Development of Ultra-Fast Silicon Detectors for 4D Tracking

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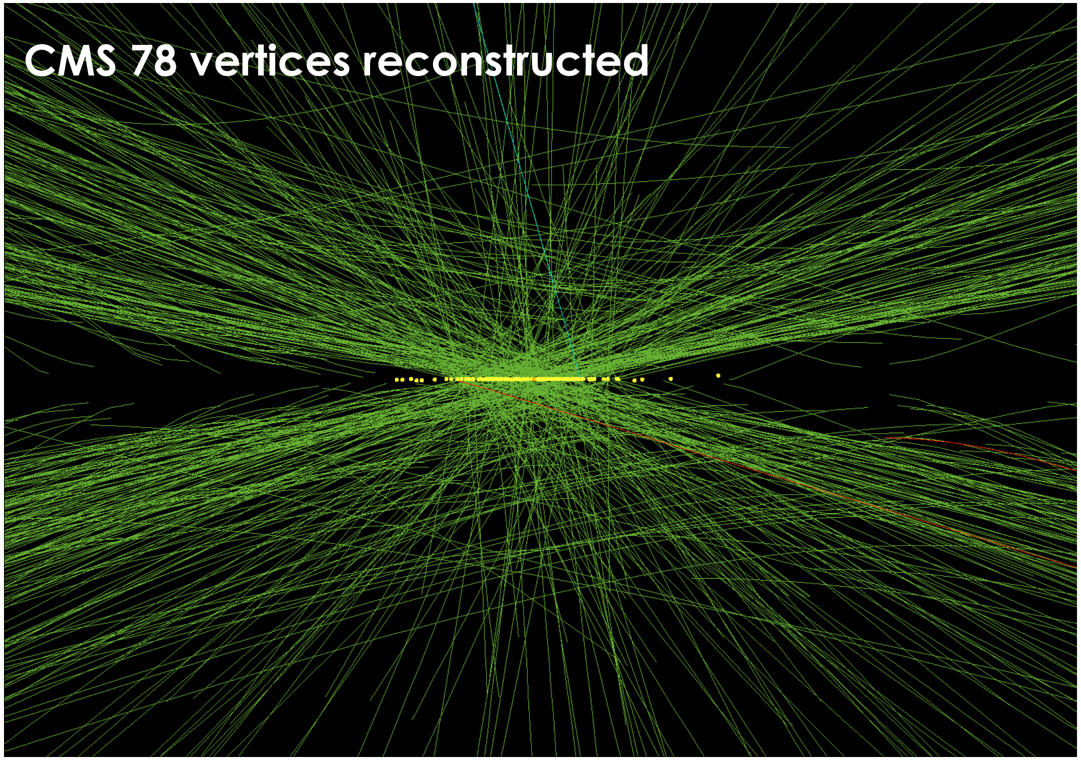
International Workshop on Future Linear Colliders

Timing at High Luminosity HEP Experiments

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

Silicon Detectors can provide excellent spatial resolution, **~10 μm**

The idea is to add the capability of determining the time of a particle with a resolution of **~10 ps**



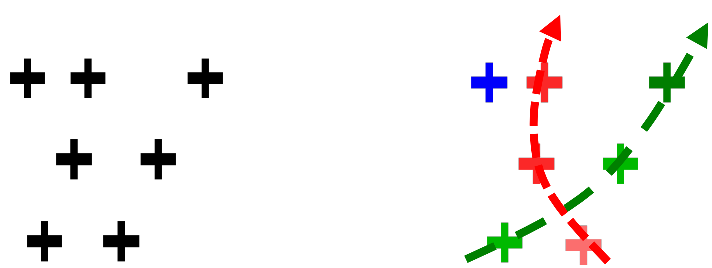
Current best performance obtained in **NA62**: Gigatracker detector - 300x300 microns pixel matrix - with **130 ps** (in 2016). [see E. Migliore talk at Vertex 2017]

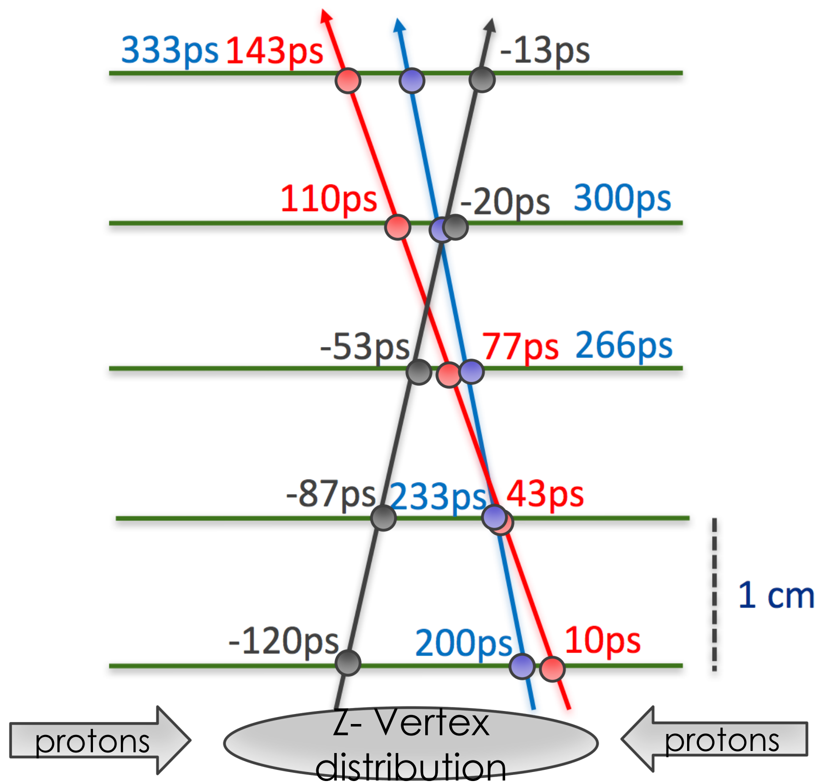
How to make use of timing information

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

The time information can be available:

1) At each point along the track
2) At track level
3) At the trigger level





Massive simplification of patter recognition using only "time compatible points"

How to make use of timing information

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

The time information can be available:

