provide timing information



Lindsey Gray, FNAL



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



How do we build a 4D tracking system?

Time resolution

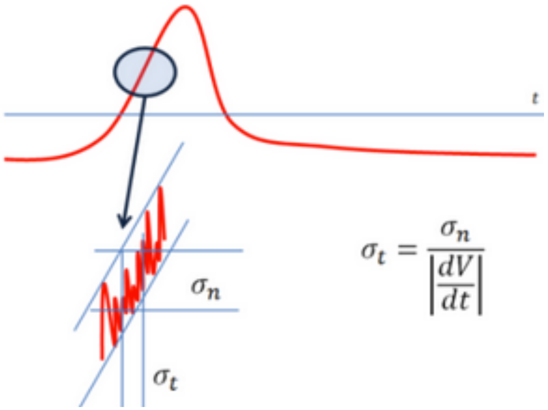
$$\sigma_t = \left(\frac{N}{dV/dt}\right)^2 + (\text{Landau Shape})^2 + \text{TDC}$$

Usual "Jitter" term

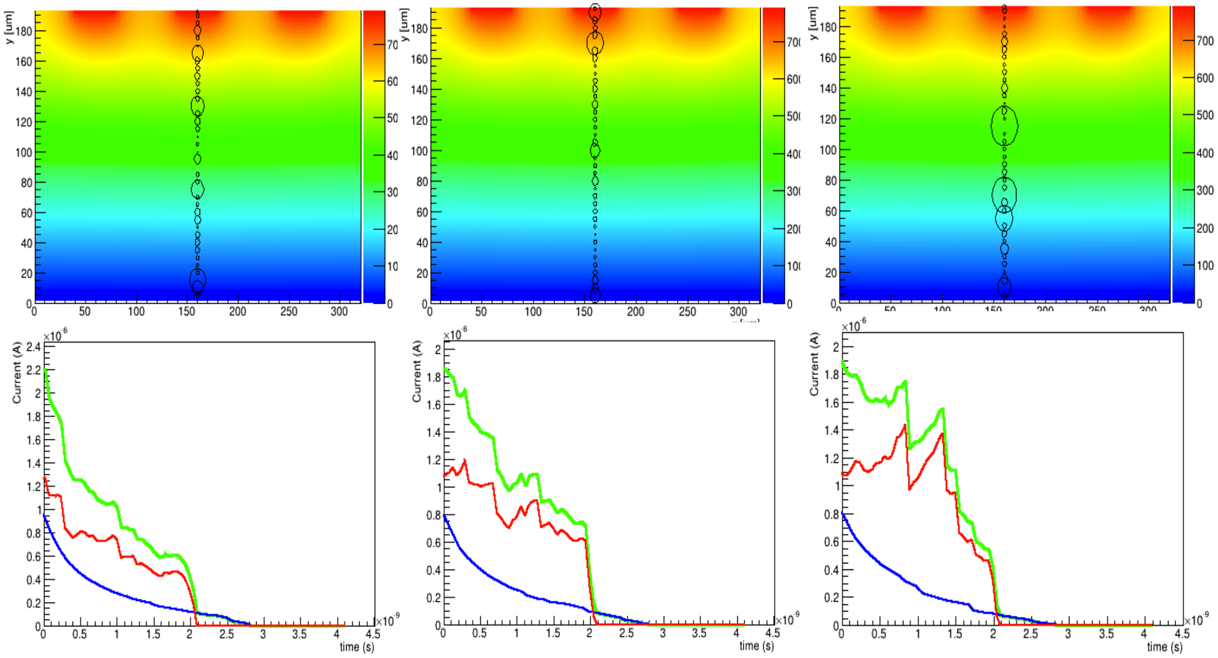
Here enters everything that is "Noise" and the steepness of the signal

Time walk: time correction circuitry

Shape variations: non homogeneous energy deposition



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



Possible approaches for timing systems

We need to minimize this expression:

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

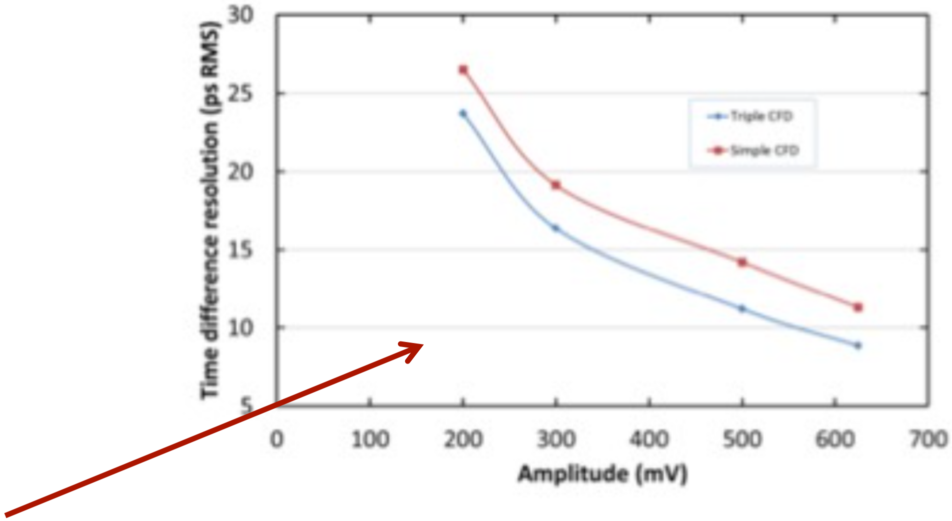
- **APD** (silicon with gain ~ 100): maximize dV/dt
  - Very large signal

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

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

The APD approach

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



So far they reported excellent time resolution on a single channel.

