Development of Ultra-Fast Silicon Detectors for 4D Tracking

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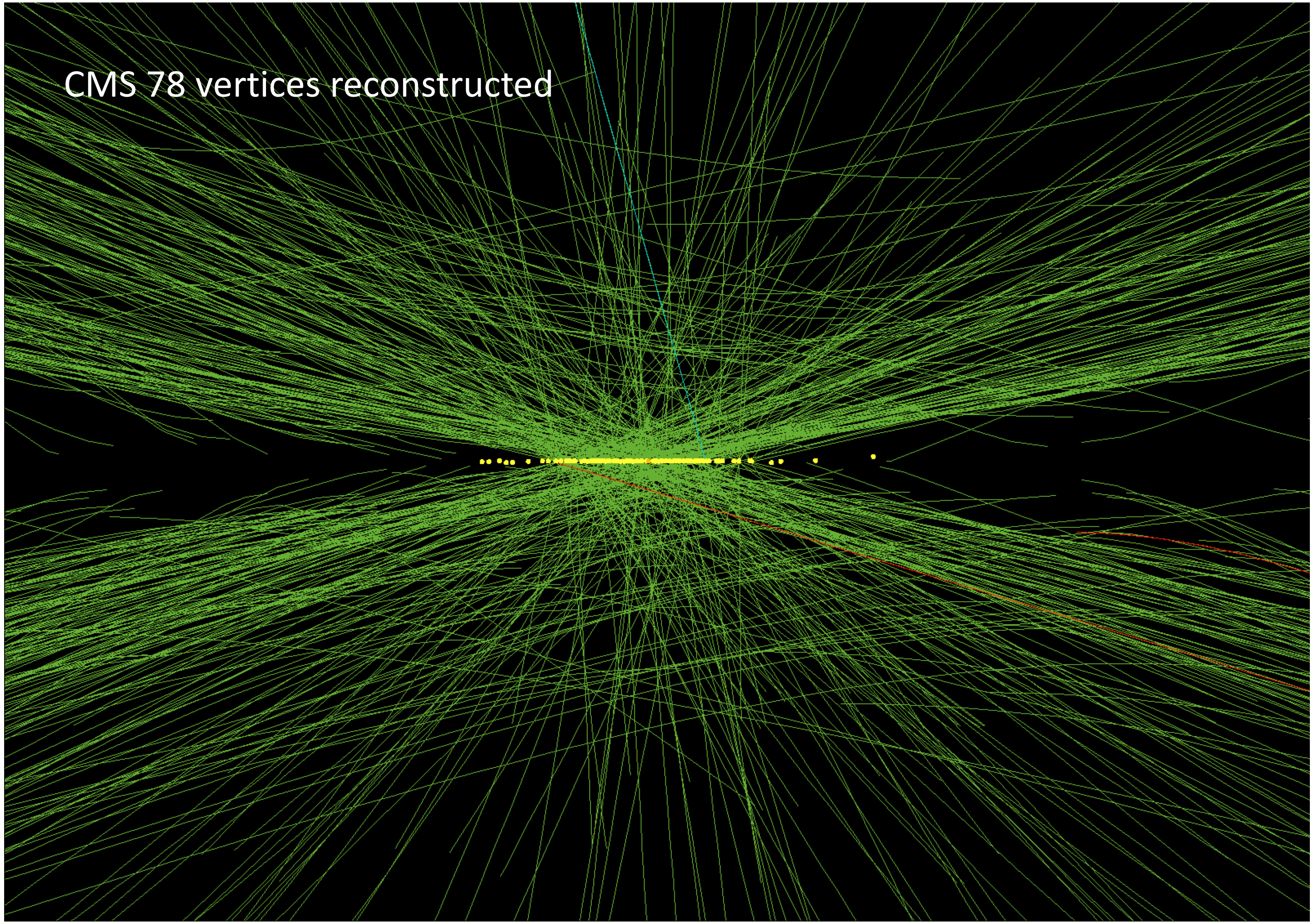
Timing at High Luminosity HEP Experiments

Time can be considered a 4th dimension coordinate in particle tracking in High Luminosity HEP experiments

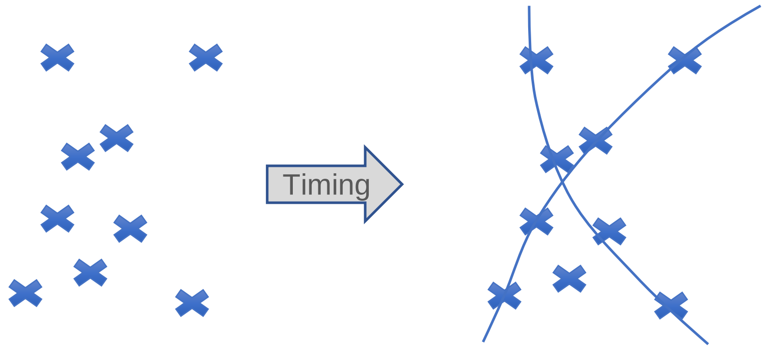
Silicon Detectors provide excellent spatial resolution (**~10μm**), aim is to determine the timing of the passage of the particle with resolution **~10ps** (current best performance in NA62, 300x300μm pixel Gigatracker with **150ps**)

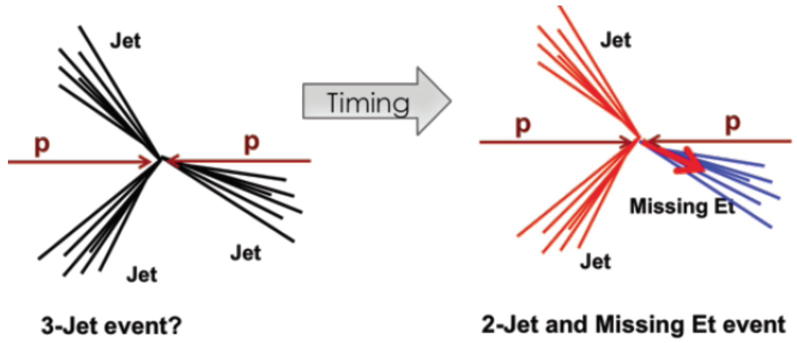


How to make use the timing information

1. Improve reconstruction by adding time information to each track point
2. Determine the correct vertex track assignment

Correct **event reconstruction** | Correct **trigger assignment**

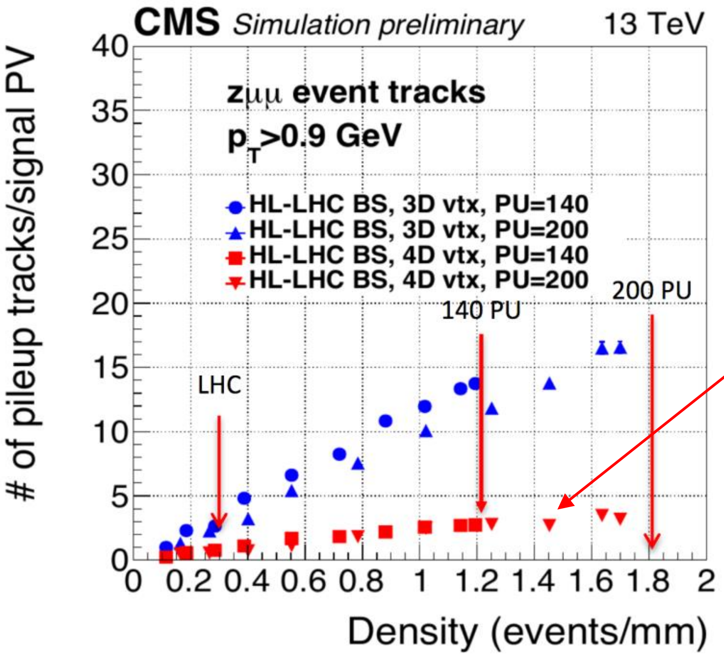




IN HL-LHC

- 150-200 vertices / beam crossing
- $<\Delta z_{vertices}> = 500\mu m$
- $<t_{vertex}>_{RMS} = \sim 200ps$
- a vertex separation resolution of 250-300µm ➔ 10-15% overlapping 2 events

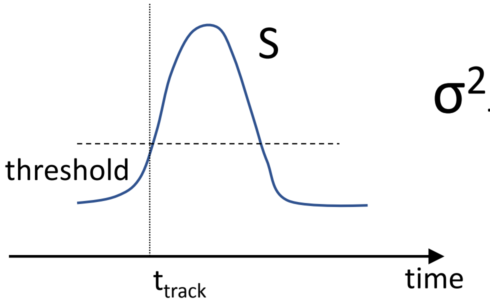
Event loss = Luminosity loss



4D = add 30ps timing information

~x5 pileup (@ PU=200) reduction in terms of associated tracks

Silicon Detector Time Resolution



$$\sigma^2_t = \sigma^2_{Jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{Landau\ Noise} + \sigma^2_{Distortion} + \sigma^2_{TDC}$$