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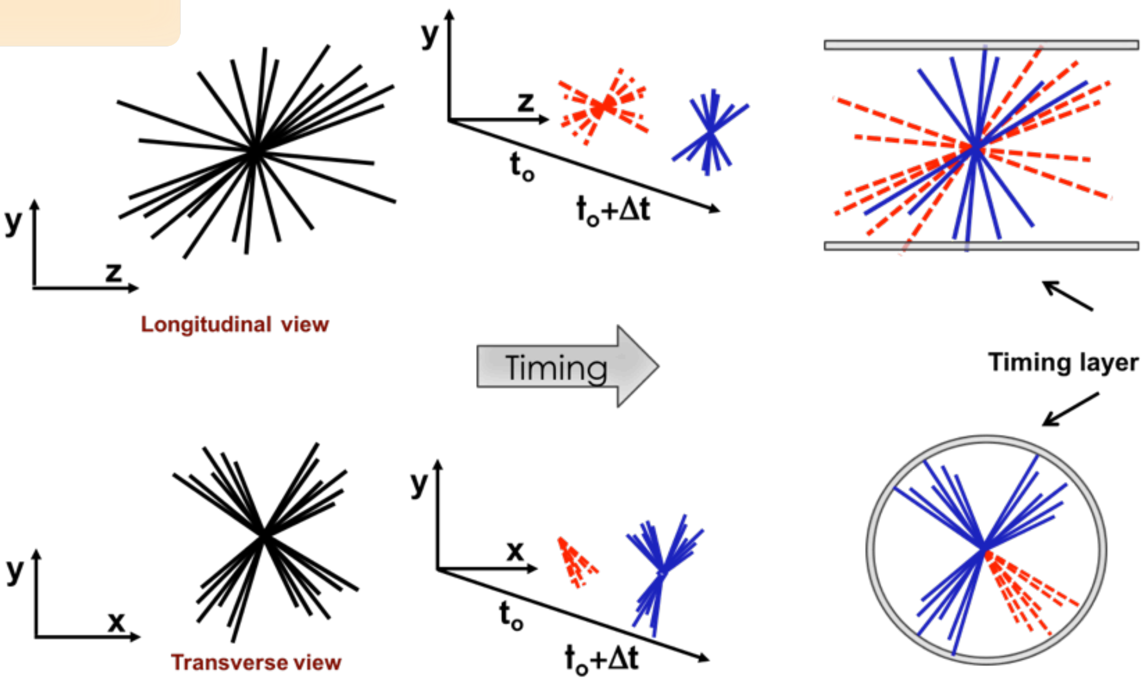
2) At track level
3) At the trigger level

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



How to make use of timing information

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

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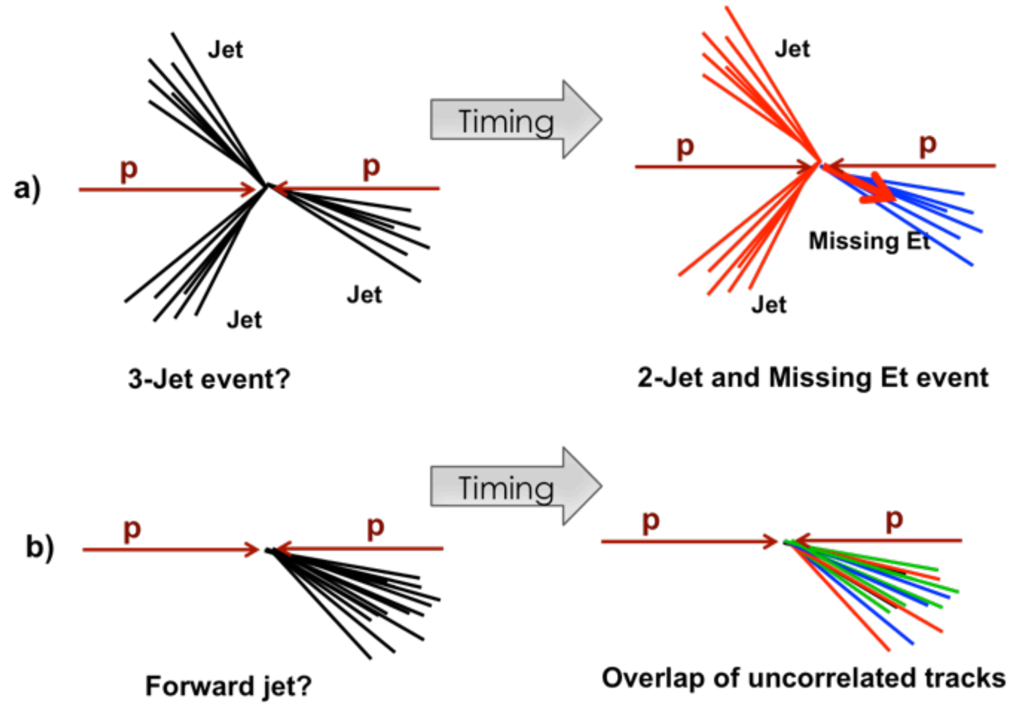
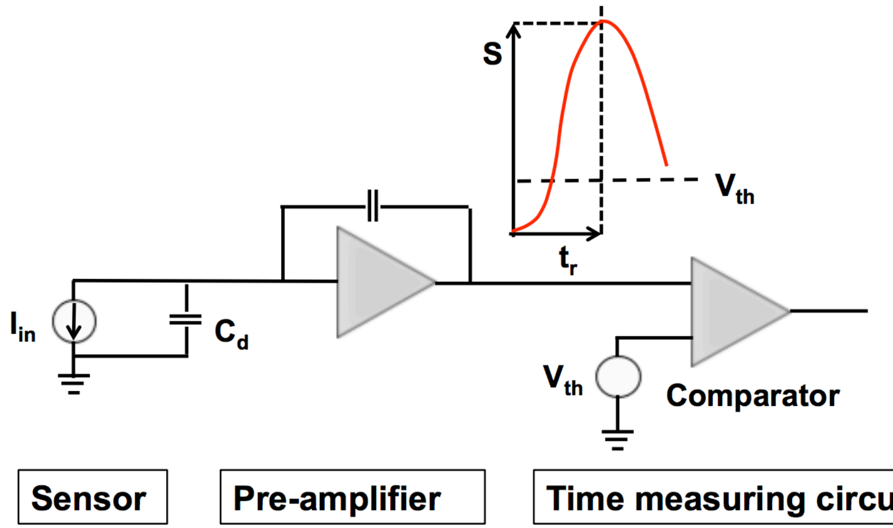
1) At each point along the track
2) At track level
3) At the trigger level

trigger rate reduction: topologies can be better identified at trigger level



How do we measure the time



Time is set when the signal crosses the comparator threshold

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

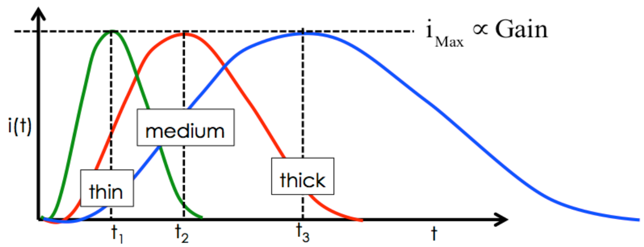
Minimized by correction techniques

Minimized by optimized RO electronics

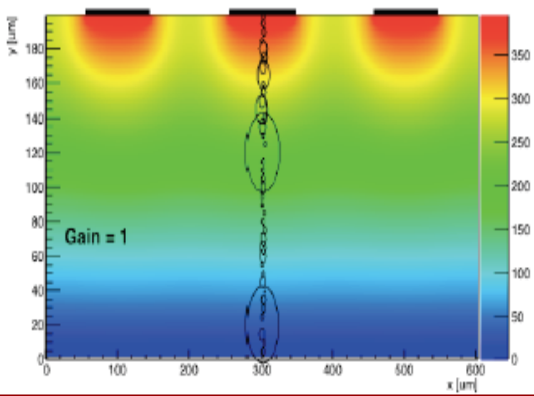
How do we measure the time

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

- need **gain** to increase S
- need **thin detector** to decrease t_{rise}



Non uniform charge deposition
Decreases with detector thickness



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Minimized by correction techniques