To be done:

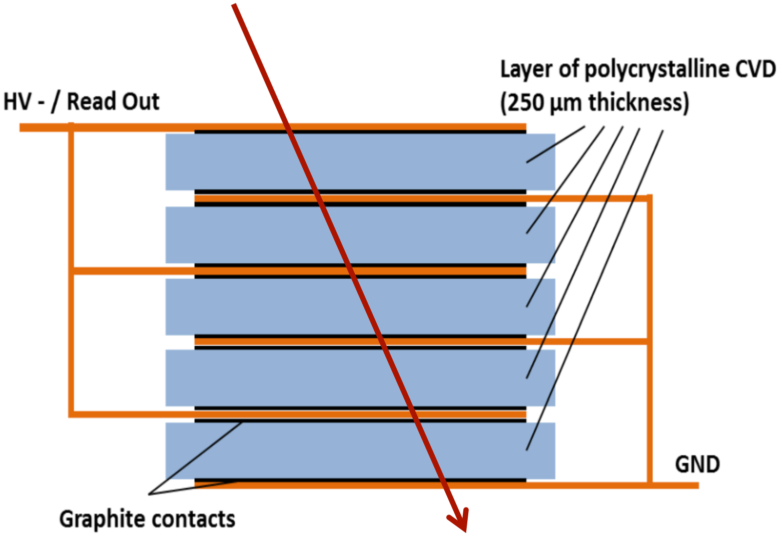
- Radiation hardness above 10^{14} n_{eq}/cm^2
- Fine Segmentation
- How to deal with shot noise (proportional to gain)

The Diamond approach

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

1) Multilayer stack

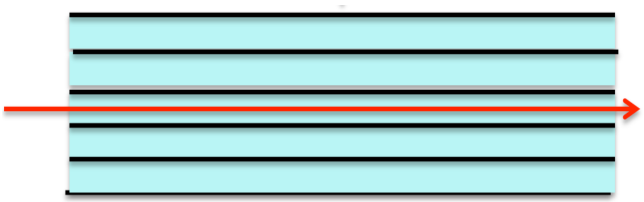
The signal is increased by the sum of many layers while keeping the rise time short



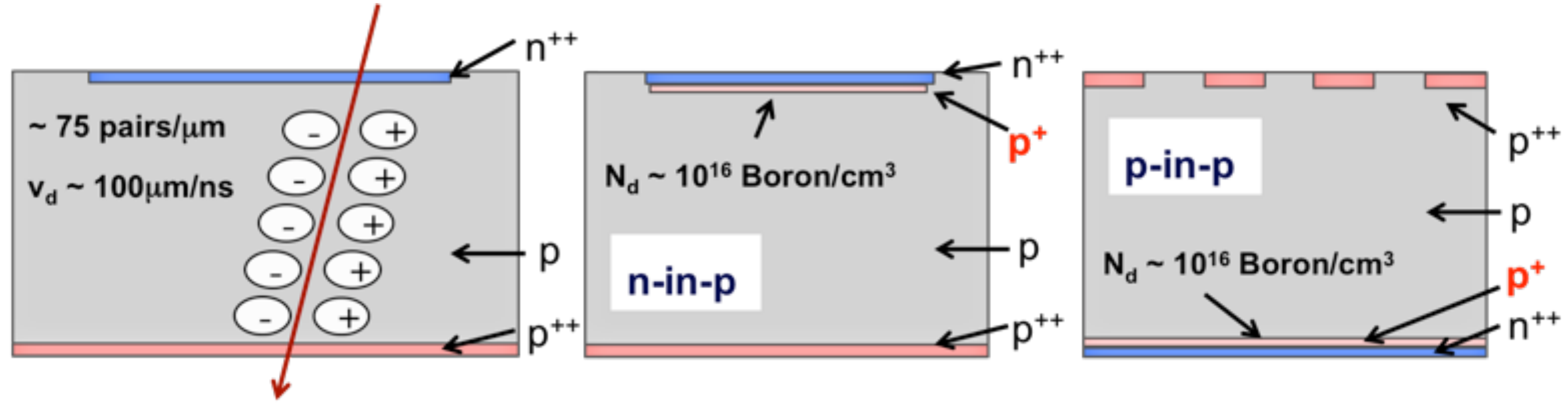
Best resolution: ~ 100 ps

2) Grazing

The particle crosses the diamond sensor along the longitudinal direction



LGAD - Ultra-Fast Silicon Detector

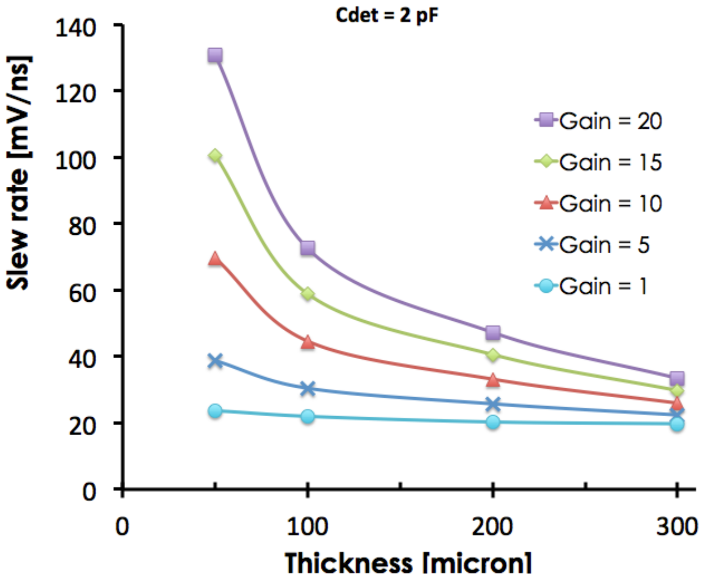


Traditional Silicon Detector **Ultra-Fast Silicon Detector**

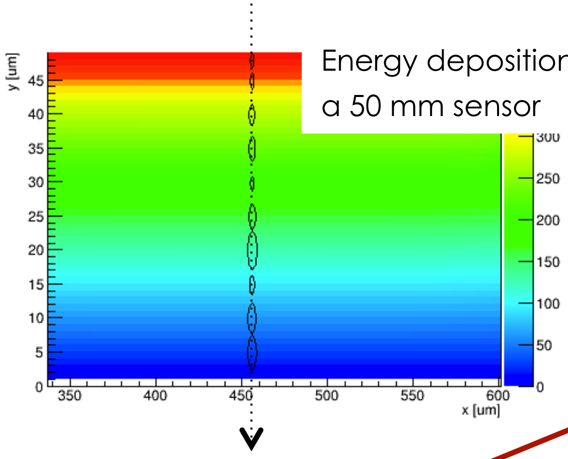
Adding a highly doped, thin layer of of p-implant near the p-n junction creates a high electric field that accelerates the electrons enough to start multiplication. Same principle of APD, but with much lower gain.