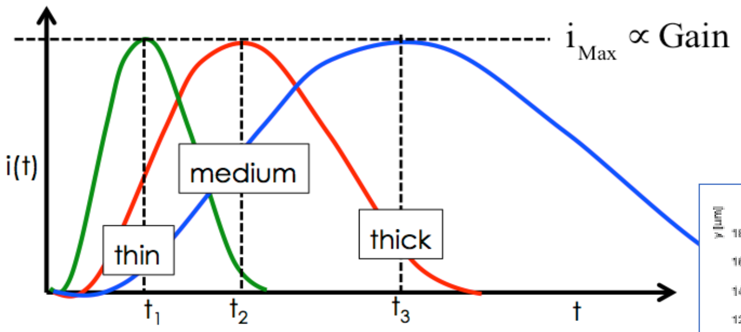
Negligible
Optimize FE electronics

Negligible
Optimize RO electronics

$\sigma_{Jitter} \approx N/(dV/dt) \approx t_{rise}/(S/N)$

➔ needs **Gain** to increase S

➔ needs **thin detector** to decrease t_{rise}



NB: signal amplitude DOES NOT depend on detector thickness

$I_{Ramo} \approx q\, v_{drift}\, E_w$

Requires **uniform v_{drift} and E_w**

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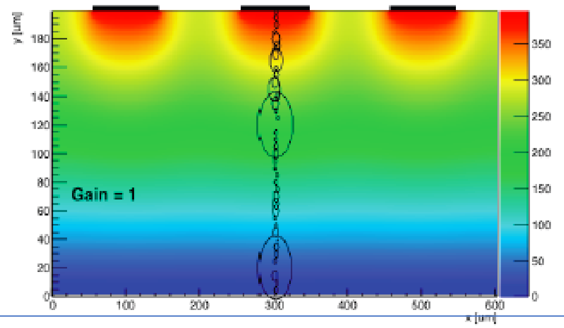
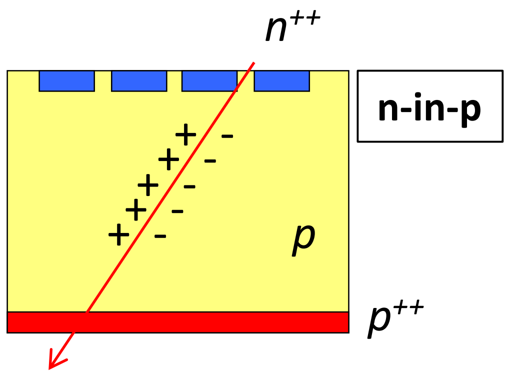


Decreases with detector thickness

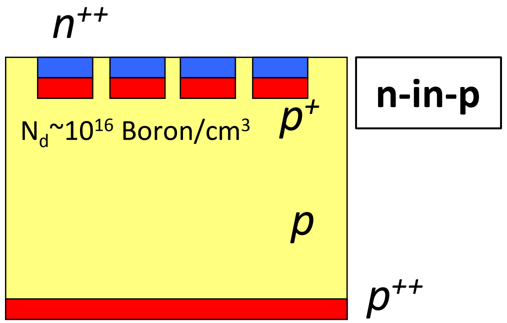
Intrinsic Limit $\sigma_{Landau\ Noise} \approx 20ps$

use **Low Gain Avalanche Detectors layout** (Gain ~5-20 in p^+/n^{++} junction with E~300kV/cm) and optimize design in order to

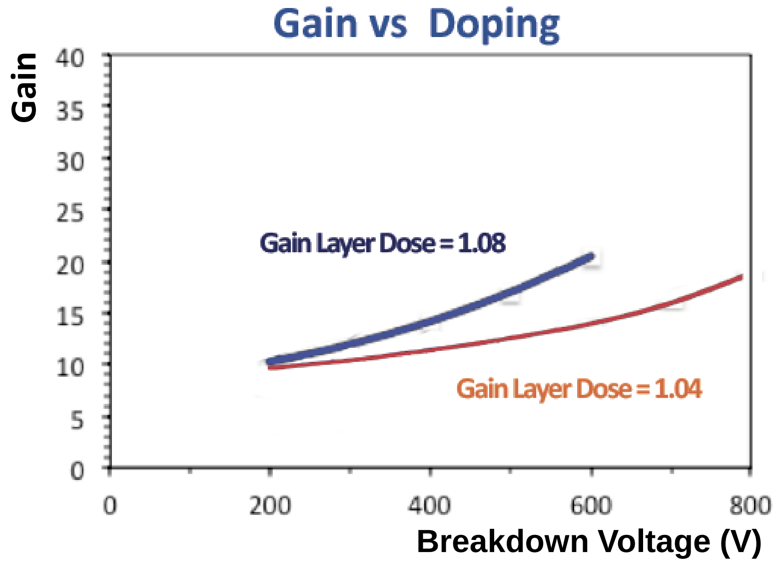
- use high E to saturate and uniform v_{drift}
- high resistivity to have uniform E
- use high density segmentation
- low gain ➔ better uniformity
- gain ➔ thin detectors (~50µm) to have low signal t_{rise}



Traditional Si detectors

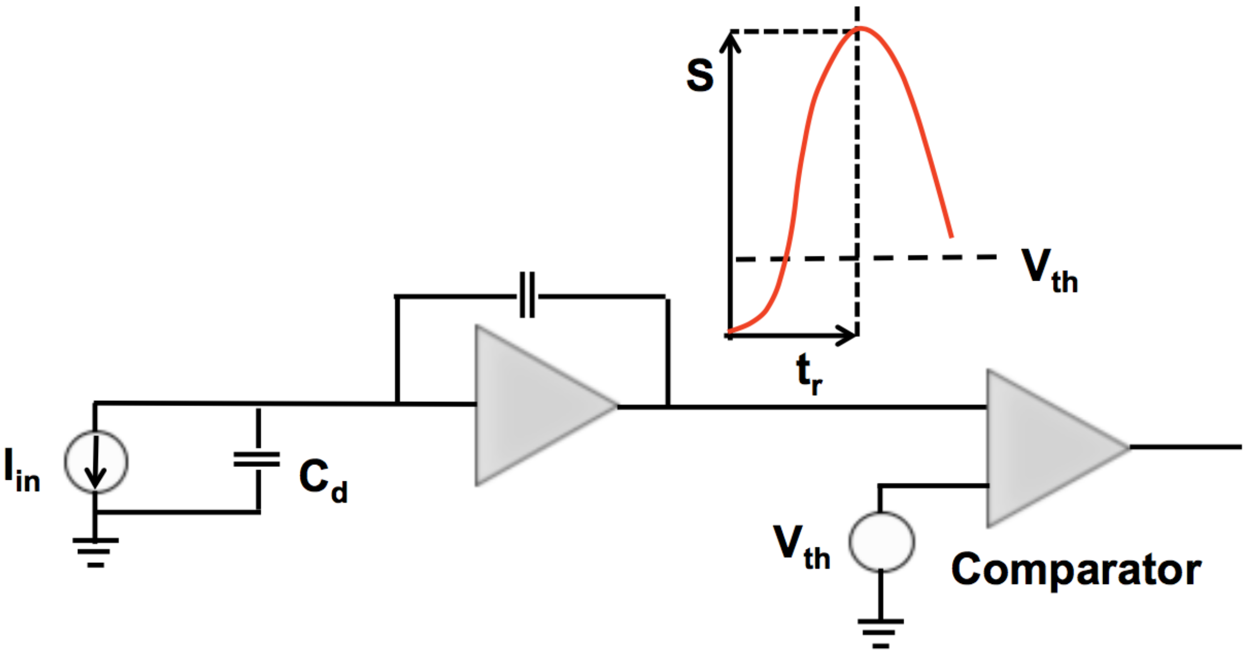


Ultra Fast Si detectors



Gain **very sensitive** to doping concentration (few %)

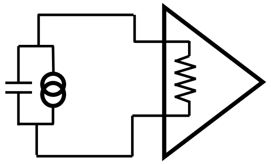
Characteristics of FE Electronics



Correct Time Walk by:

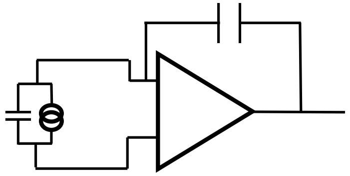
Sensor | Pre-amplifier | Time measuring circuit → Time over Threshold / Constant Fraction Discriminator

Current Amplifier



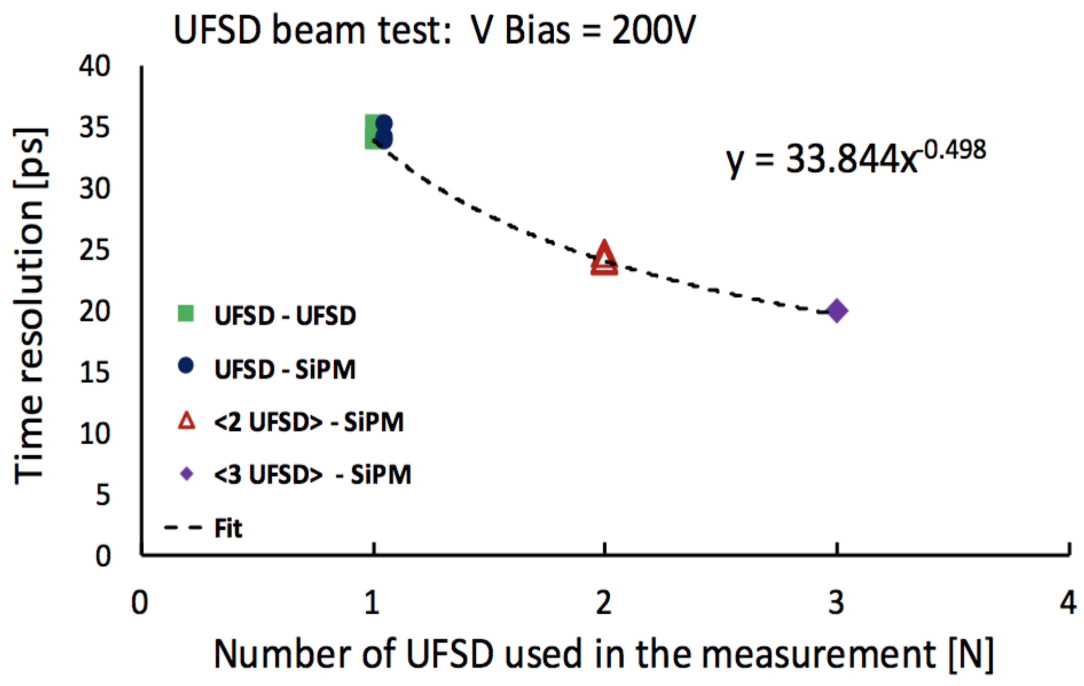
- Fast slew rate
- Higher noise
- Sensitive to Landau bumps
- More power

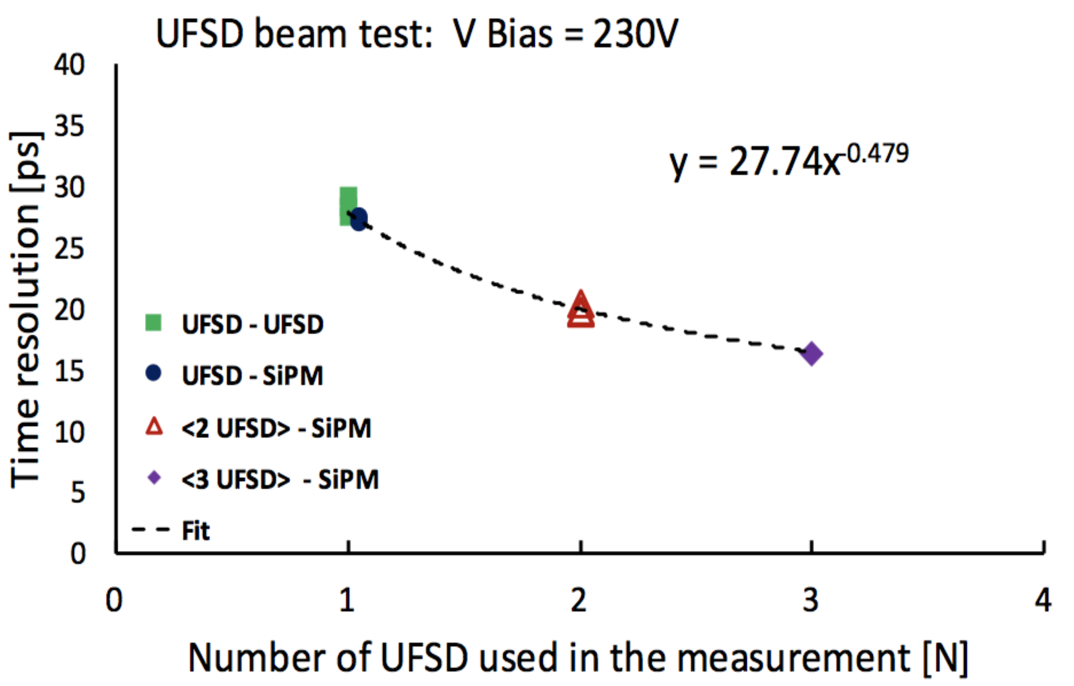
Integrating Amplifier



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

Time Resolution: Beam Test Measurements

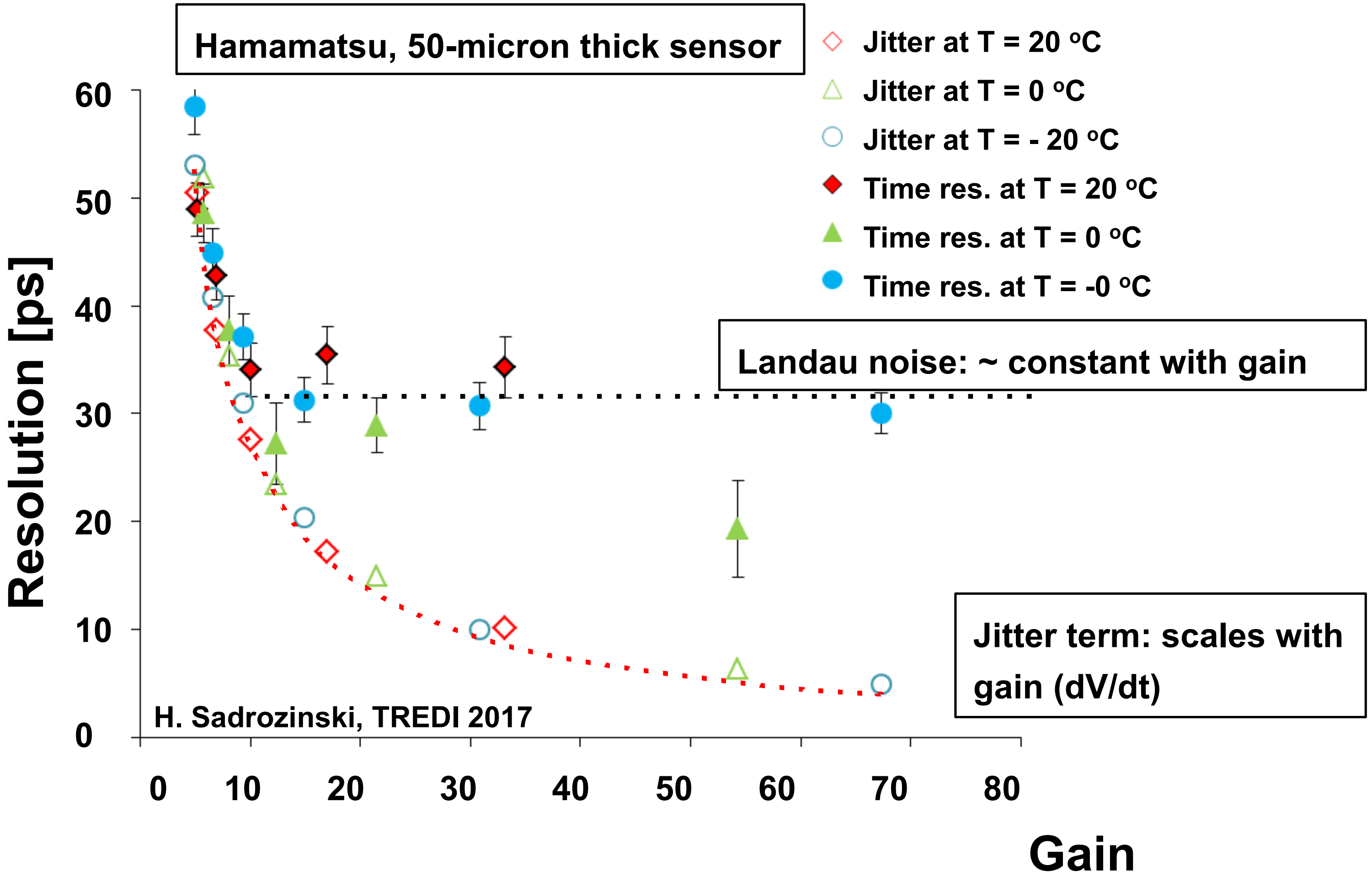




3 **CNM** 45µm thin detectors, 1.7mm^2 single pad + 1 SiPM on quartz for timing crosscheck

