Precise Timing Measurement for the CMS Upgrade & Beyond

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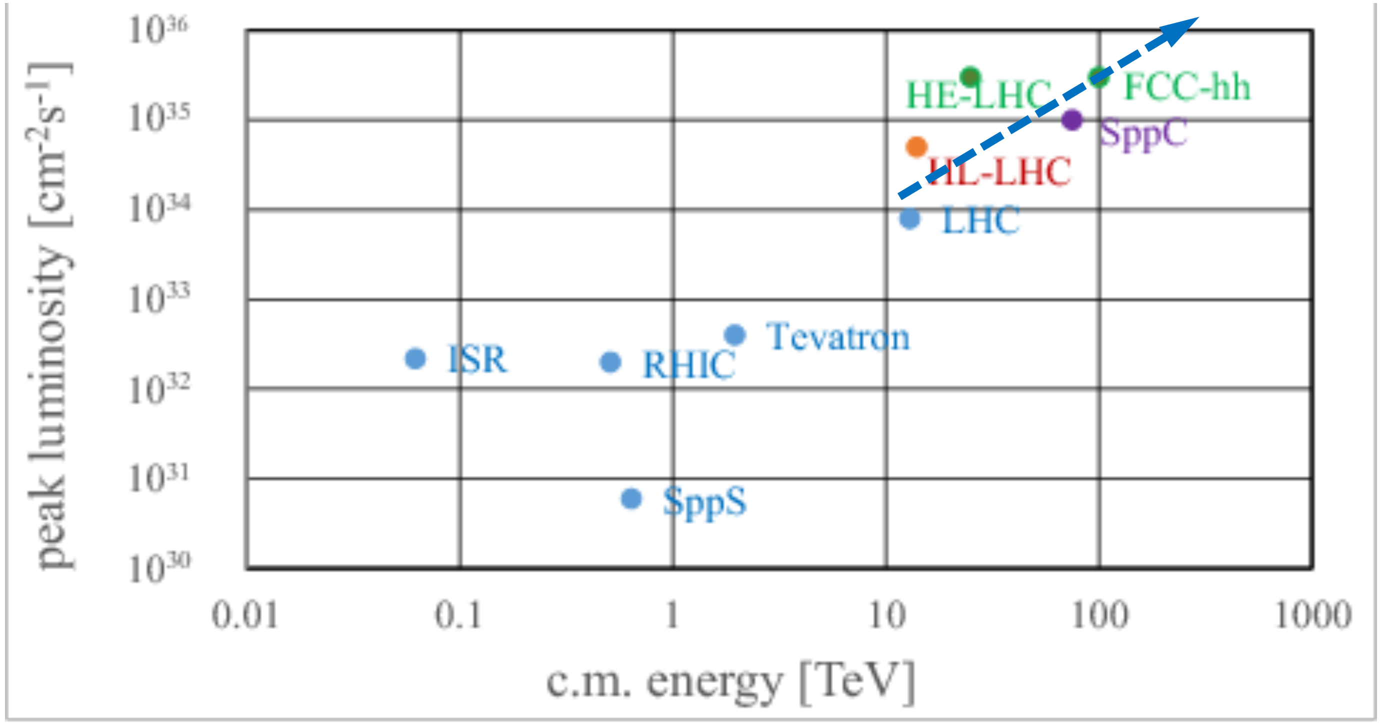
TOWARDS 4D TRACKING

The search for new physics pushes forward the high-luminosity and high-energy frontiers



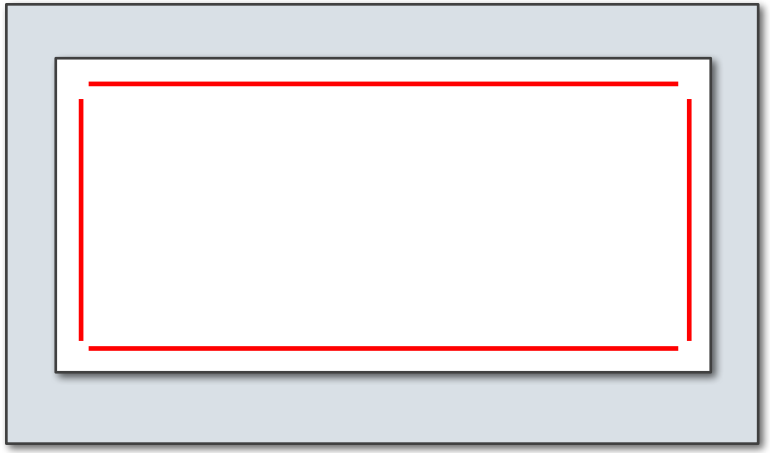
⇒ The R&D for the detectors in such environment already started

THE EFFECT OF TIMING

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, in increasing order of complexity:

✎ Timing in the event reconstruction ⟶ **Timing Layers**
This is the easiest implementation, a layer ONLY for timing