Gain changes very smoothly with bias voltage.

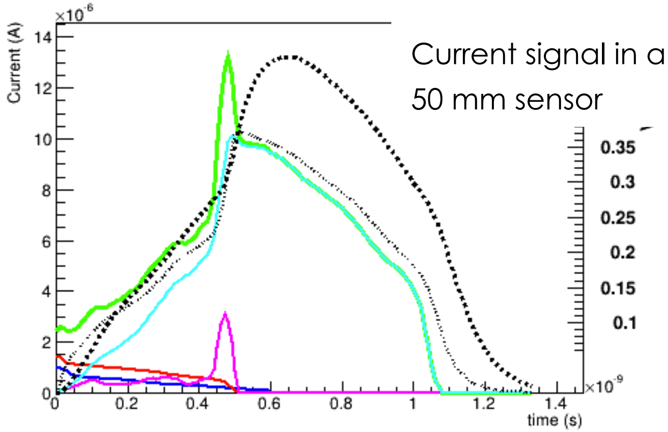
Easy to set the value of gain requested.



What is the best pre-amp choice?

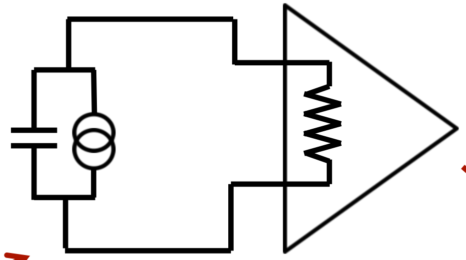


Energy deposition in a 50 mm sensor

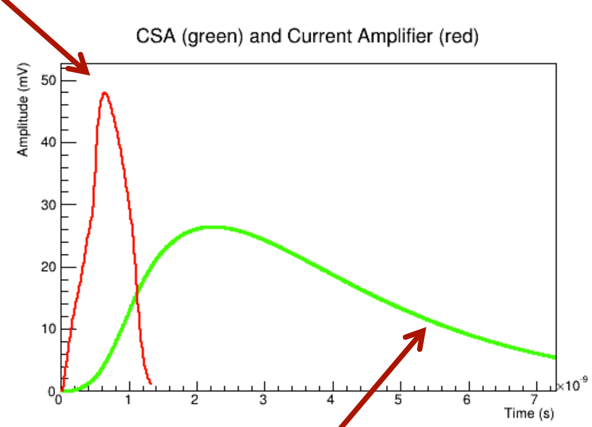


Current signal in a 50 mm sensor

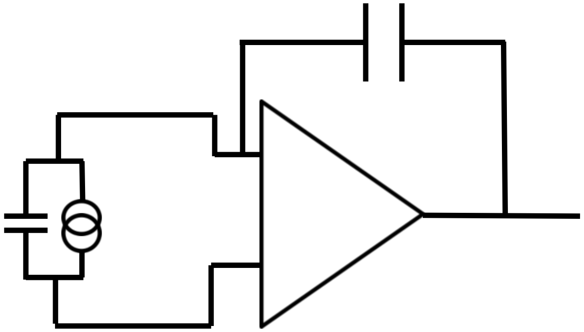
Current Amplifier



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



Integrating Amplifier