Minimized by optimized RO electronics

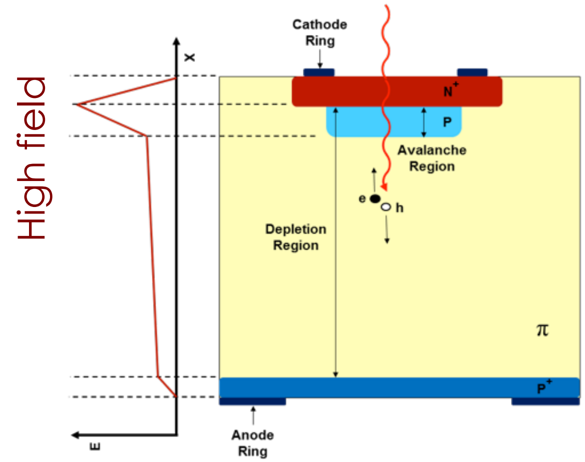
$\mathbf{I_{Ramo} \approx q\, v_{drift}\, E_w}$

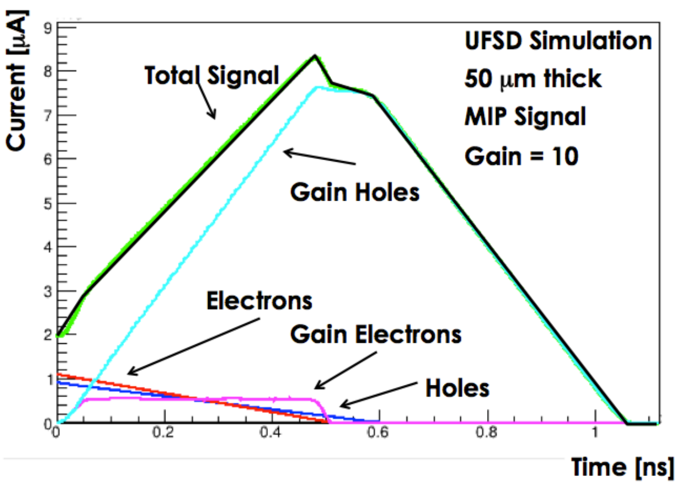
Requires **uniform** $\mathbf{v_{drift}}$ **and** $\mathbf{E_w}$

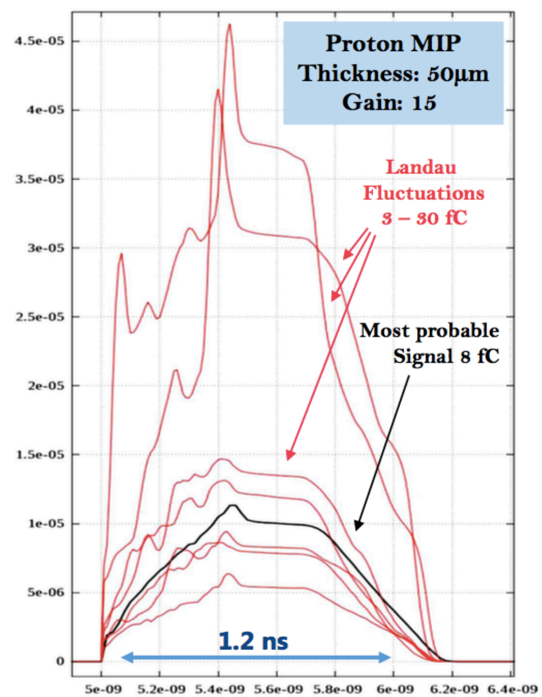
Ultra Fast Silicon Detectors

LGAD sensors optimized for timing measurement of MIPs

Low internal gain (~15-20) through thin multiplication layer
Low shot noise

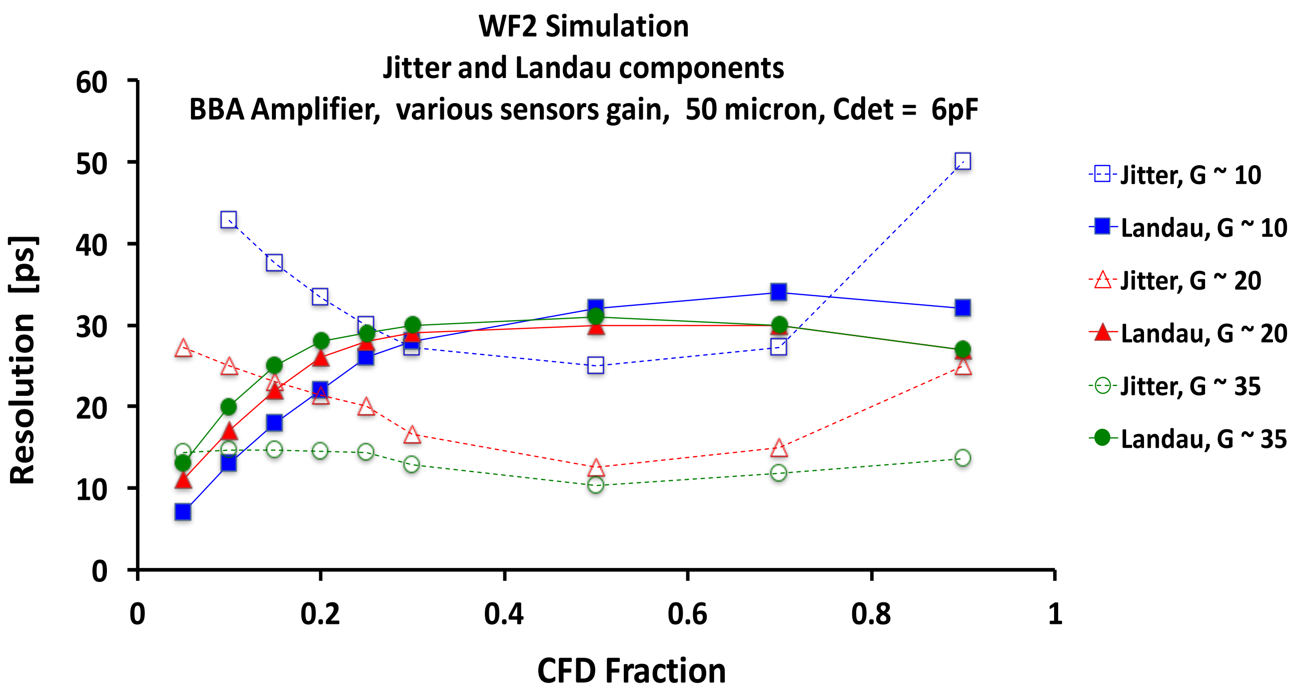






The main contribution to the signal comes from gain holes. The signal shape depends on the sensor thickness and gain