The time resolution of a single UFSD is measured to decrease with increased gain M like $M^{-0.36}$ (from **34ps**@200V to **28ps**@230V)

Time Resolution: Measurements



Consistent with simulation and CNM Beam Test Data (previous plot)

Radiation Tolerance

LGAD radiation tolerance studied within the CERN RD50 collaboration
Radiation fluences requested to operate at HL-LHC ~5 10^{15} particles/cm^2 , radiation doses of 150Mrad (primarily due to **N**on-**I**onizing **E**nergy **L**oss)

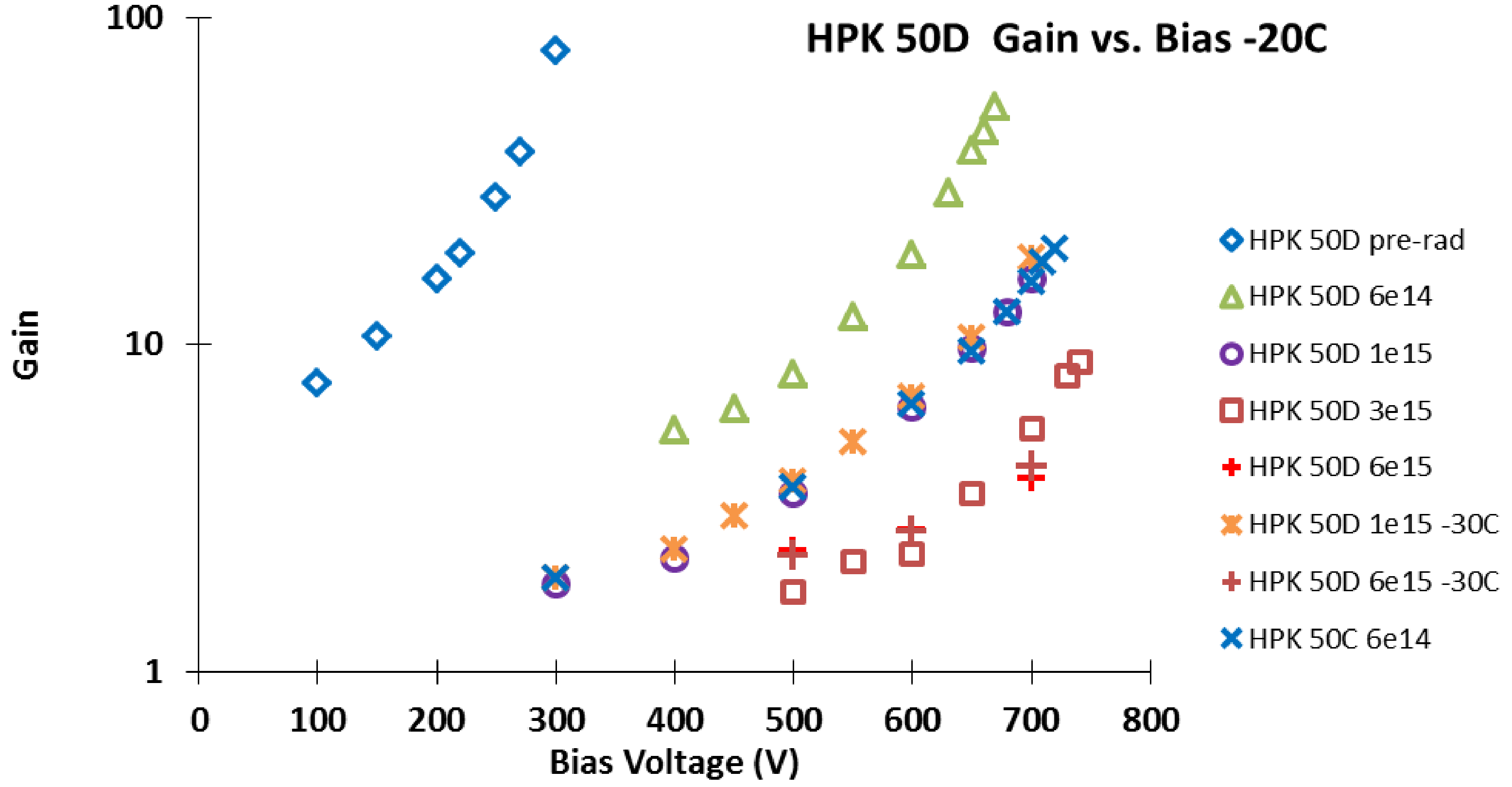
Effects:

1. Same effects of standard n-p Si detectors: increase of Leakage Current (decrease T), increase of V_{BD} and $V_{FD,}$ due to increase of doping concentration. Creation of trapping centers (minimize the effect going to **thin sensors (!)**)

2. In LGAD:
   1. Further increase of leakage current (and power) due to gain layer: **go thin, keep gain low**
   2. Gain loss due to gain layer acceptor removal. Boron atoms are displaced and become interstitial, thus not contributing to the doping profile: **increase V_{bias}, change acceptor (add Carbon to decrease interstitial phase space, and replace Boron with Gallium)**