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

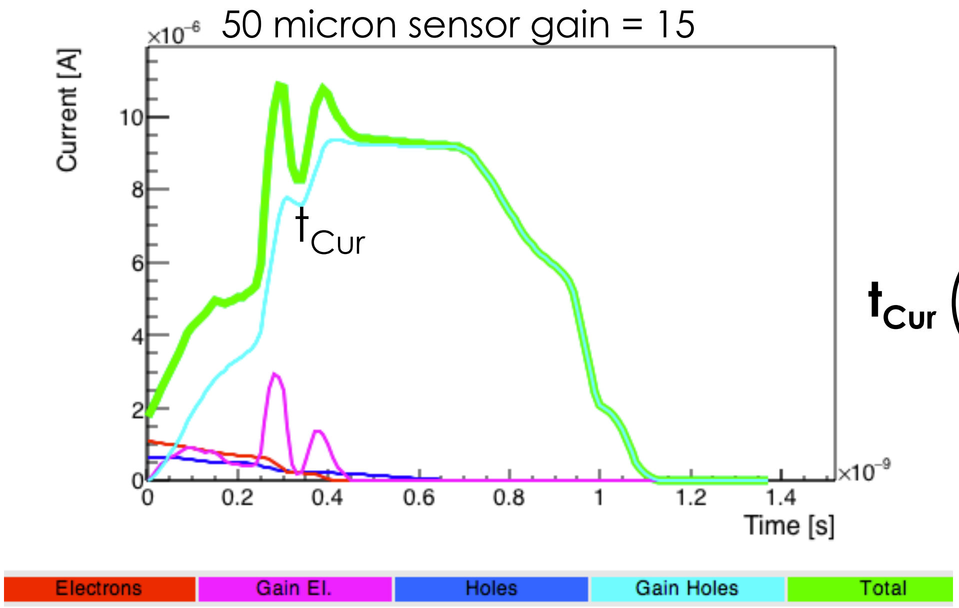
The players: signal, noise and slope

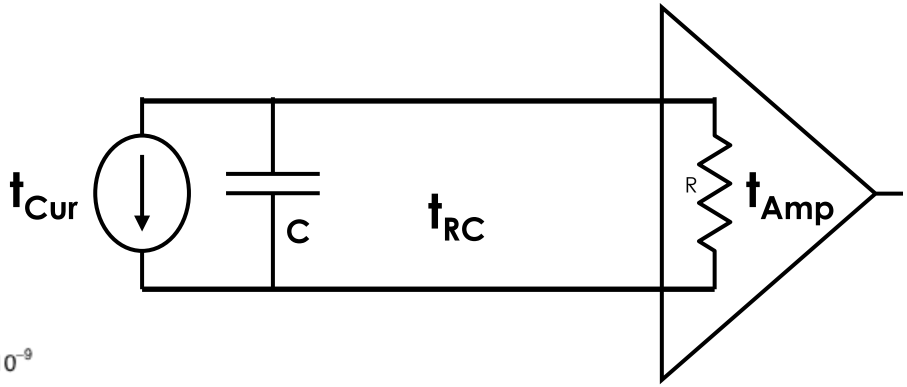
Signal dV/dt

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})

UFSD - Shot noise

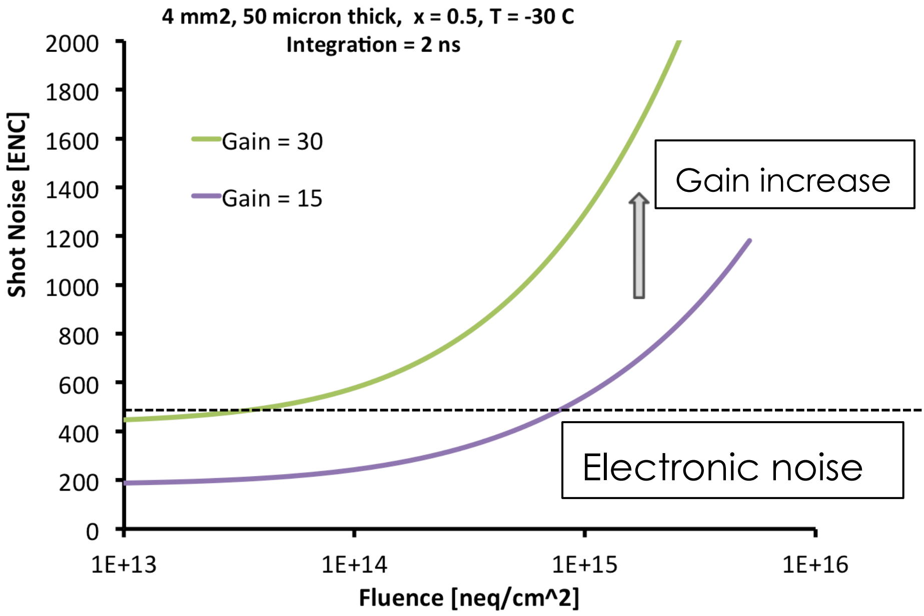
Let's assume a 4 mm^2 pad, 50 micron thick, and a electronic noise of 500 ENC

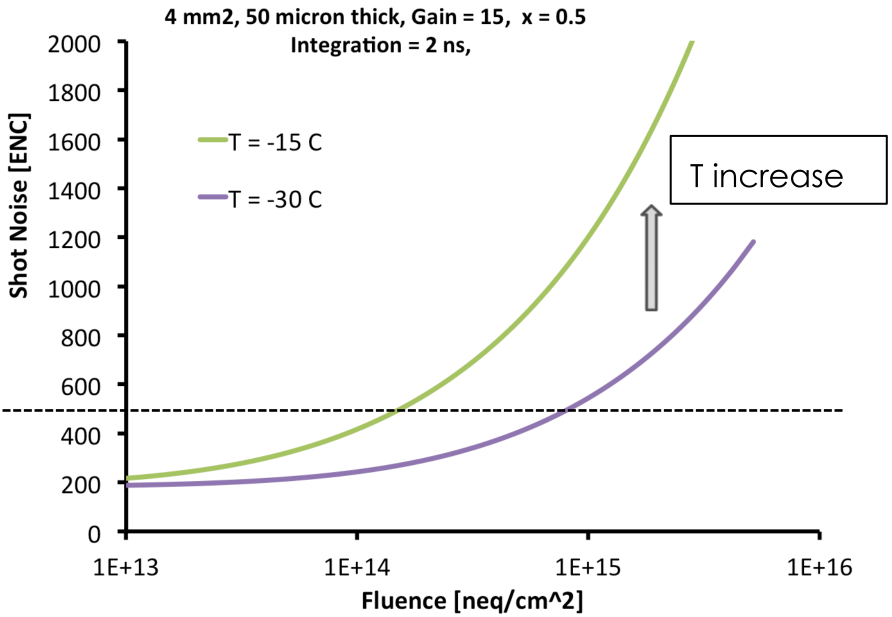
What is the effect of shot noise as a function of radiation?