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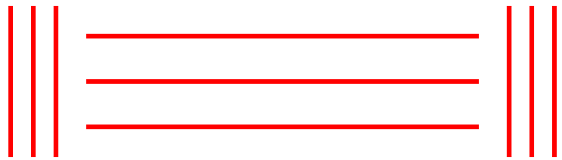

✎ Timing at each point along the track → **4D Tracking**
Tracking - Timing

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- ✎ Timing at each point along the track ⟶ **4D Tracking**
  Tracking - Timing
- ✎ Timing at each point along the track at high very high rate and high density ⟶ **High Rate (HR) 4D Tracking**
  Very high rate represents an additional step in complication, very different read-out chip and data output organization

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The ultimate goal

- ✎ Timing at each point along the track at high very high rate and high density ⟶ **High Rate (HR) 4D Tracking**
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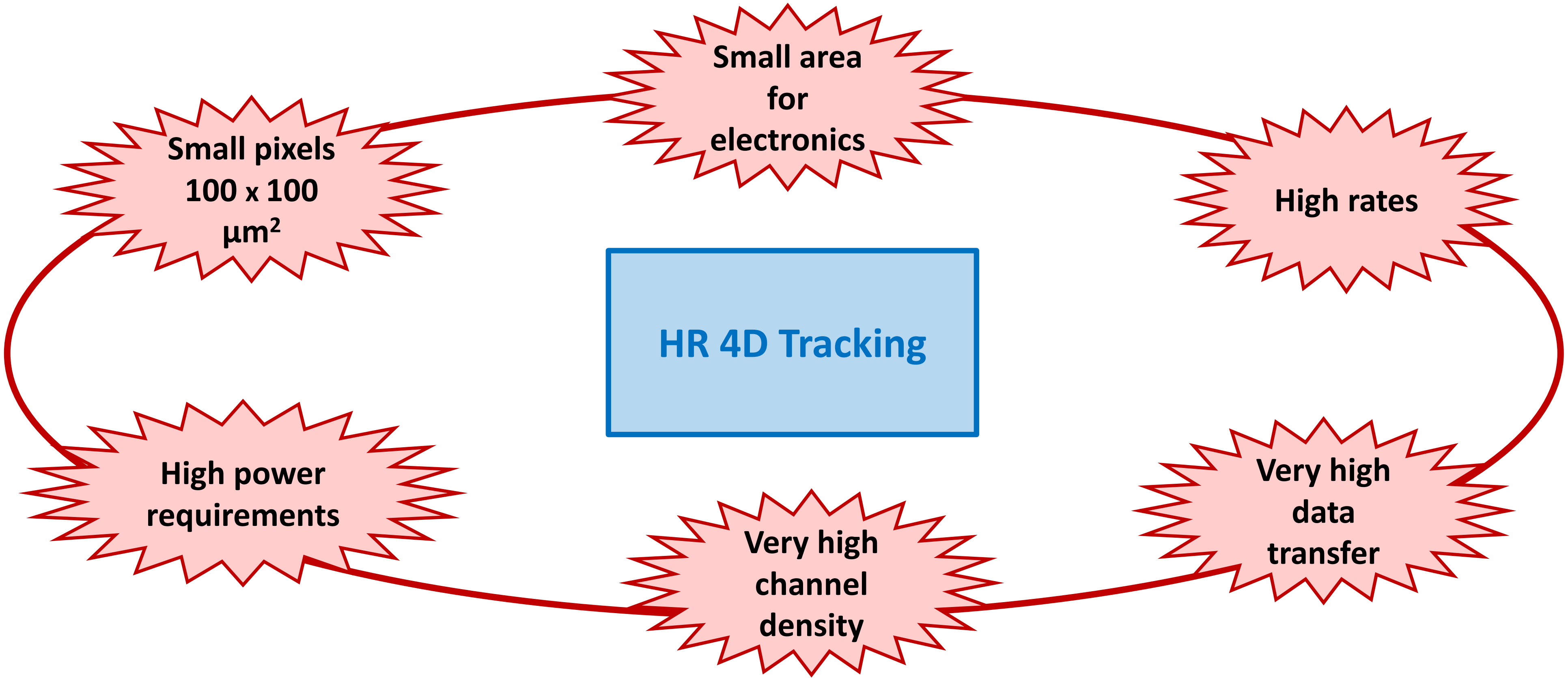
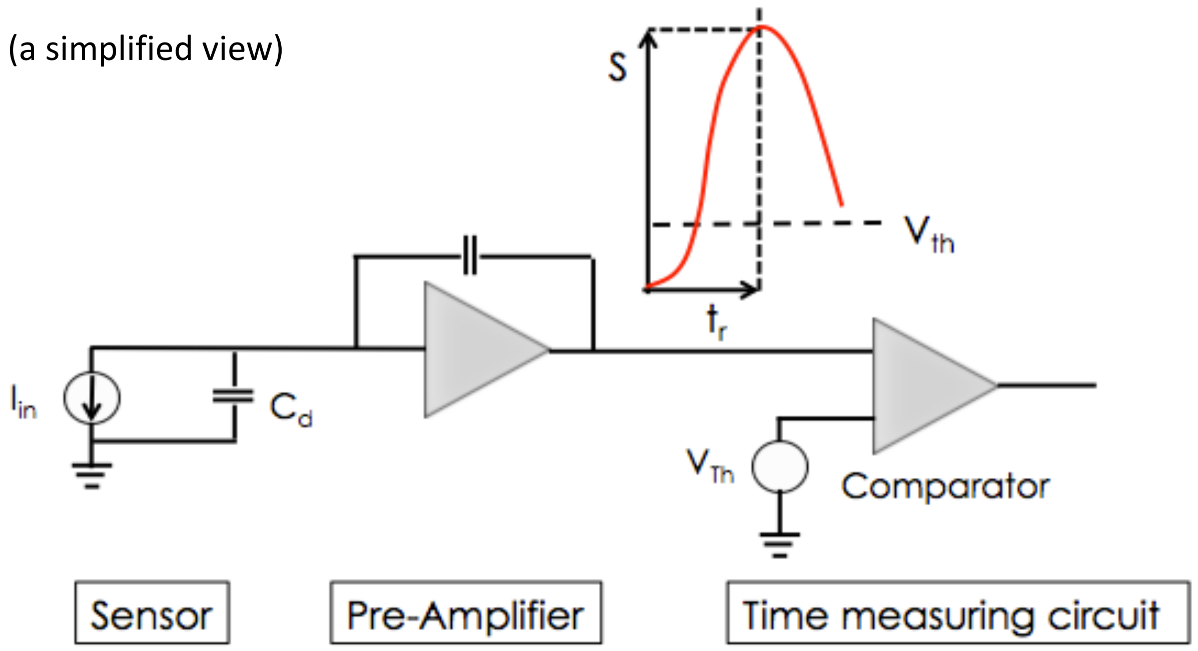
HIGH RATE 4D TRACKING