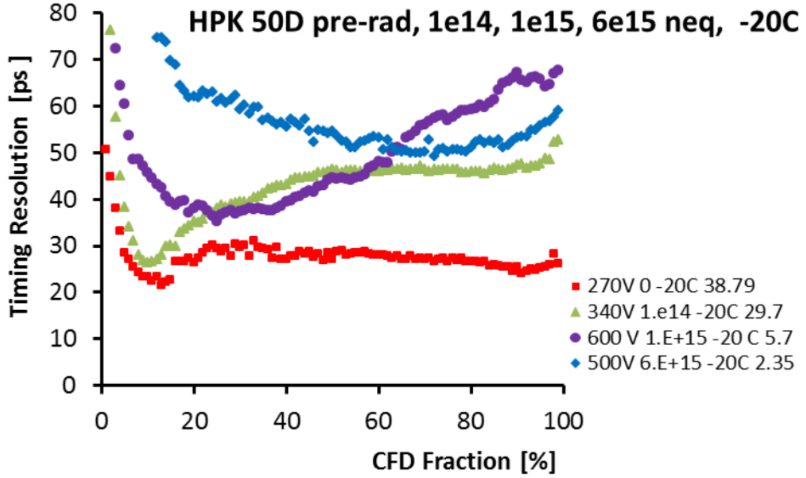
Radiation Tolerance

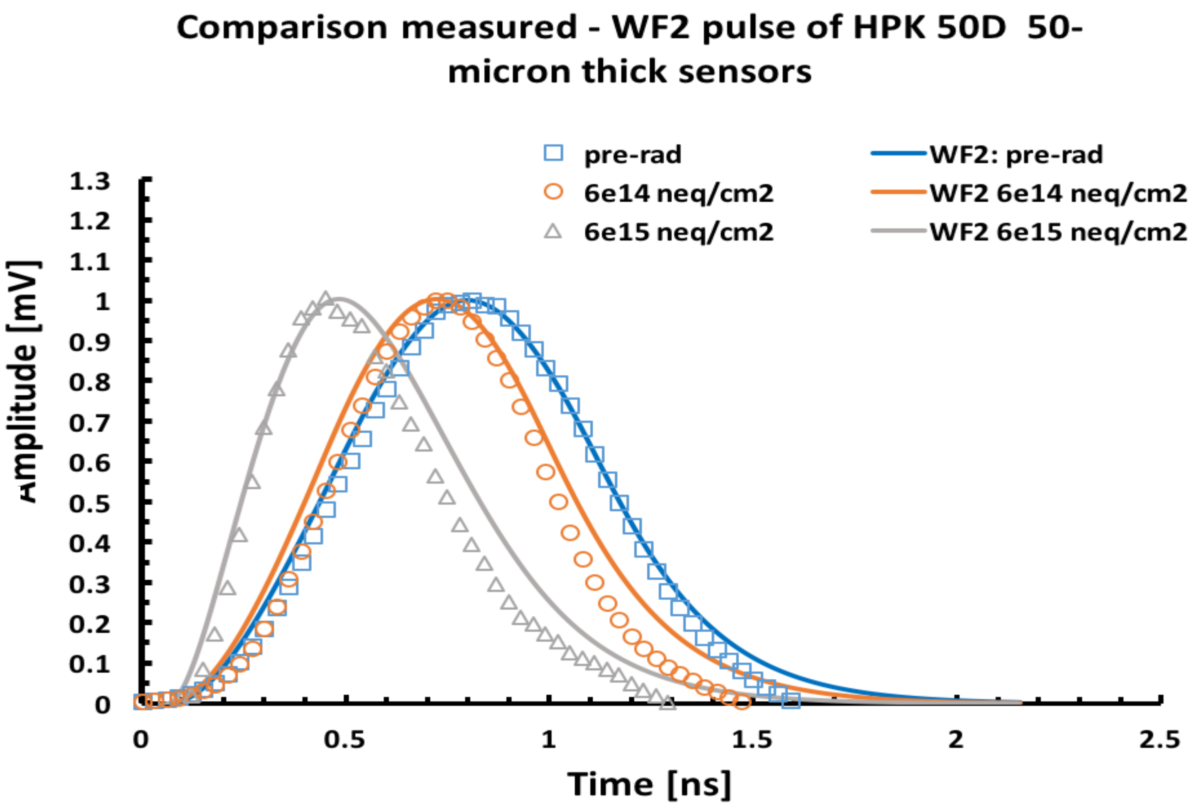
Measurements from 50μm thin HPK detectors, fully consistent with simulation expectations: gain decreases with increasing fluences and it is partially recovered by increasing V_{Bias}



Excellent agreement of signal simulation (WF2) with data.

High fluence increase dV/dt and shorten the signal. This makes preferable CFD, provided it is tuned vs fluence, over ToT time measurement.

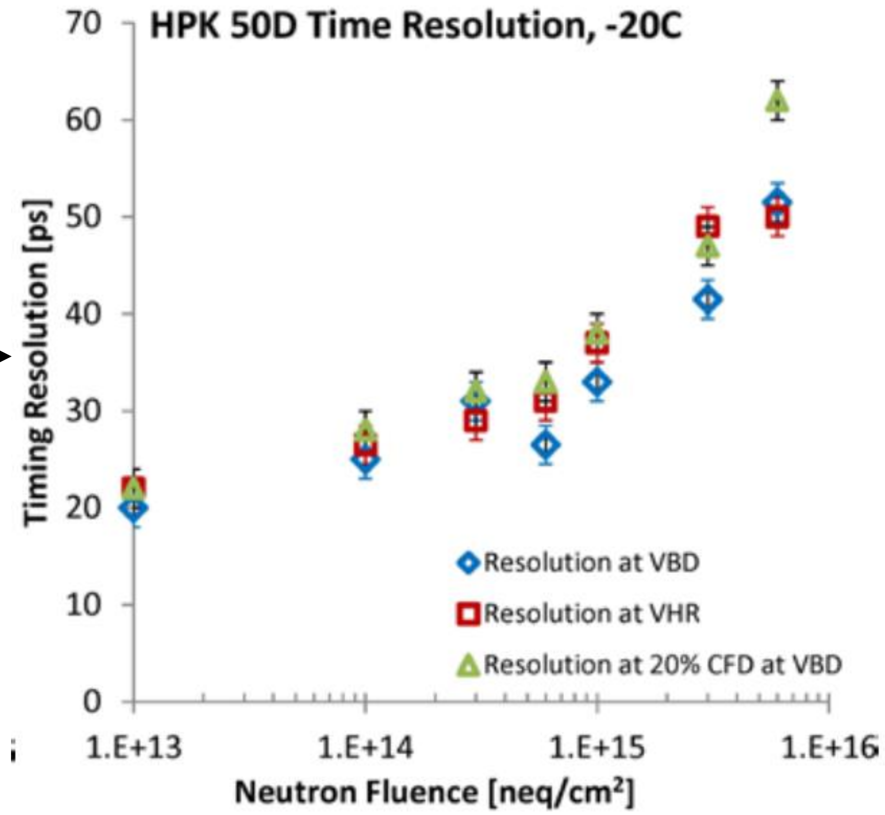




Radiation Tolerance

Increasing the fluence:

1. Break Down Voltage increases (from 300V at pre-irradiation to 750V at highest tested fluence
2. Gain at V_{BD} decreases
3. For a CFD fraction optimized for each fluence and bias, the time resolution increases from 20 ps pre-irradiation to 40 ps at 1 10^{15} n/cm^2 up to 50 ps at 6 10^{15} n/cm^2
4. Even if the gain at large fluences decreases, the increase of the rise time in the pulse height still compensates and guarantees good time resolution
5. Reducing the temperature from -20C to -30C improves the timing resolution by 10% at large fluences where the gain is reduced to below 3.
6. The “headroom” between the breakdown voltage and an operating condition at lower bias causes a reduced timing resolution of a few ps.



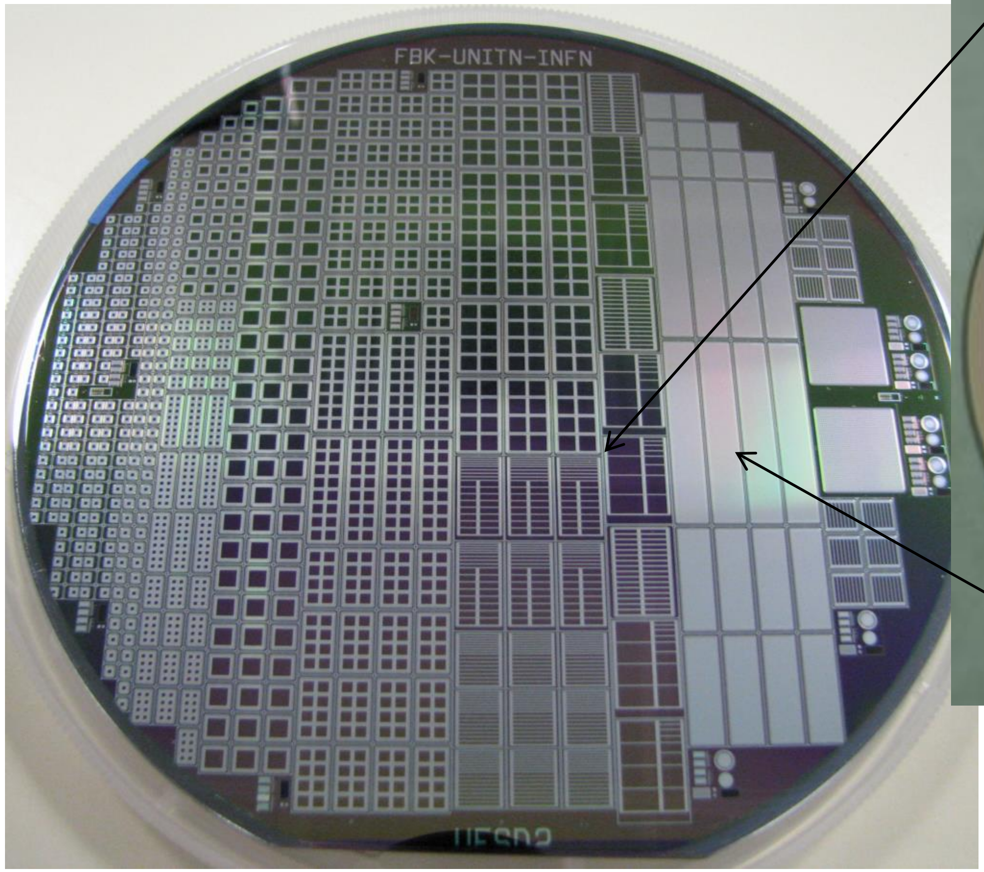
Sensor currently under test: new FBK production