Time Resolution with 50-micron thick LGAD



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

LGADs productions history

2010: LGAD proposed & developed at CNM within RD50 collaboration

2012: First 4" wafer 300 μm thick, LGAD produced by **CNM**

2016:

First 75 μm and 50 μm thick LGAD produced by **CNM** for timing applications (ATLAS HGTD and CMS CT-PPS) - SOI and SOS, 4" wafer

First 300 μm thick LGAD produced **FBK**, Trento (p-side and n-side segmentation, pixel, strip, AC coupling, ...)

2017:

First 50 and 80 μm thick LGAD produced **HPK**

First 50 μm thick LGAD produced by **FBK** (6" wafer)

First LGAD production by **Micron**

Today 4 suppliers: CNM Spain, FBK Italy, HPK Japan and Micron in UK

FBK and CNM UFSD wafers

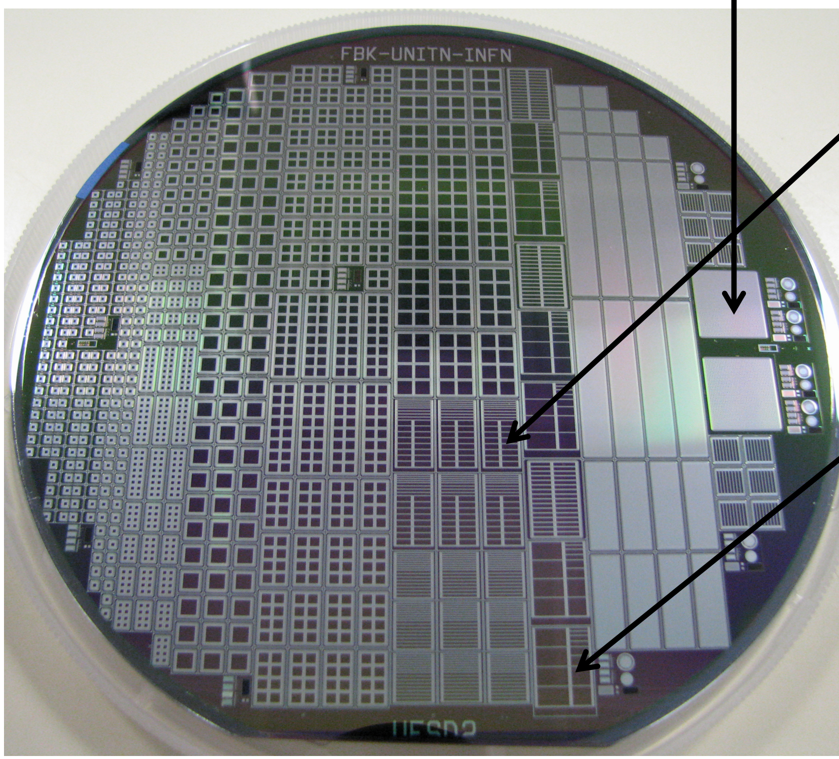
FBK 50-micron production