In an environment with ~ 1000 - 2000 tracks @ 40 MHz crossing there are several challenging aspects



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

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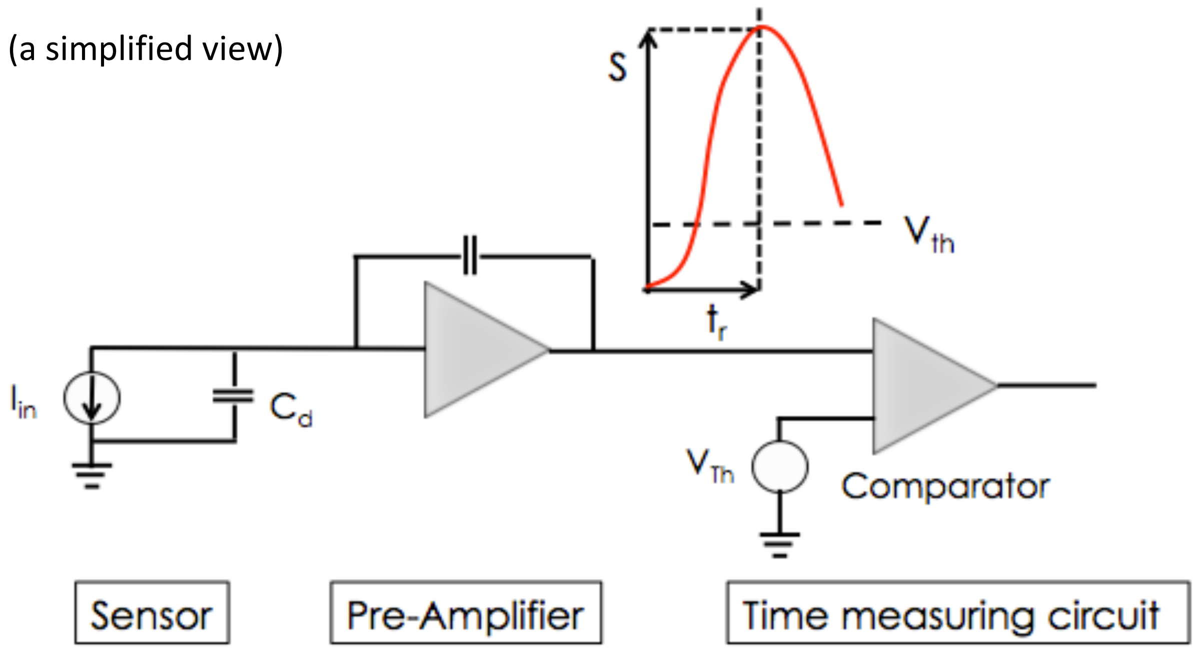