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

Steep dependence on gain

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



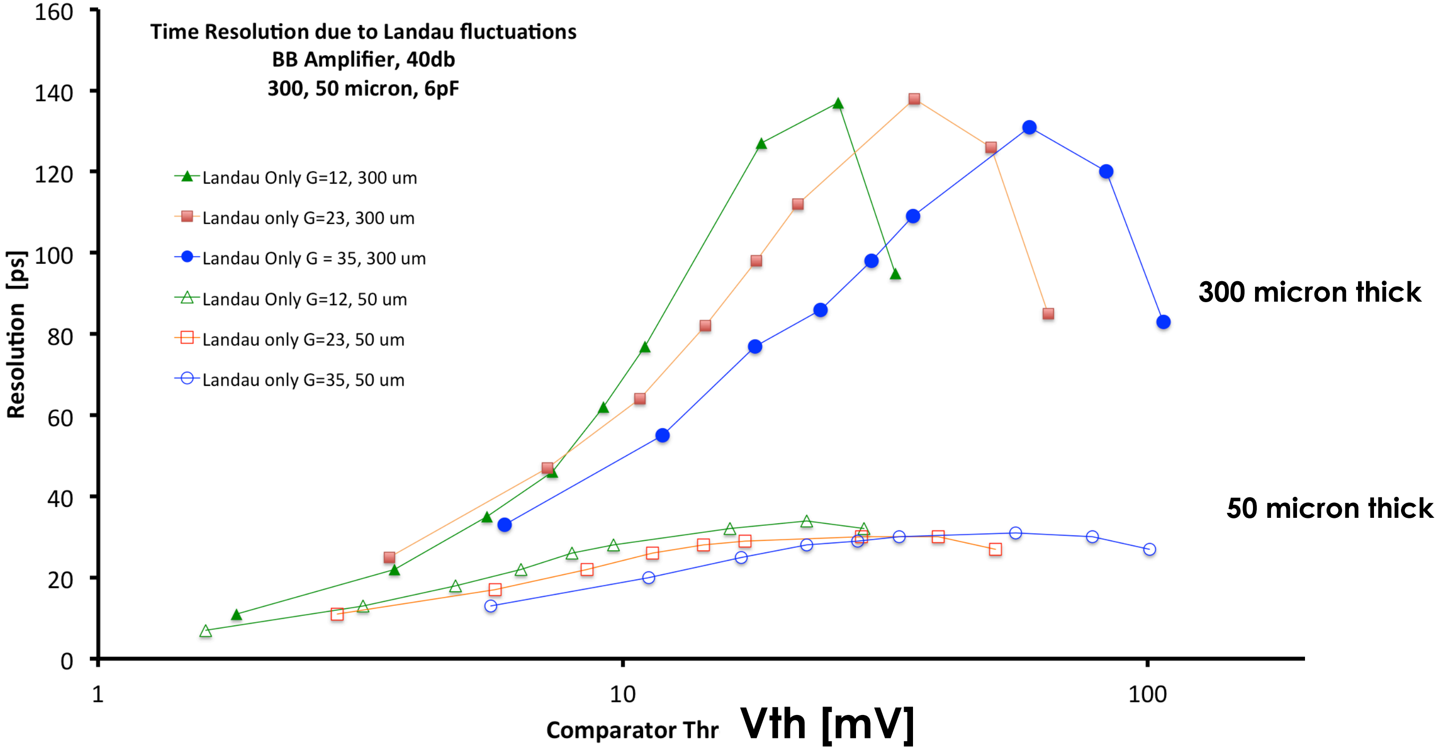


To minimize Shot noise:

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

UFSD - 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

UFSD - Irradiation - I

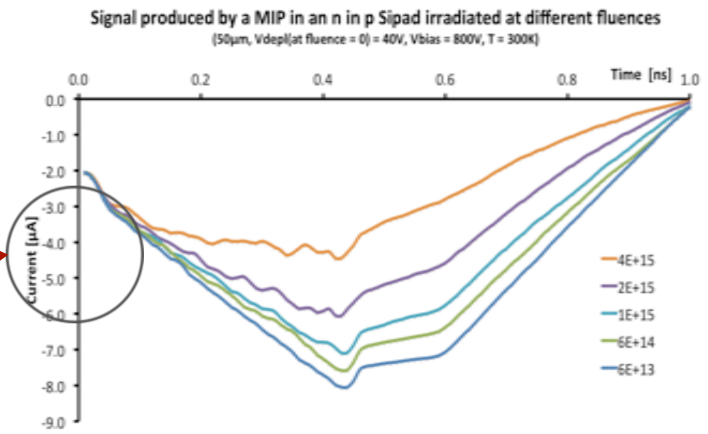
Irradiation causes 3 main effects:

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

UFSD - 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:

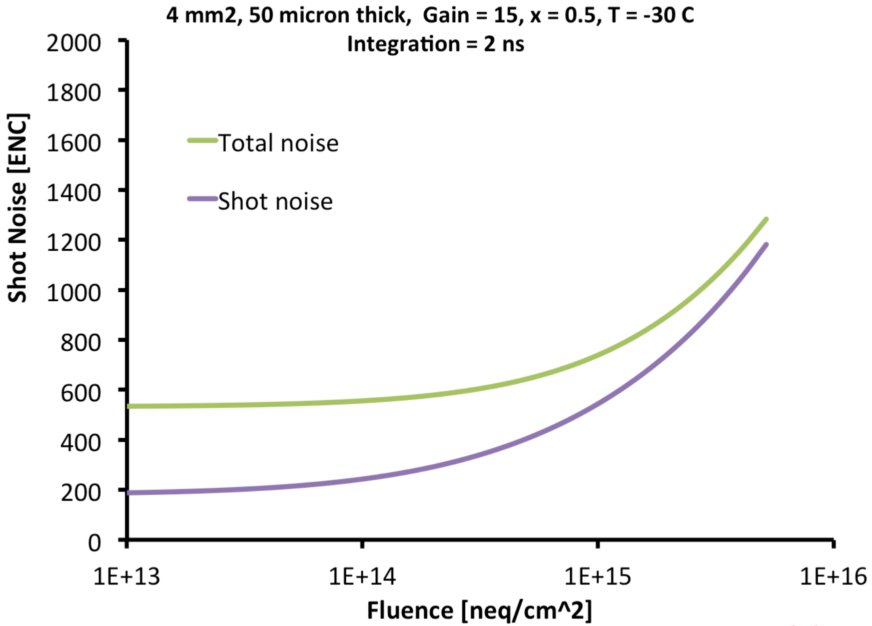
- Use Vbias to compensate for the loss on gain
- Use thin sensors: weaker dynamic effects
- Long term: Gallium doping