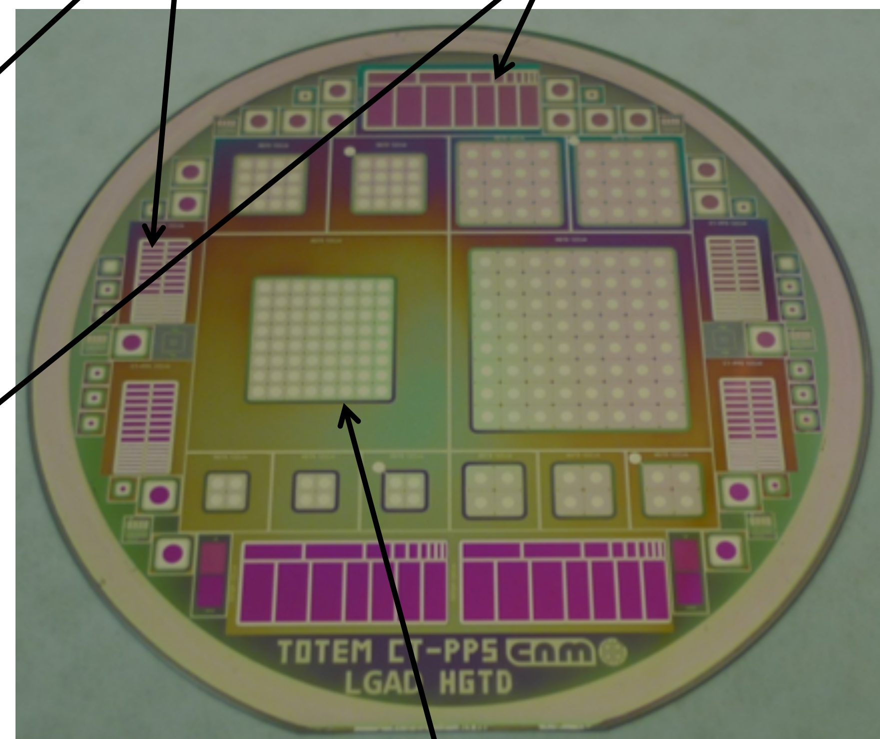
CNM 75-micron
CNM 50-micron production

NA62

CT-PPS

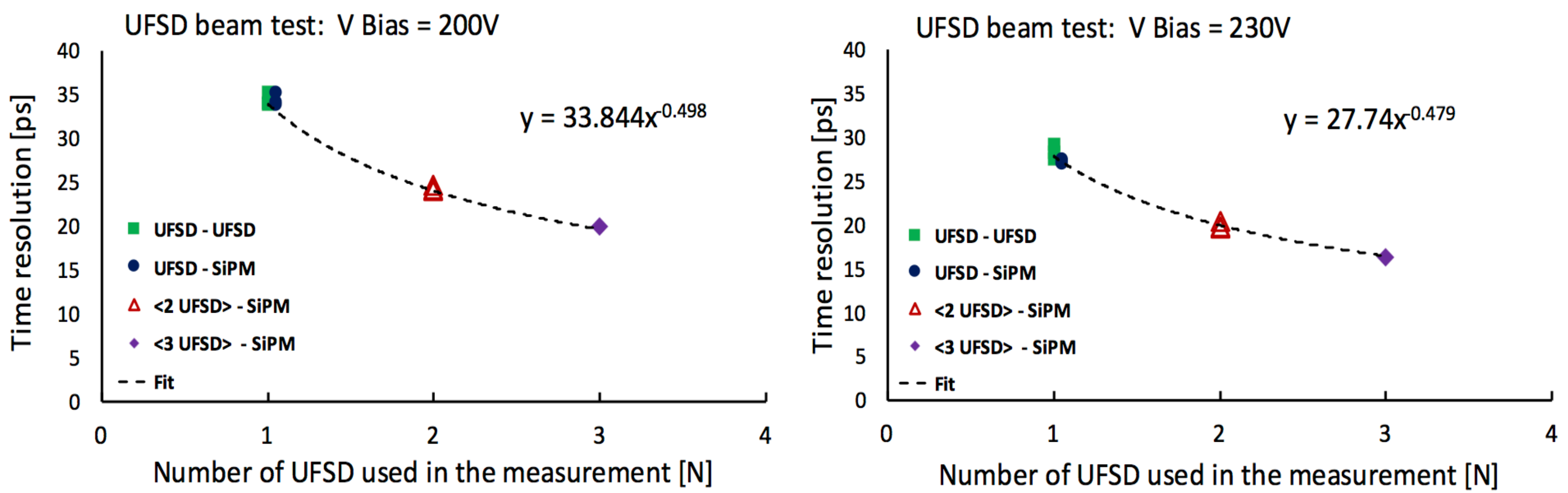
TOTEM





ATLAS High Granularity Timing Det.

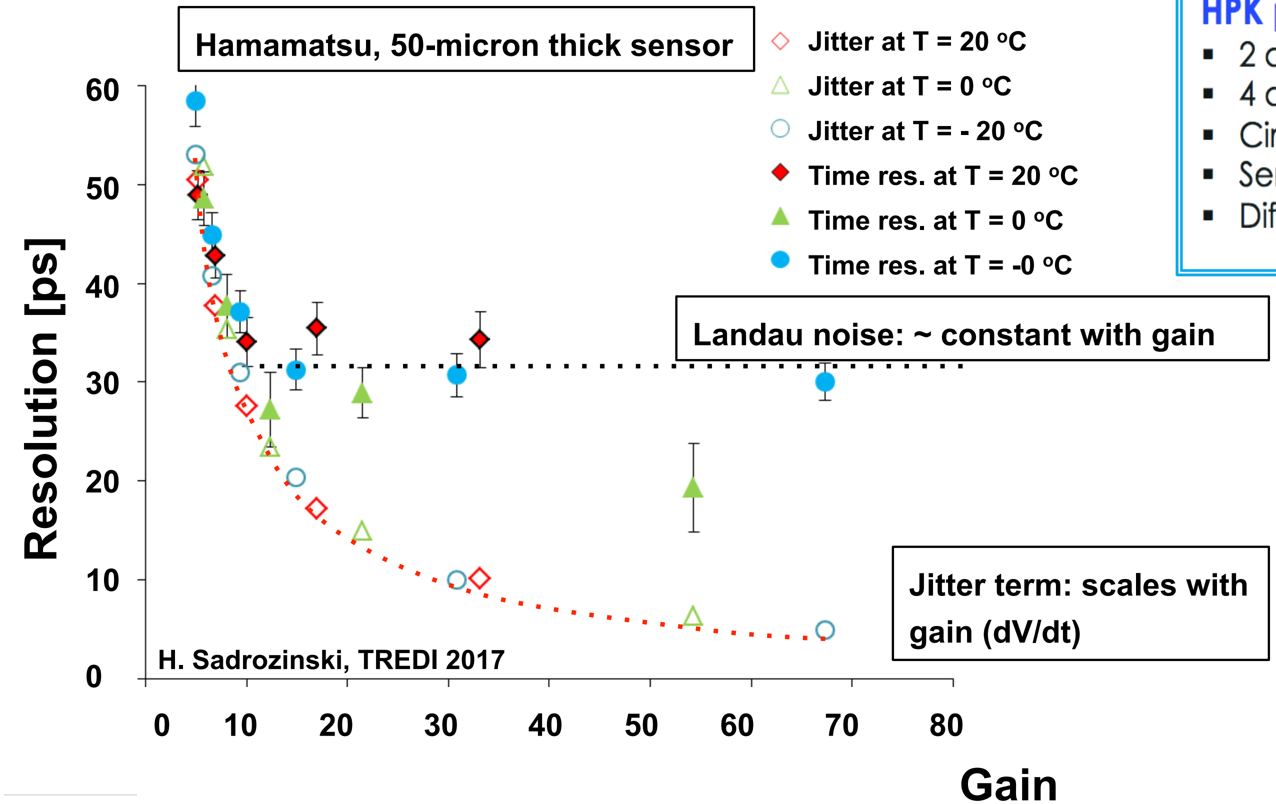
Recent Beam Tests results with CNM pads



3 **CNM** 50μm thin detectors, 1.7mm^2 single pad + 1 SiPM on quartz for timing crosscheck
Full Custom Hybrid Electronics (developed by UCSC)

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

HPK UFSD Time Resolution



HPK production

- 2 different thickness: 50 μm - 80 μm
- 4 different gains
- Circular single pad sensors
- Sensor active area: ~1 mm^2
- Different guard ring design

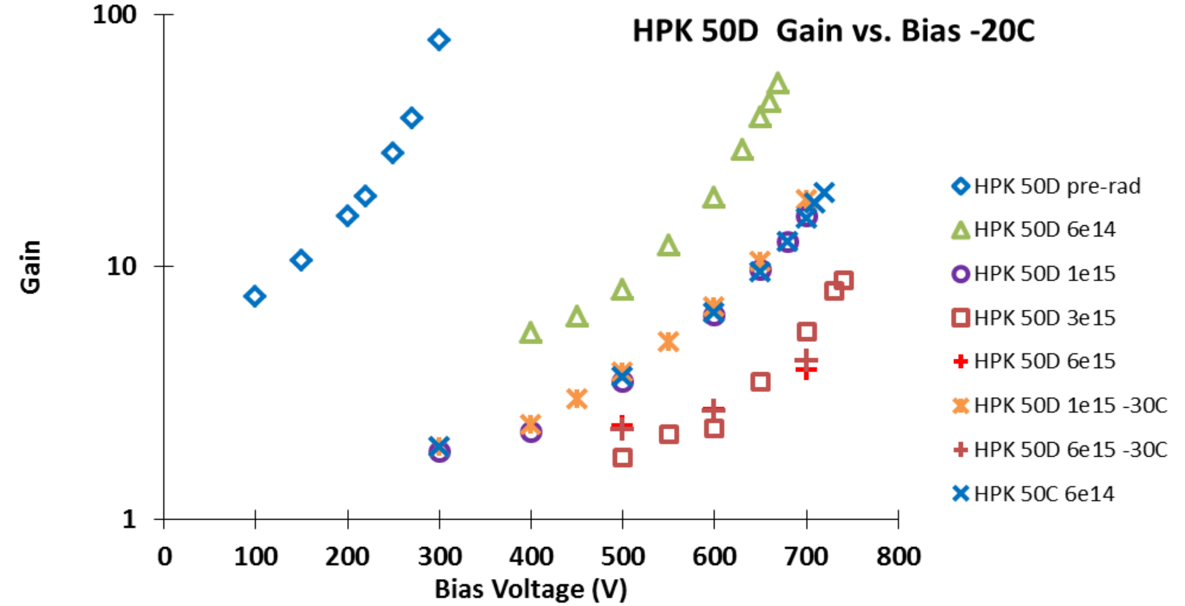
1 mm^2, 50 μm thick HPK UFSD pads

Readout: custom made BBA optimized for 50 μm LGAD (UCSC board)