Time is set when the signal crosses the comparator threshold

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⇒ Strong interplay between sensor and electronics

FAST TIMING - THE INGREDIENTS

For a planar detector geometry $\boldsymbol{\sigma_t^2 = \sigma_{Current}^2 + \sigma_{Jitter}^2 + \sigma_{Time\,Walk}^2 + \sigma_{TDC}^2}$

with a saturated velocity, the σ_t main contributors are **current fluctuations** and **jitter**

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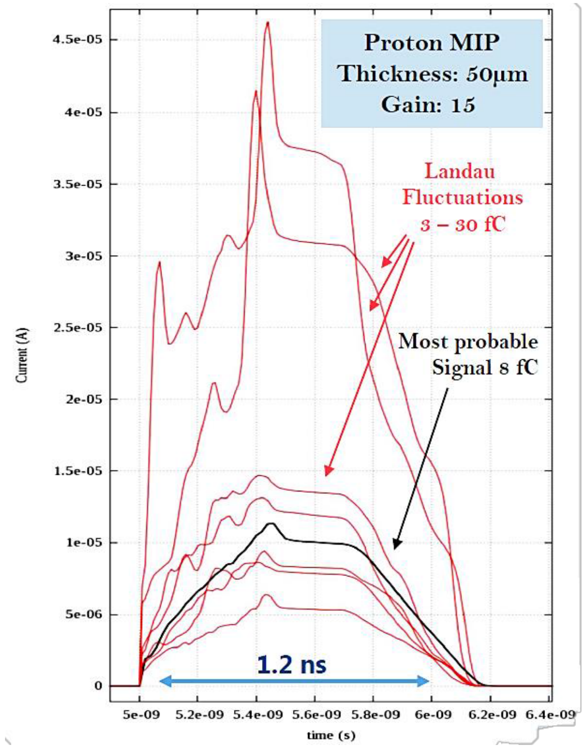
Current fluctuations are due to the physics of MIP ionization (Landau fluctuations)



✎ Improves with thin sensors
✎ Does not depend on the gain

For 50 µm thick sensors contribute ~ 30 ps

→ **Physical limit to time resolution**

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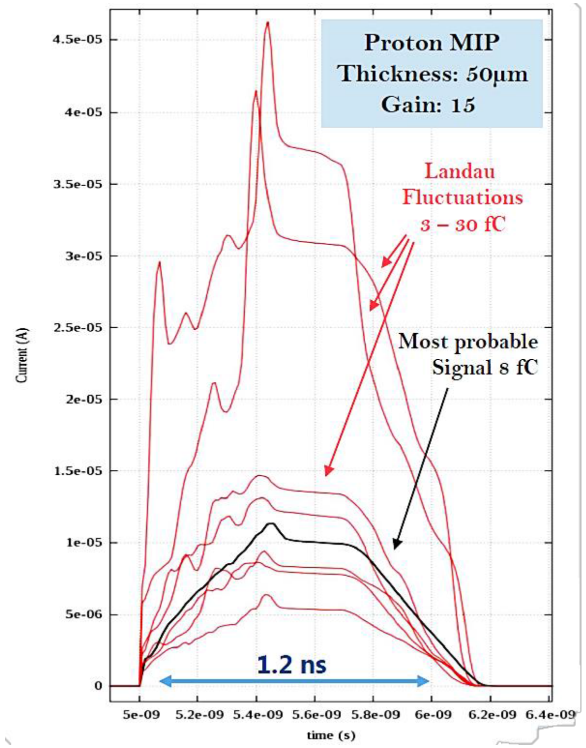

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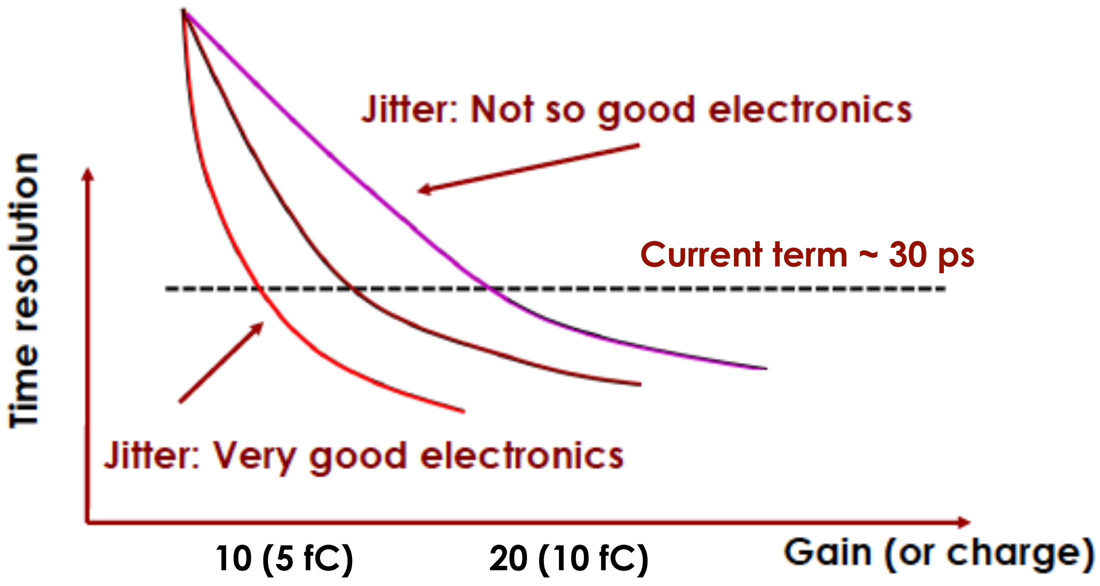
Jitter is driven by the electronics