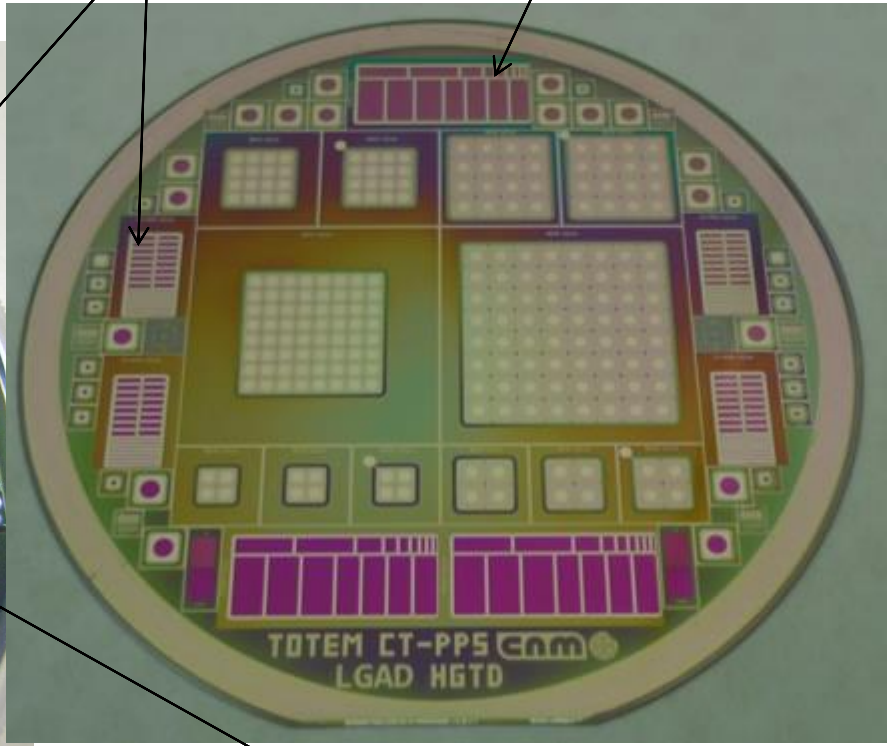
FBK 50-micron production (II FBK Run)
Very successful, good gain and overall behavior
Gain layer: **Boron, Gallium, Boron+Carbon, Gallium+Carbon**

CNM 75-micron
CNM 50-micron production

x4 CT-PPS

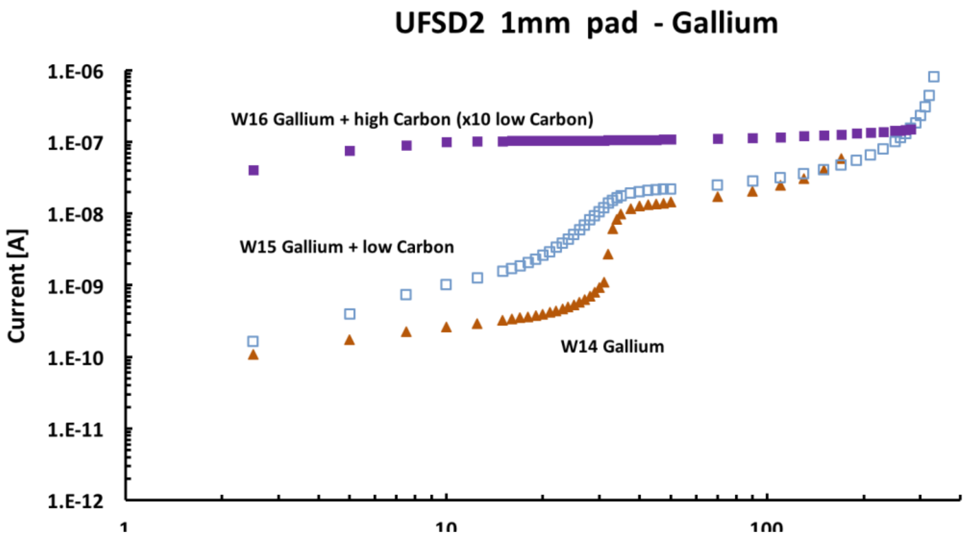
x3 TOTEM

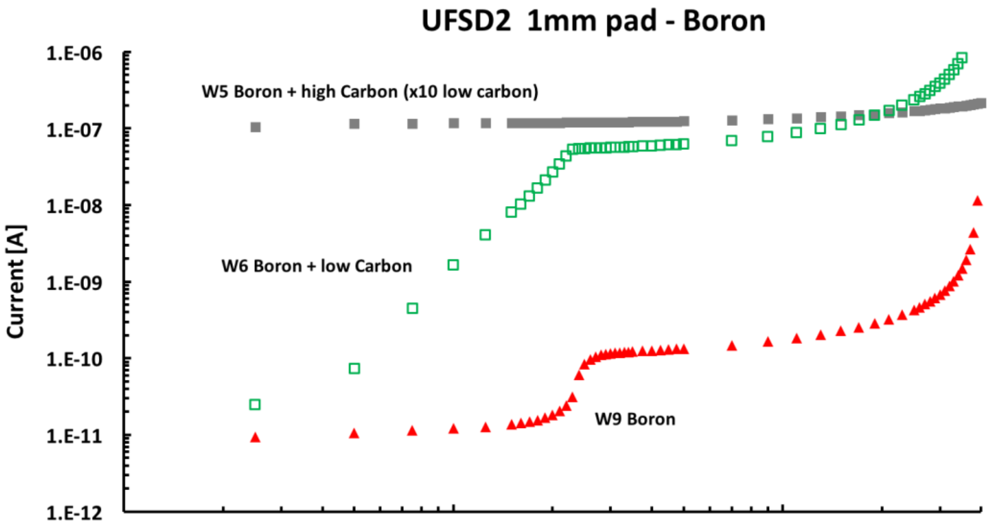


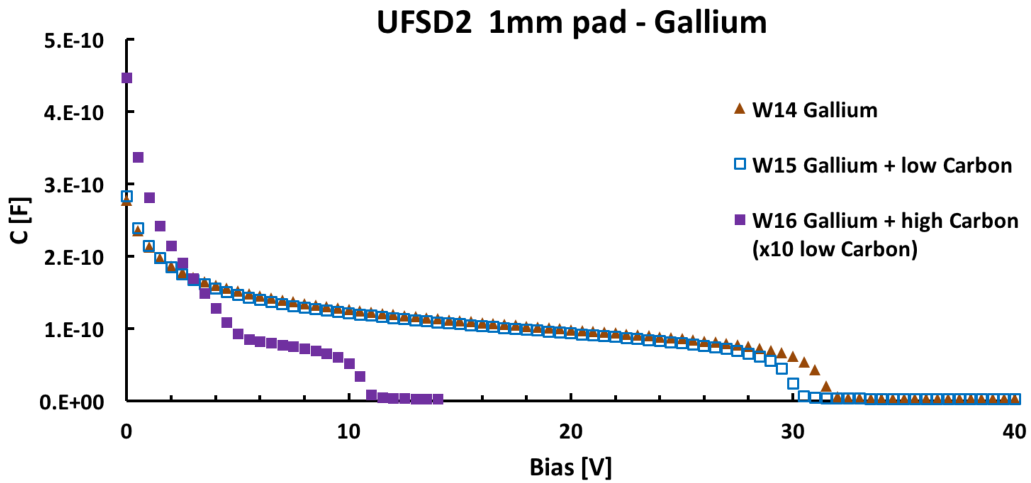


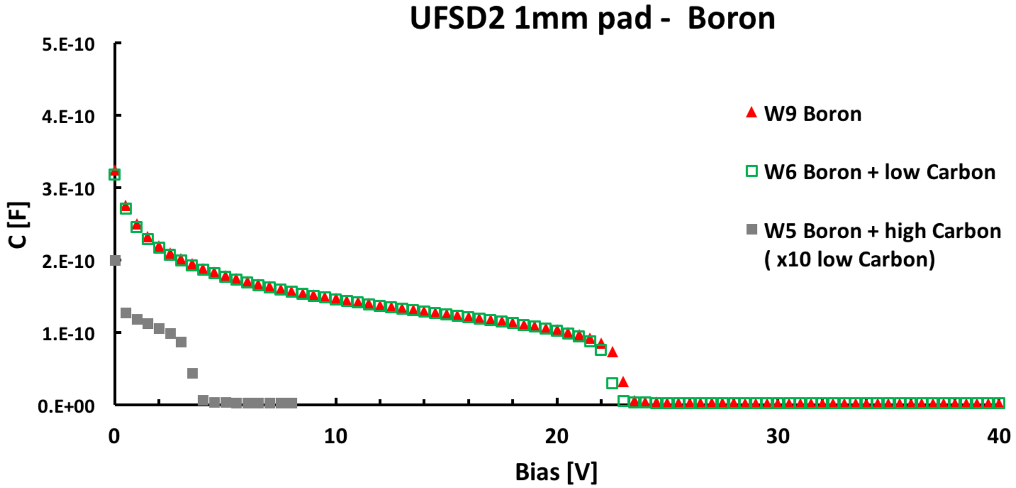
Medical Physics Timing Det.