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



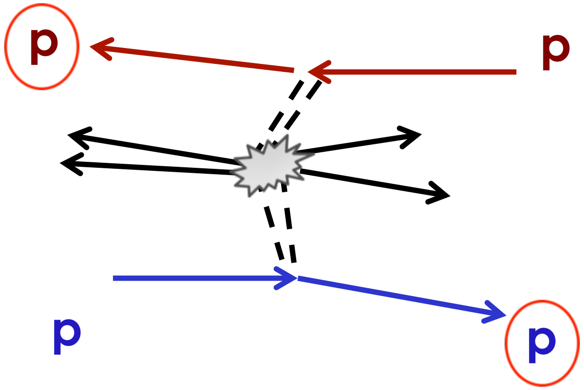
The CT-PPS detector for forward protons

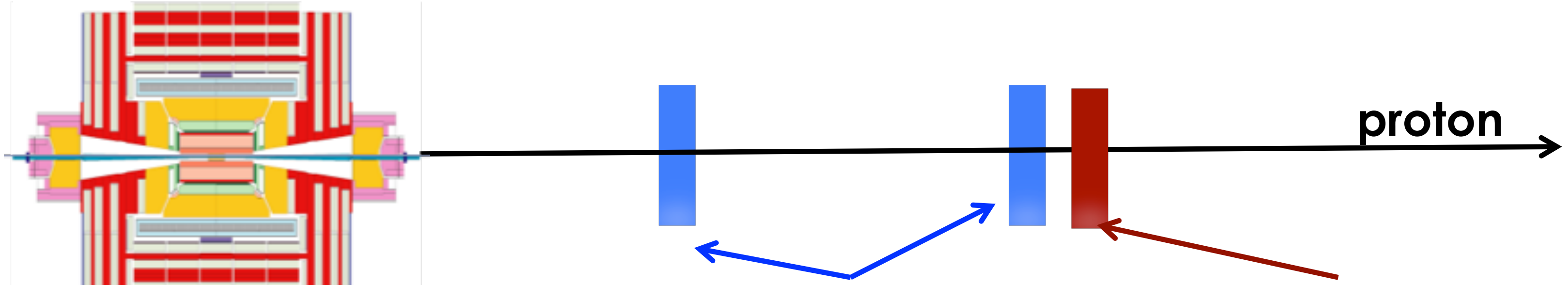
There is a class of events with 2 protons in the final states. We need to measure these protons:

Tracking and timing in Roman pots

How do we determine the proton vertex?

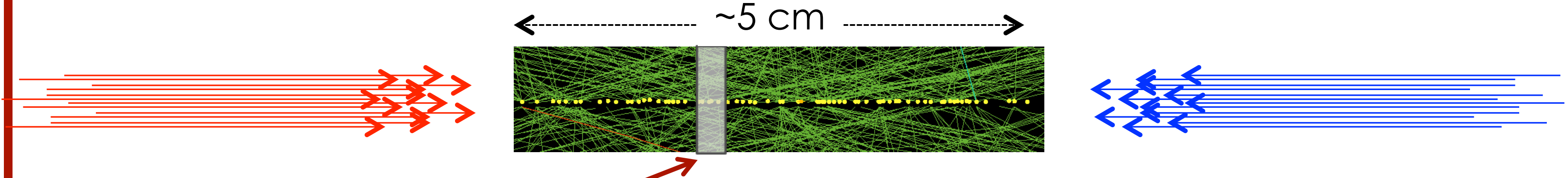
Using z-by-timing





2 RP for Tracking

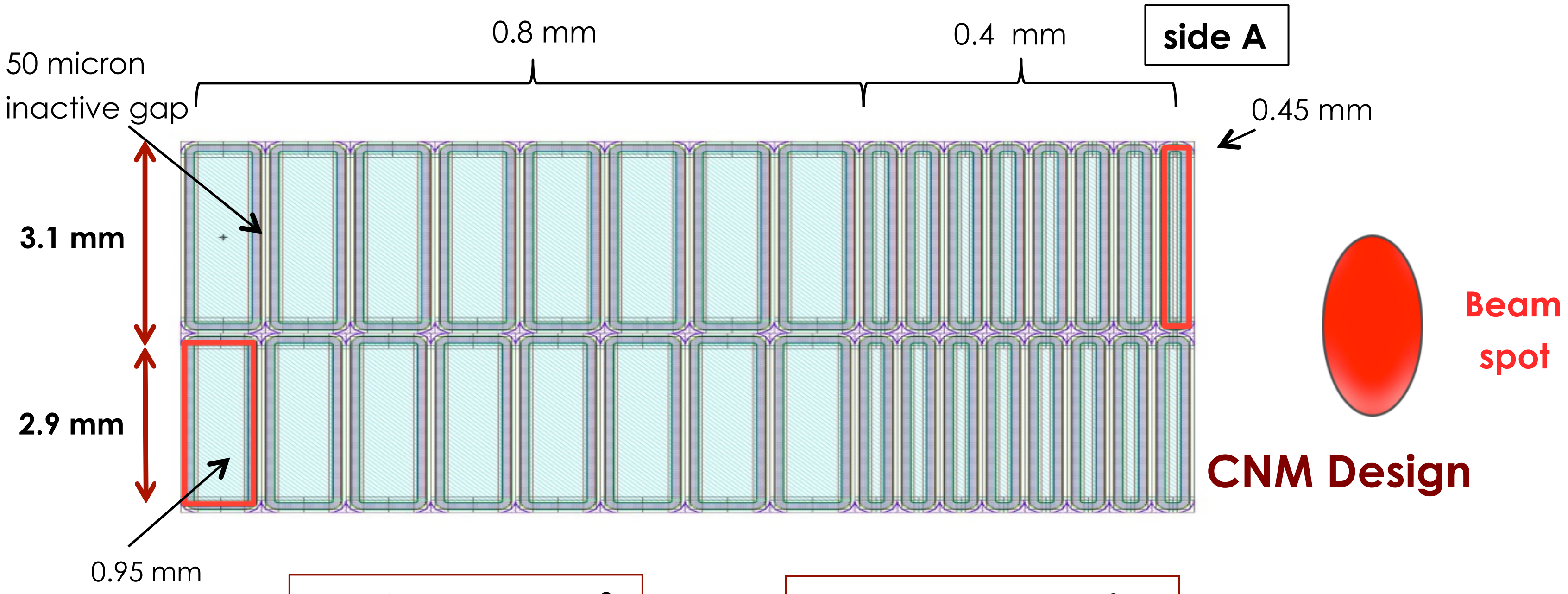
1 RP for Timing



20 ps ~ 4.2 mm

A precision of ~20 ps on the time of each proton will determine the vertex position with a precision of ~ 4.2 mm ("z-by-timing" resolution $\mathbf{\Delta z = c\, \Delta (t_1 - t_2)/2}$)