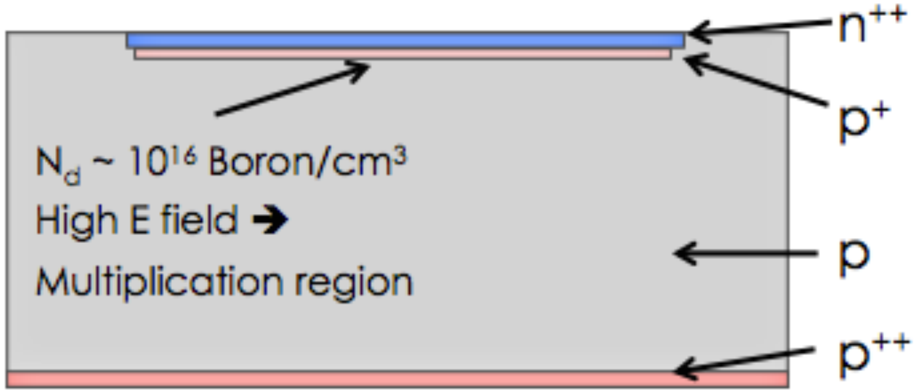


$$\sigma_{jitter} = \frac{N}{(dV/dt)_{V_{th}}} = \frac{t_{rise}}{S/N}$$

SILICON SENSORS FOR FAST TIMING

Must have:

- ➢ **Large dV/dt to minimize jitter**
- ➢ **Segmentation**
- ➢ **Radiation hard**



The game changer is the introduction by CNM of the LGAD[*] idea:

- ➢ Add a thin layer of doping to produce low controlled multiplication
- ➢ This idea retains almost (segmentation) the benefit of standard silicon sensors

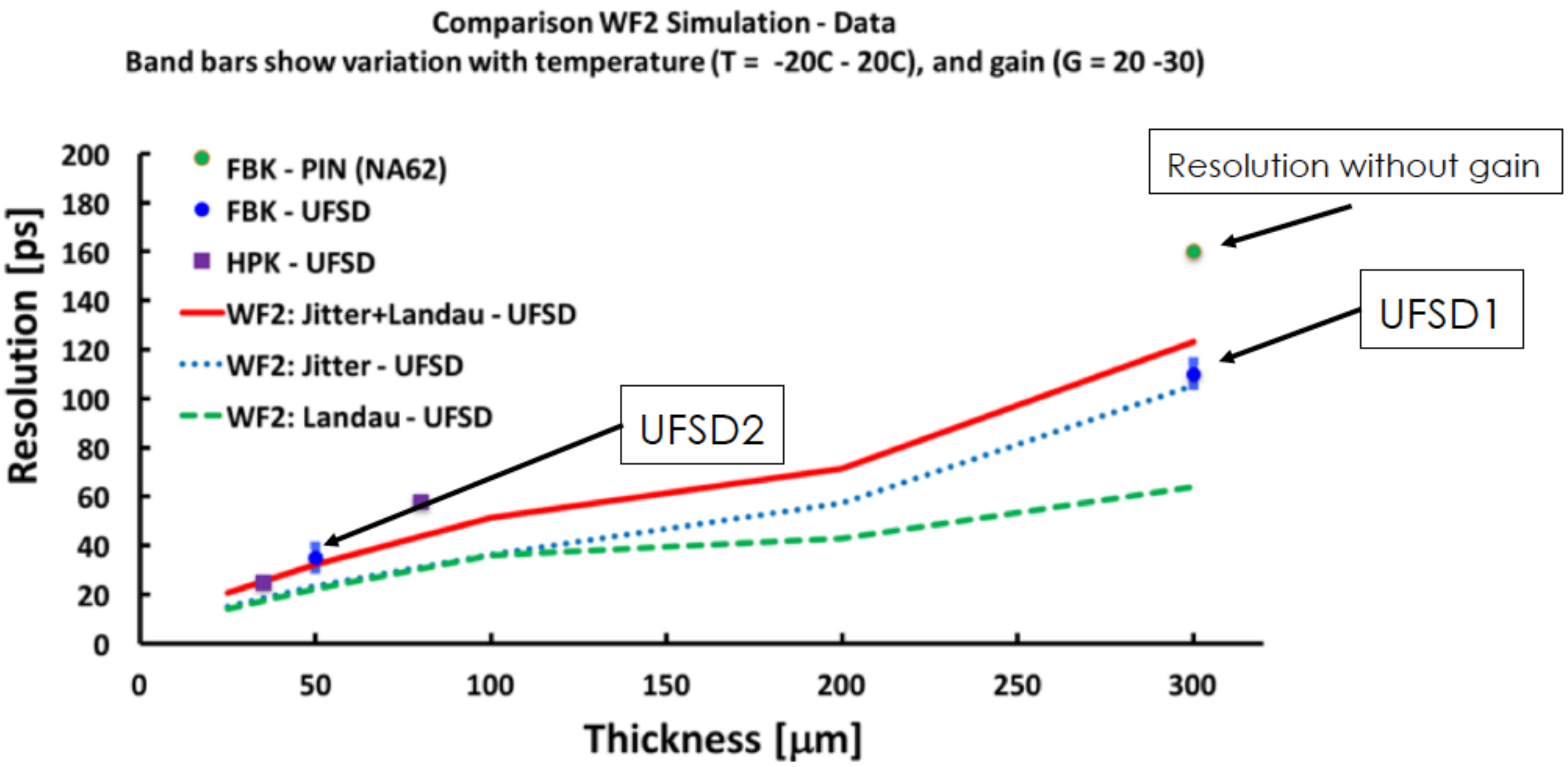
→ **UFSD[**]: LGAD sensors, optimized for timing**