Sensor currently under test: new FBK production, Ga, B and C



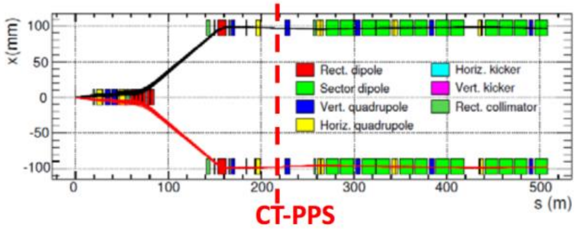




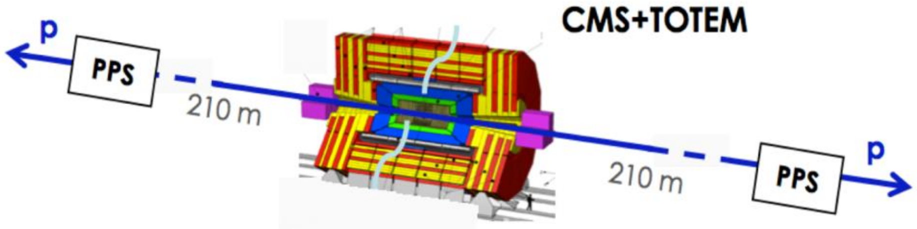


CT-PPS Project

- The CMS TOTEM Precision Proton Spectrometer (CT-PPS) aims at measuring the surviving scattered protons on both sides of CMS in standard LHC running conditions, using LHC magnets to measure the proton momentum
- Tracking and timing detectors at ~ 220 m from CMS inside Roman Pots to be able to move as close as possible to the circulating beams
  - Tracking to measure proton momentum
  - Timing to disentangle pile-up



- Project TDR approved in Dec. 2014 by LHCC and CERN Research Board
- CT-PPS already took data in 2016 with an 'accelerated program' configuration (see M. Murray's talk for results)
  - Si strip & Diamond detectors from TOTEM experiment used
- CT-PPS started data taking with the baseline detector configuration in May 2017 and detector commissioning is ongoing
  - 3D Silicon Pixels & Strips for tracking
  - Diamonds + UFSD for timing

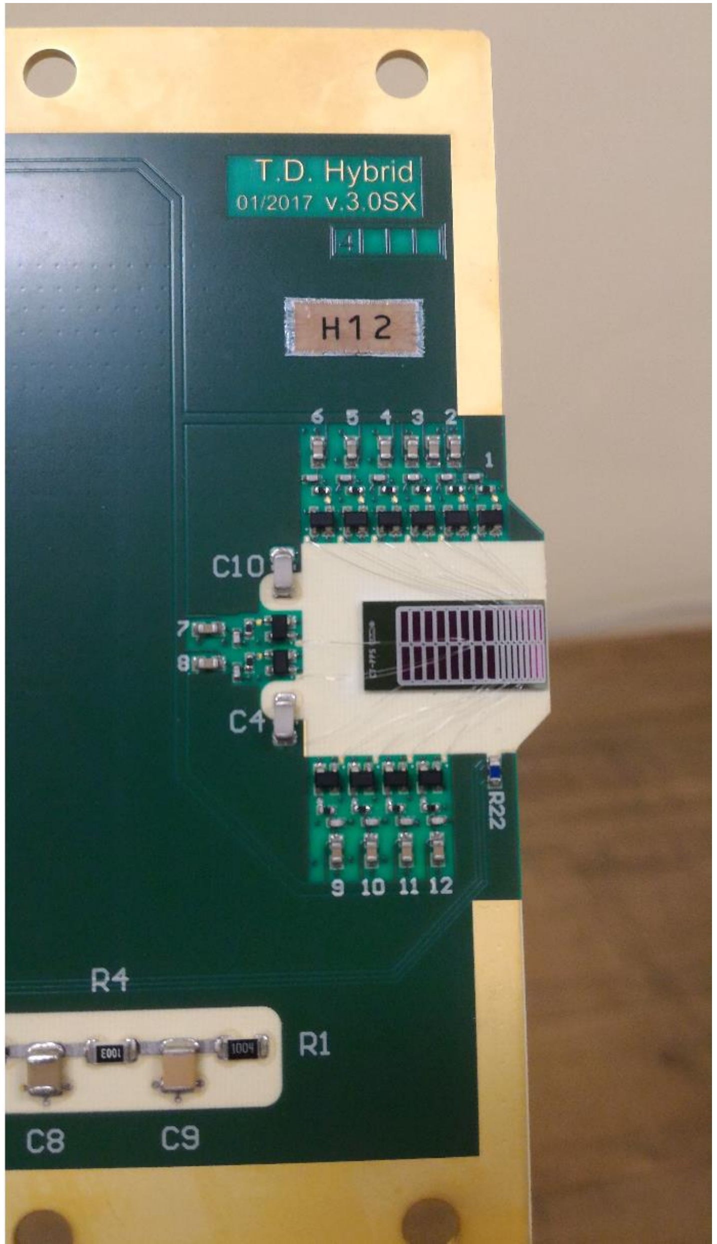


CT-PPS UFSD Timing Detectors

1 UFSD Plane installed (first prototype on HEP experiment!)

- 8 0,5x6mm^2 and 4 1x3mm^2 pads
- Expected time resolution 35ps/plane
- FE electronics on TOTEM custom hybrid
- RO with NINO chip and HPTDC
- Timing signal to be compared with a parallel scCVD Diamond detector

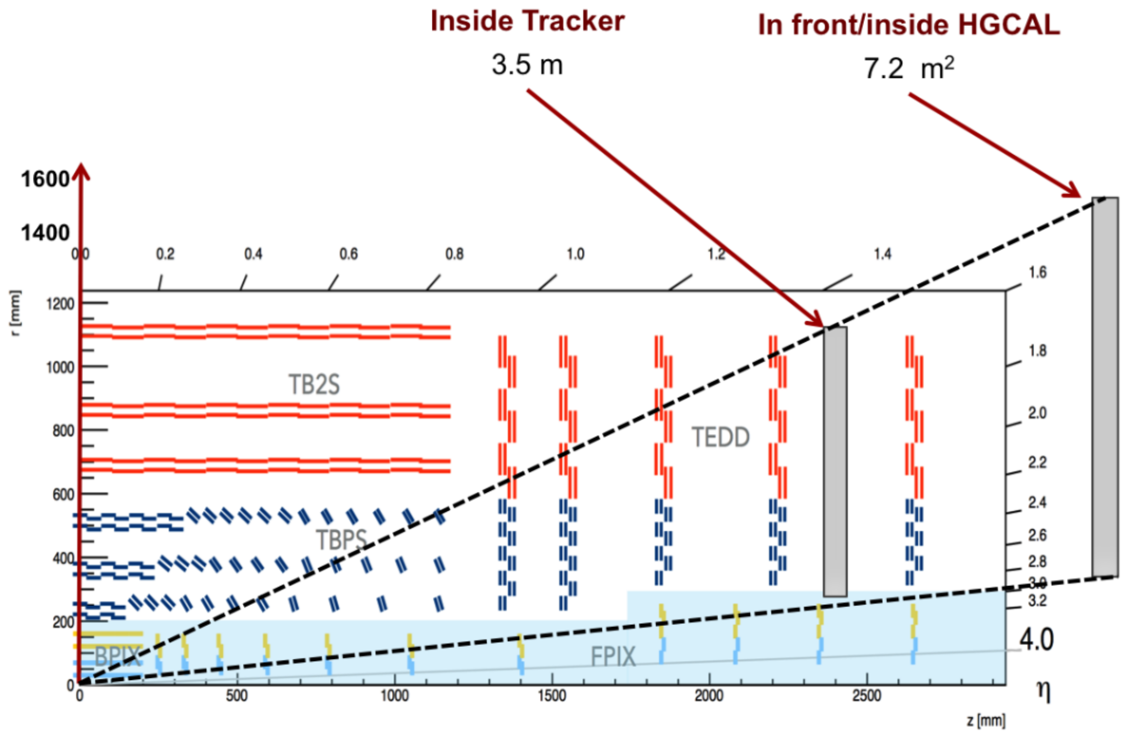
Installation completed in April 2017 and system currently taking data



Proposal for a Forward Timing Layer for CMS HL-LHC

ATLAS and CMS are discussing the possibility to equip the experiments with a large area Timing Layer made of UFSD.
In CMS would cover the region $1.45 < \eta < 3$

- keep occupancy < 1%
- low pad surface area (low leakage current to allow increased V_{Bias}, tipically <3mm^2)
- Low Gain to keep Low noise (Gain<20)
- minimize dead area
- sustain fluxes up to ~10^{15} particles/cm^2
- total detector area ~10m^2



UFSD Summary

- Good results on timing capabilities (~**30ps** from beam test)
- Good results after NIEL at **6 10^{15} neq/cm^{2}**, levels to be considered in HL-LHC. New implants (**Ga, C**) currently under test (last FBK run)
- Good agreement with simulations (**WF2** and **TCAD**)
- Technological interest, many manufacturers (**CNM** (Spain), **FBK** (Italy), **HPK** (Japan), **Micron Semiconductor** (UK))

INFN

Acknowledgments

Thank you for your attention !