Sensor geometry for CT-PPS



16 Pixel ~ 3 mm^2
Cap. Pixel ~ 6 pF

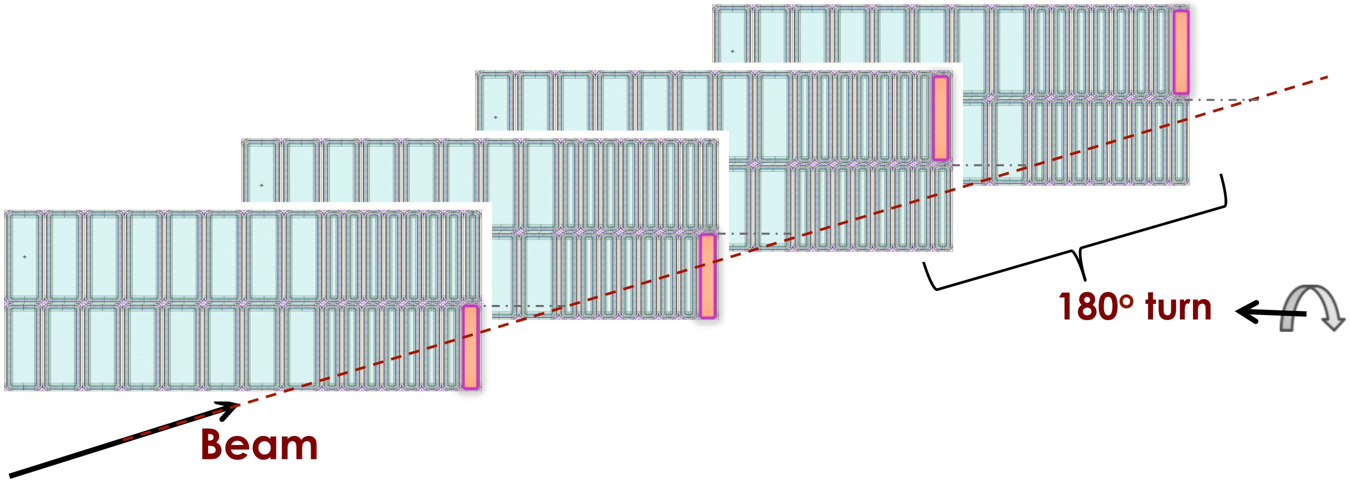
16 Pixel ~ 2 mm^2
Cap. Pixel ~ 4 pF

Asymmetric design
Area = 12mm x 6mm;
Thickness = 50 um;
# of channels = 32 Gain ~ 15
Slim edge of ~200 um on side A

Expected time resolution: ~30 ps

Layout of detector planes

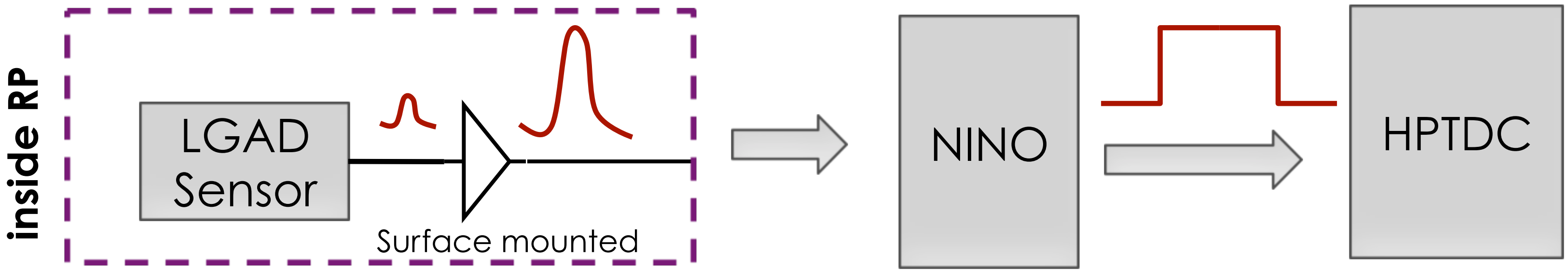
4 (6) planes per station (qualitative sketch):