[*] **LGAD = Low-Gain Avalanche Diodes**

[**] **UFSD = Ultra-Fast Silicon Detectors**

UFSD TIME RESOLUTION

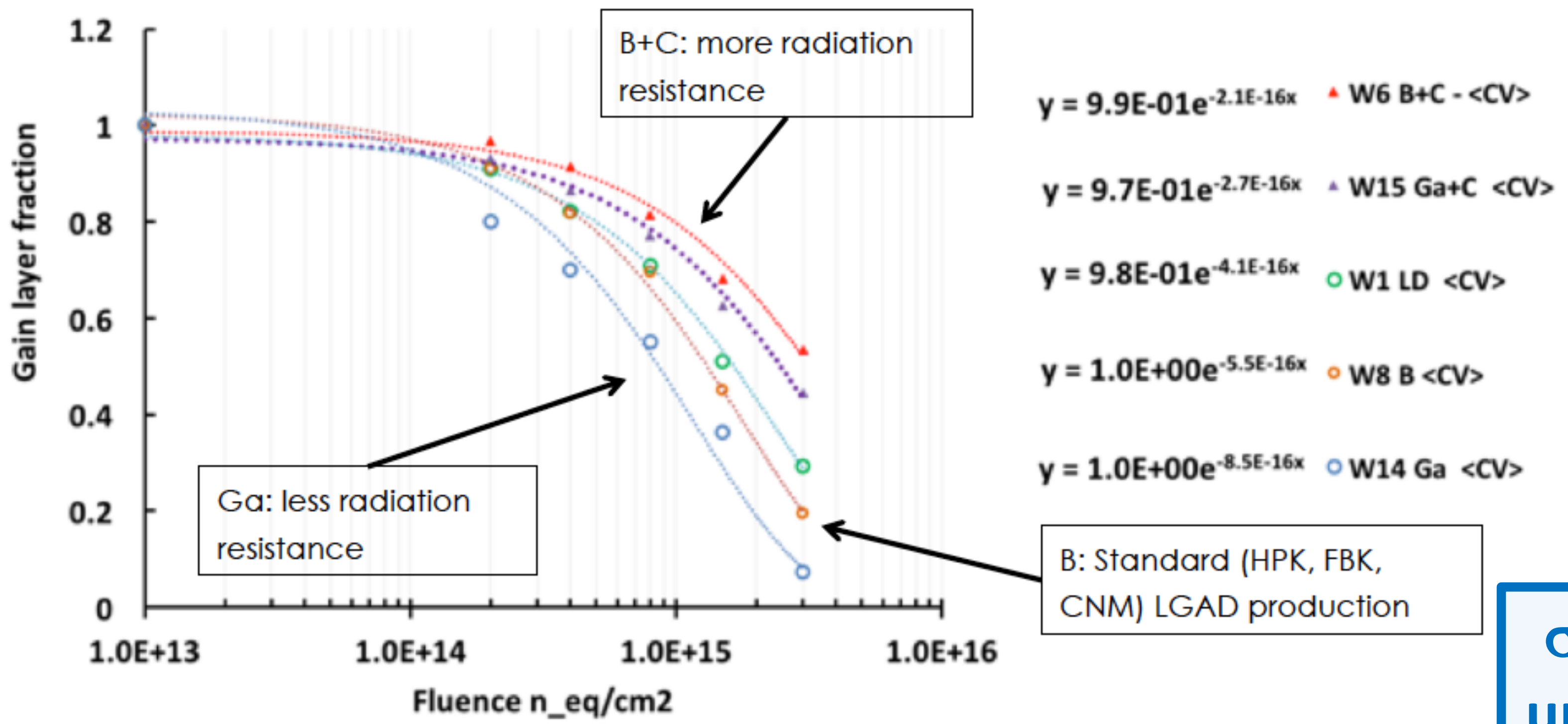
⇒ **UFSD achieved 30 ps time resolution, in line with our target**