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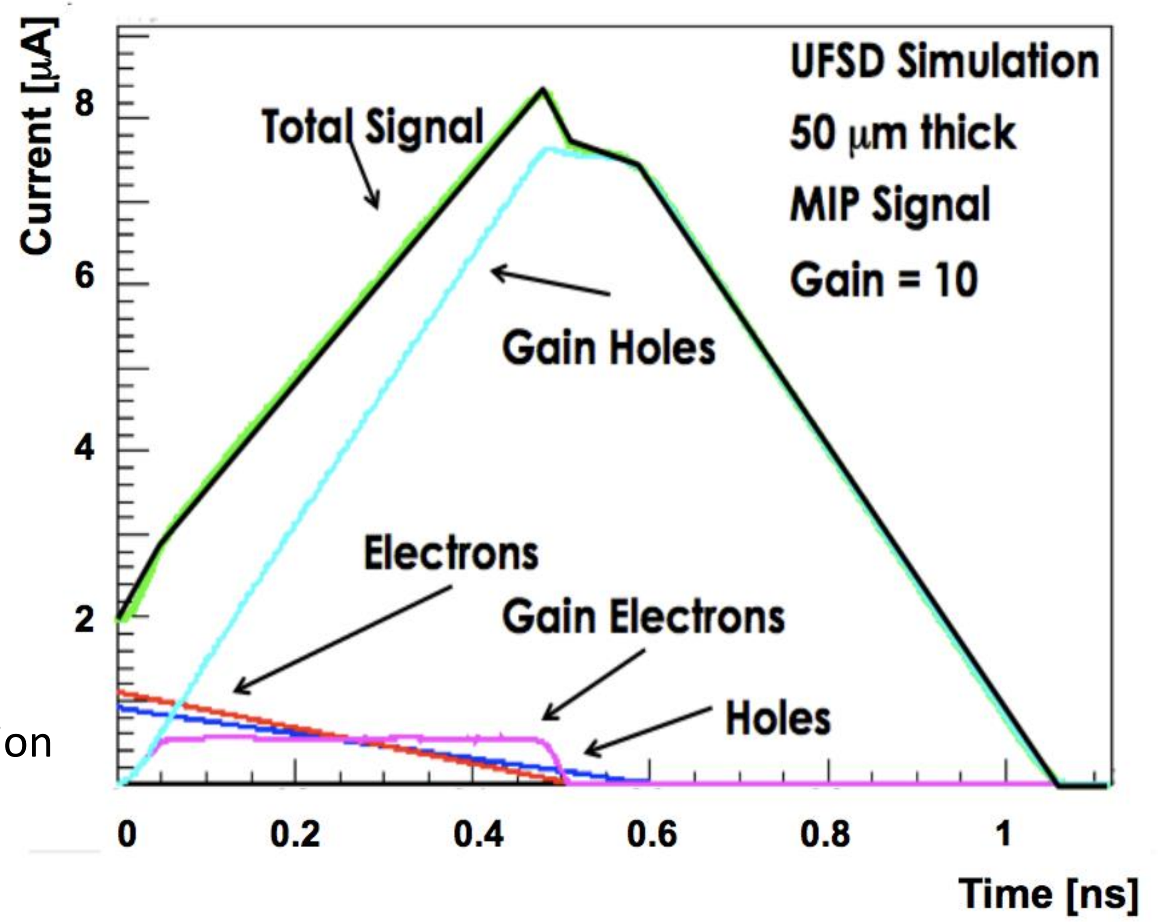
BACKUP SLIDES

LGAD Signal

Signal rise-time is given by electrons drift time

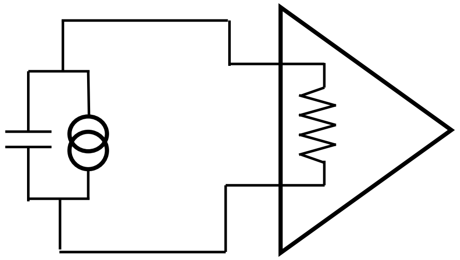
Charge formation and multiplication takes a considerable fraction of time.
Gain Holes dominate the signal, whilst Gain Electrons current contribution is negligible.



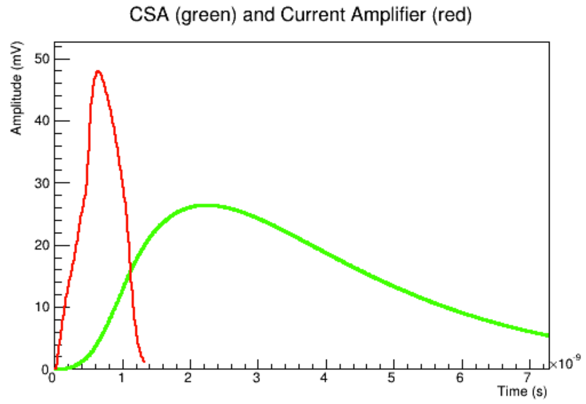
Weightfield2 Simulation

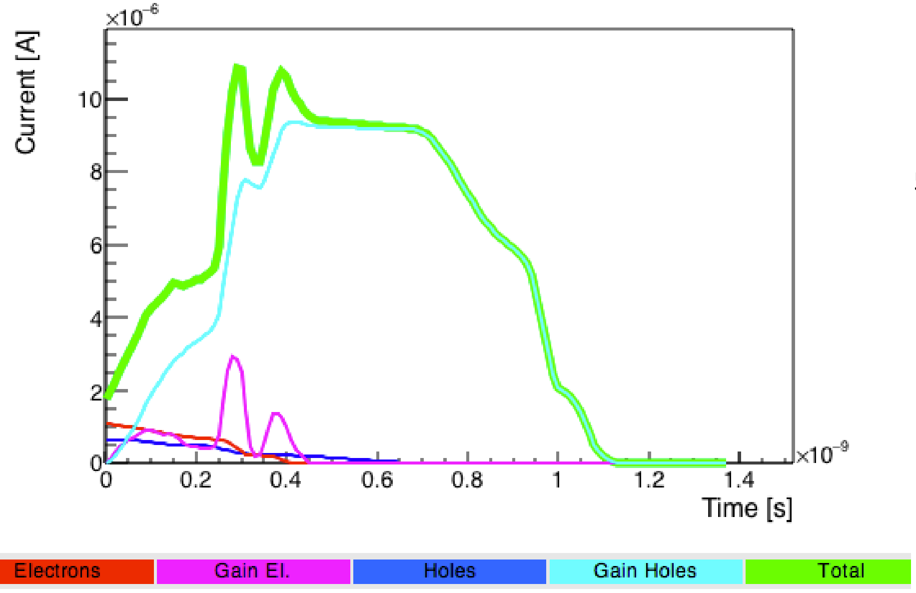
Possible Choices of Preamplifier

Current Amplifier



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





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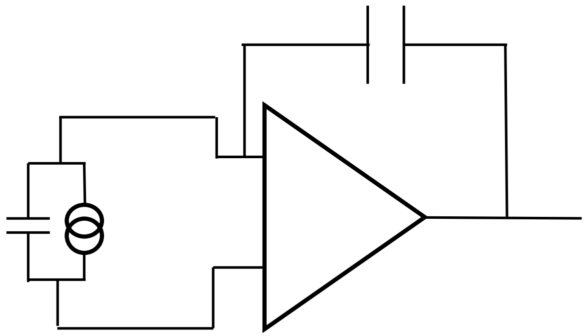
Integrating Amplifier



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

Time Resolution Optimization

As expected, the jitter contribution follows the inverse of the signal derivative: at the start and at the end of the pulse the contribution decreases, as the pulse shape is less steep. The effect of gain is rather predictable: higher gains yield to lower jitter. The Landau noise term, on the other hand, is rather insensitive to the gain value, but shows a clear dependence upon the CFD settings: it is minimized using the minimum possible threshold.