30 ps time resolution achieved (gain >= 20) in agreement with simulations

Irradiation Effects

- **As in standard Si detectors: increase of leakage current, decrease of charge collection efficiency** due to trapping centers (minimize the effect going to **thin sensors**)
- **In LGAD:**
  - **Further increase of leakage current** due to gain layer: **go thin, keep gain low**
  - **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?**



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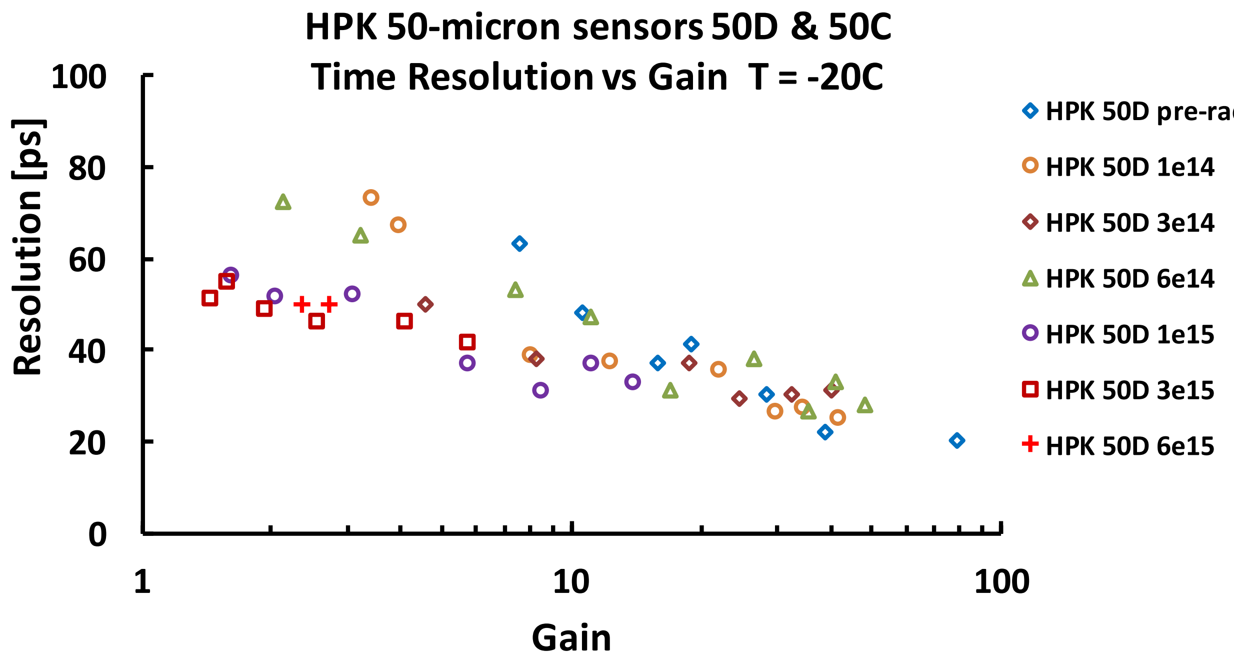


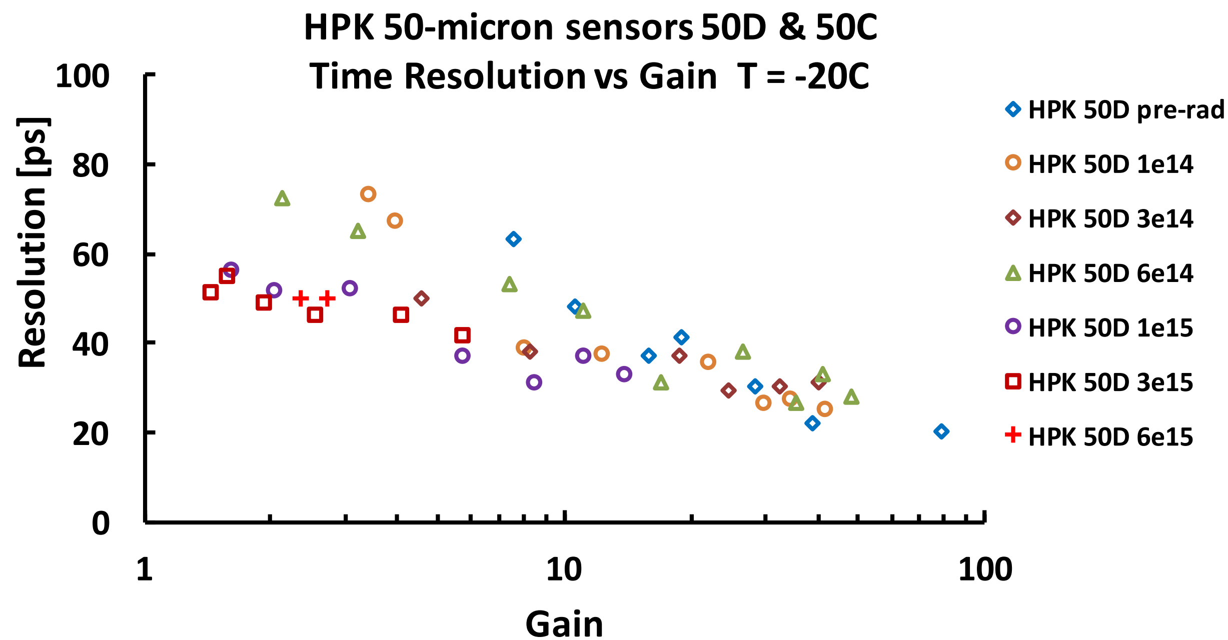
Small degradation in time resolution: ~ 30 ps (un-irrad) ➔ ~ 60 ps (5e15 n/cm^2)

Irradiation Effects

Two alternatives to reduce the gain layer disappearance:

1) **Use Gallium** instead of Boron: Gallium is less prone to become interstitial