UFSD RADIATION TOLERANCE

UFSD suffer for gain reduction due to irradiation

FBK used both Boron and Gallium as gain layer dopant, and added Carbon in the gain layer volume



$\Rightarrow$ **The usage of Carbon double the radiation hardness of UFSD**

$\sigma_t \sim 30$ ps achievable up to $1.5 \cdot 10^{15}$ n_{eq}/cm^2 using Carbon

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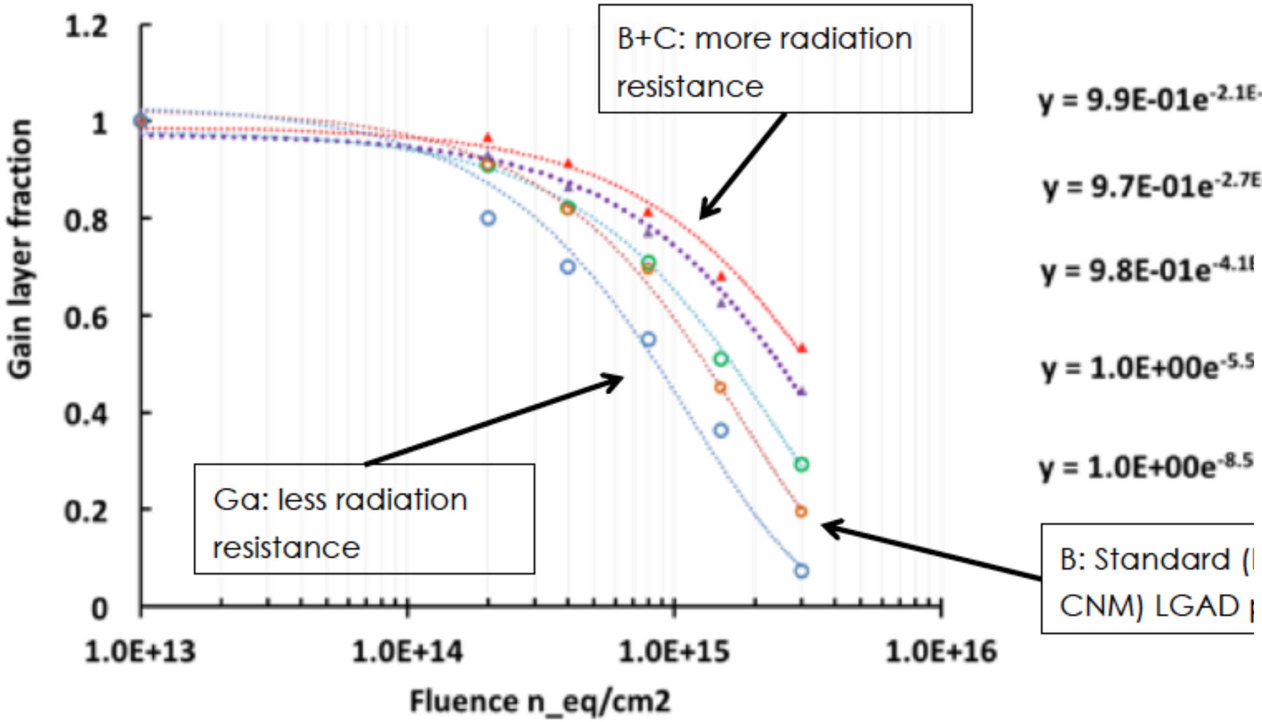
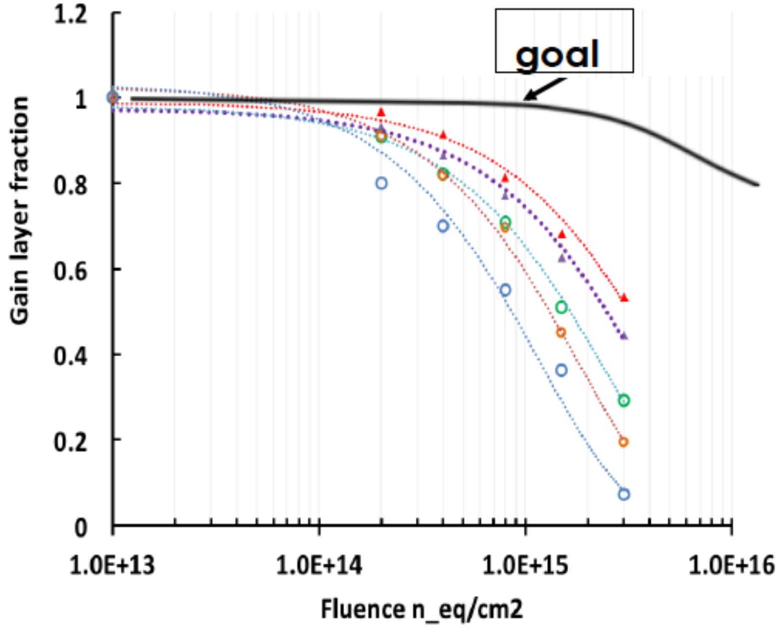