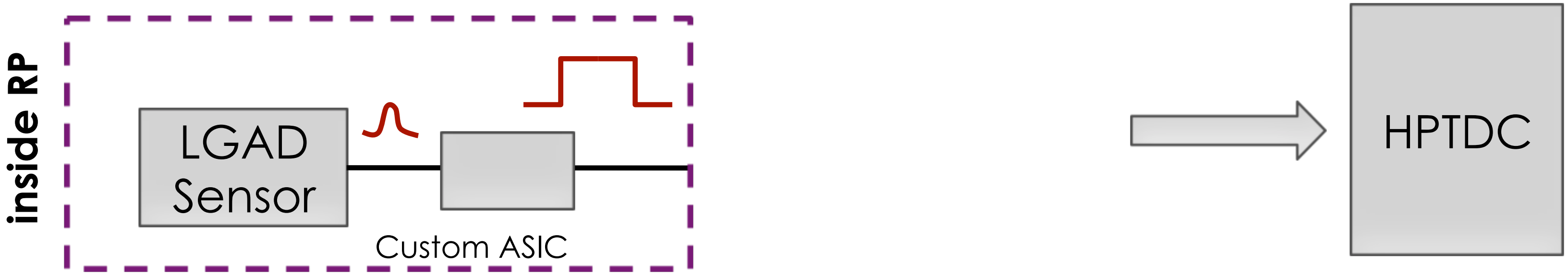


No cracks aligned:
2 (3) planes facing the beam
2 (3) turned by 180°

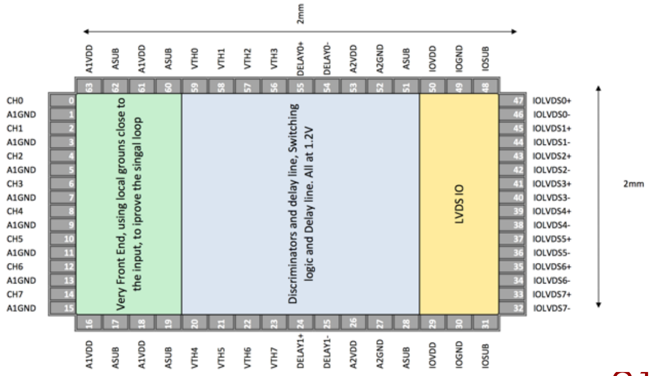
CT-PPS read-out system

Two readout systems under developments:





- Noise performance: ~ 500 ENC for 6pF detector (slope 50 ENC/pF)
- Design of the comparator completed
- Implementation of Time Over Threshold for time walk compensation
- Submission date: May (130 nm)
- Ready in July



Acknowledgments

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

Summary and outlook

Tracking is 4 Dimensions is a very powerful tool

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

Why **low** gain?

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

Why **thin** sensors?

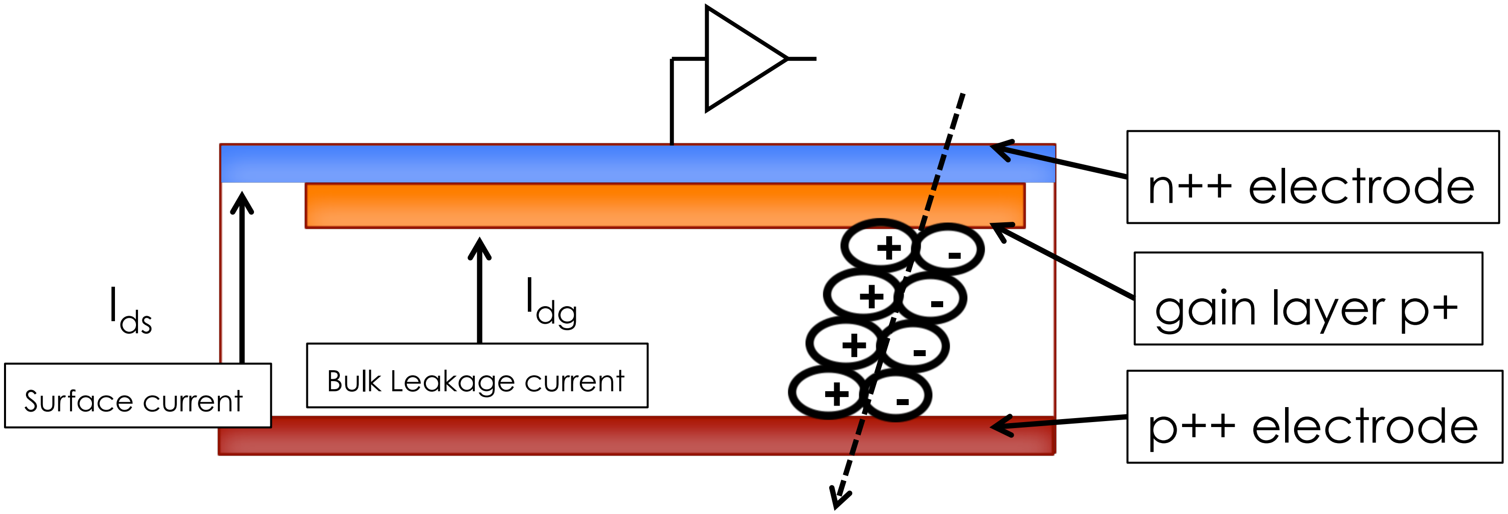
Higher signal steepness, more radiation resistance, easier to achieve parallel plate geometry, smaller Landau Noise

UFSD activities 2016:

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

Backup

Shot noise in LGAD - APD



n++ electrode

gain layer p+

p++ electrode

I_{ds}

I_{dg}

Surface current

Bulk Leakage current

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

Current density, nA/sqrt(f)

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

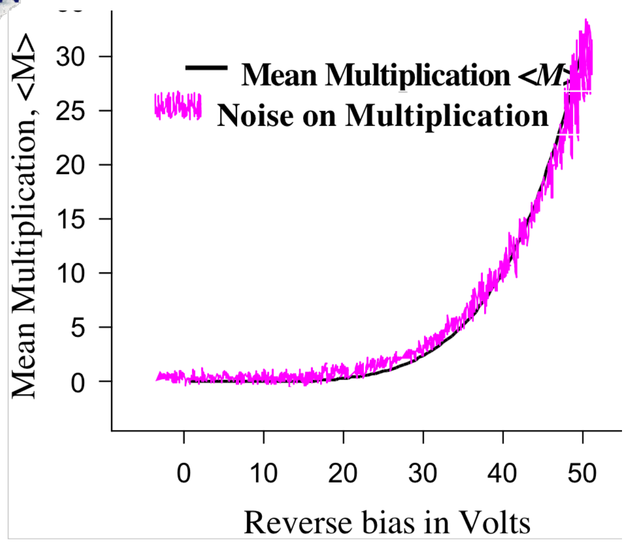
$$F = Mk + \left(2 - \frac{1}{M}\right)(1-k)$$

$$F \sim M^x$$

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

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: ~ 40 for APD, With segmentation probably lower ~ 20