2) **Add Carbon to Boron/Gallium**: Carbon should become interstitial before the Boron/Gallium



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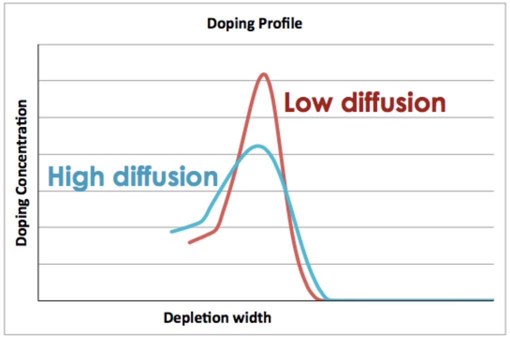
FBK-UFSD2 production

FBK-UFSD2 production main goals

- Demonstrate the ability of producing thin LGADs (in multiple geometries, which yield?)
- **Address the radiation tolerance level of LGADs:**
  - Several flavors for the gain layer doping: B, B+C, Ga, Ga+C
  - Different doping profiles for B

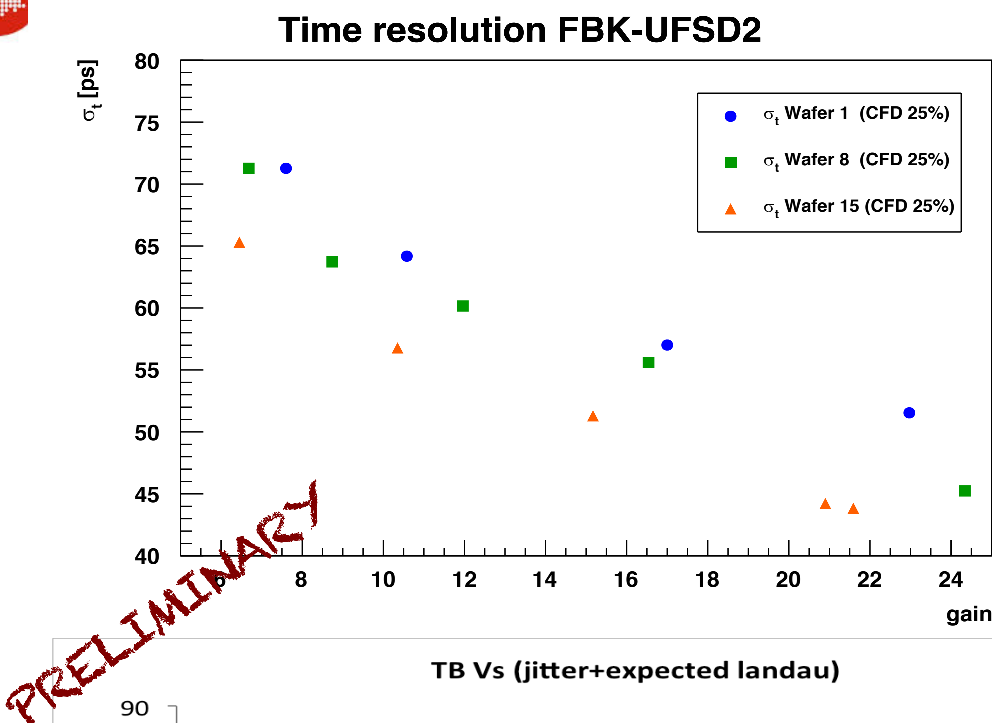
Key question: is Gallium doping or the doping with carbon more radiation hard than Boron doping?

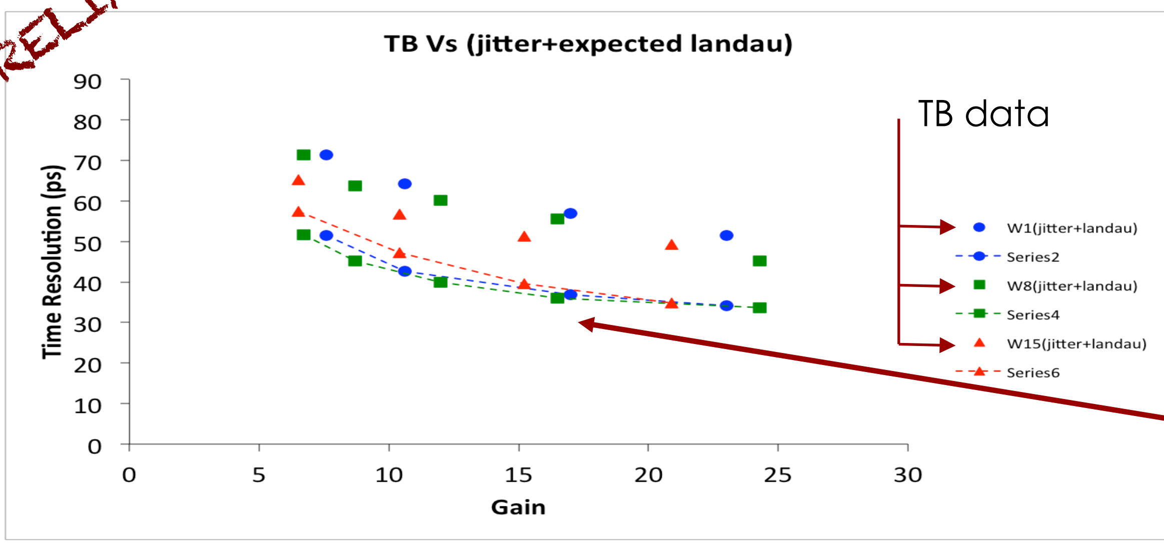


Beam test

Wafer #	Dopant	Gain dose	Carbon	Diffusion
1	Boron	0.98		Low
2	Boron	1.00		Low
3	Boron	1.00		HIGH
4	Boron	1.00	Low	HIGH
5	Boron	1.00	HIGH	HIGH
6	Boron	1.02	Low	HIGH
7	Boron	1.02	HIGH	HIGH
8	Boron	1.02		HIGH
9	Boron	1.02		HIGH
10	Boron	1.04		HIGH
11	Gallium	1.00		Low
12	Gallium	1.00		
13	Gallium	1.04		Low
14	Gallium	1.04		
15	Gallium	1.04	Low	Low
16	Gallium	1.04	HIGH	Low
17	Gallium	1.08		Low
18	Gallium	1.08		

FBK-UFSDII Beam Test





First test beam end of August @ SPS-H8 – 180 GeV pion beam

Small telescope with 4 stations
Several 1mm^2 pads, read out by Cividec Amplifier, under test: not the best configuration, but easily inter-changeable

W8: Boron 1.2 Hdif
W1: Boron 0.98 Ldif
W15: Gallium/lowC 1.04

Time Jitter (from laser measurement in lab) + 30 ps estimated Landau contribution: 20 ps offset to be understood.

UFSD Summary

4-D tracking can be achieved using planar silicon sensors with internal gain (UFSD design based on the LGAD technology)

Sensors R&D is very active.

Technological interest from many manufacturers (**CNM** (Spain), **FBK** (Italy), **HPK** (Japan), **Micron Semiconductor** (UK))

- Good results on time resolution:
  - **~30 ps** from beam test (gain ~ 20 with CFD ~ 20%) when new
  - **~50 ps** (gain ~ 7-10 with CFD ~ 50%) at 1e15 neq/cm^2
- New implants dopants (**Ga, C**)- to address the radiation hardness level - currently under test

Acknowledgements

Thank you for your attention !

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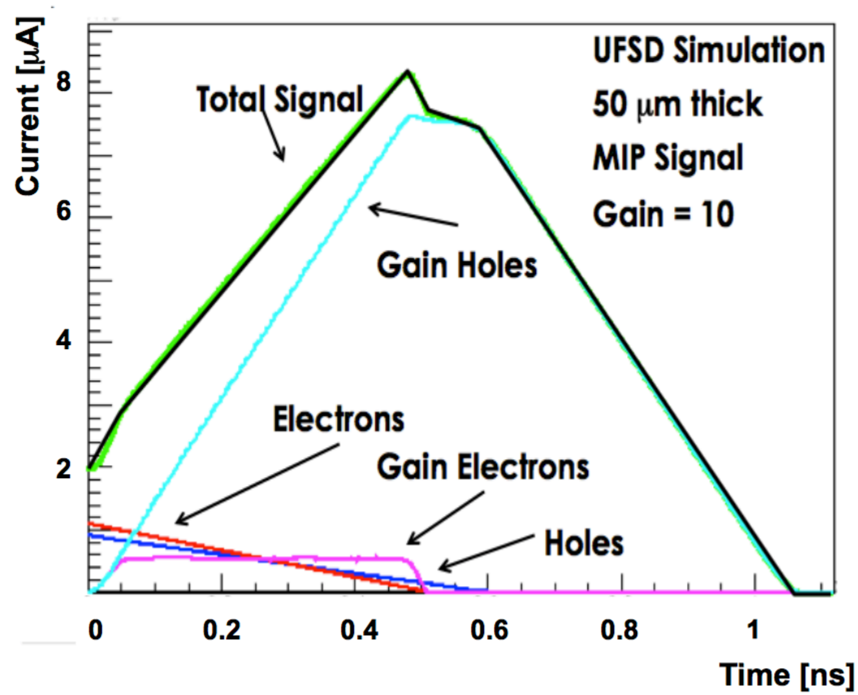
Backup

LGAD Signal

Signal rise-time is given by electrons drift time

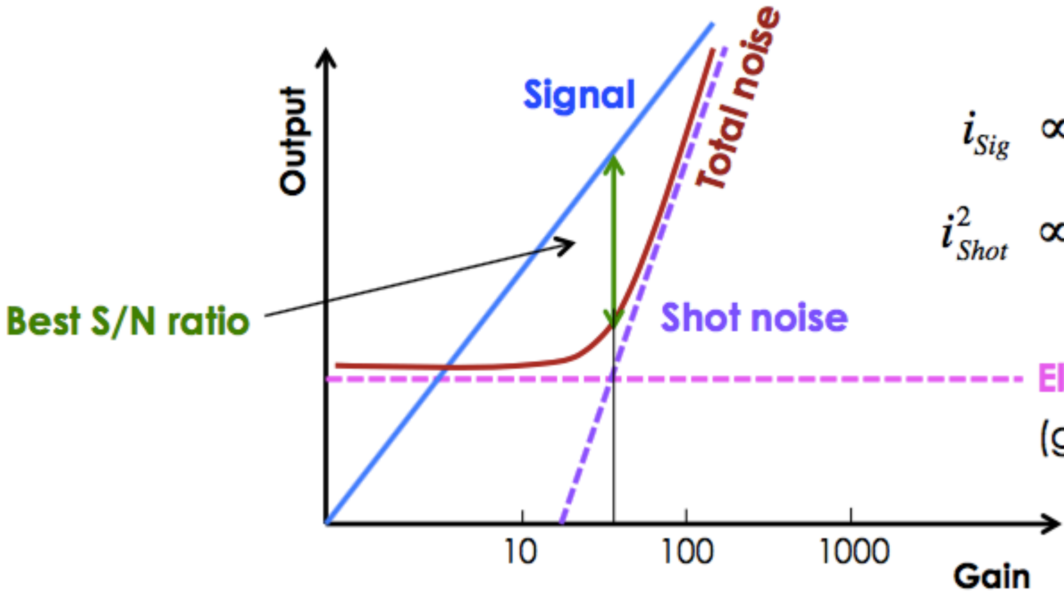
Charge formation and multiplication takes a considerable fraction of time.
Gain Holes dominate the signal, whilst Gain Electrons current contribution is negligible.

Weightfield2 Simulation



On the UFSD Gain

Why low gain?



$$i_{Sig} \propto G$$

$$i^2_{Shot} \propto \left[I_{Surface} + (I_{Bulk}) G^2 F \right]$$

Excess Noise Factor

Noise increases faster than then signal

→ the ratio S/N becomes worse at higher gain

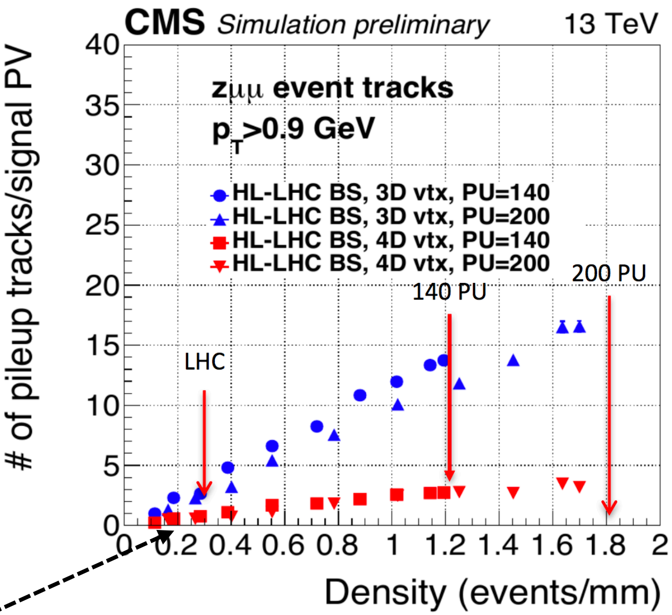
Shot noise

- normally much smaller than electronic noise for un-irradiated detectors
- can become the **dominant source of noise for irradiated detectors**

What happens at HL-LHC

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

➡ Event loss = Luminosity loss



A. Apresyan | Americas Workshop on Linear Colliders 2017

4D = add 30 ps timing information

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

Proposal for a 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 <3 mm^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