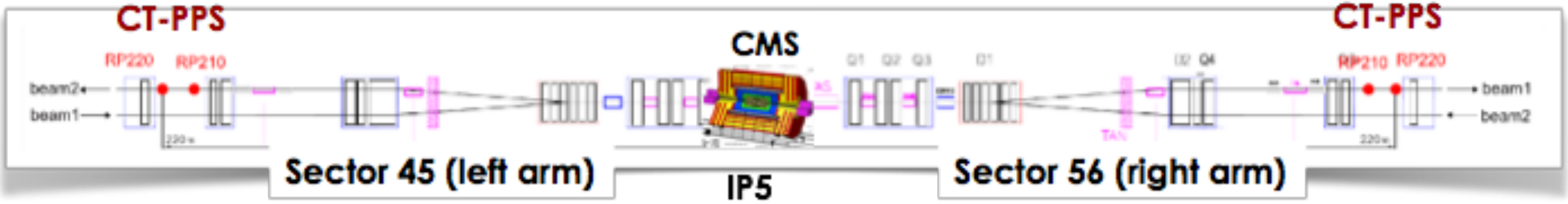
Future R&D



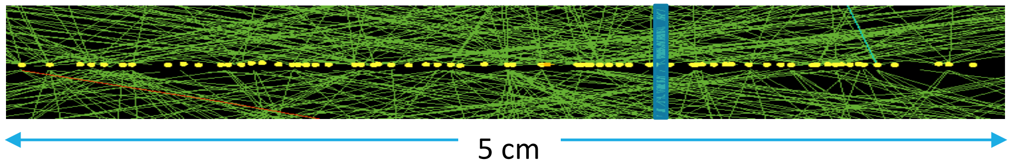
⇒ The usage of Carbon double the radiation hardness

UFSD IN PPS

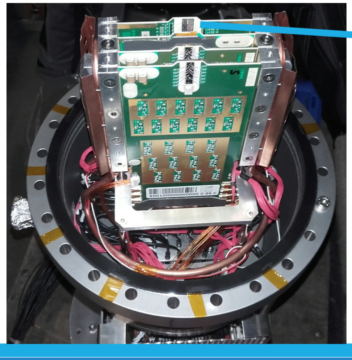
The CMS TOTEM Precision Proton Spectrometer (CT-PPS) aims at measuring the surviving scattered protons on both sides of CMS in standard LHC running conditions → 1 plane of UFSD has been installed on both sides of CT-PPS in 2017

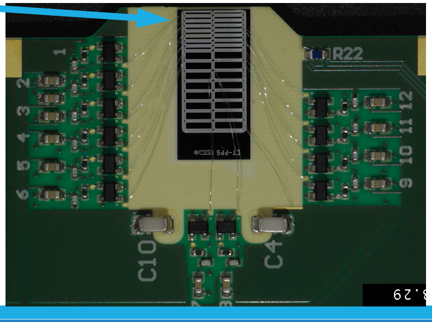


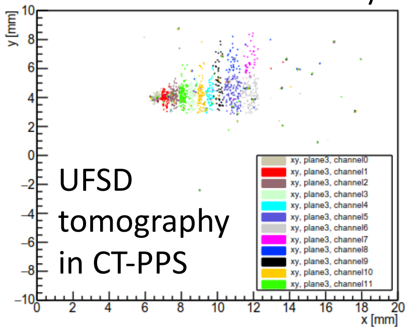
- Aim: disentangle primary vertex from pile-up



$$\sigma_{z_{vtx}} = \frac{c}{2}\sqrt{2\sigma^2_{\Delta t}} \overset{\sigma_{\Delta t}=10\text{ps}}{\approx} 2\text{ mm}$$

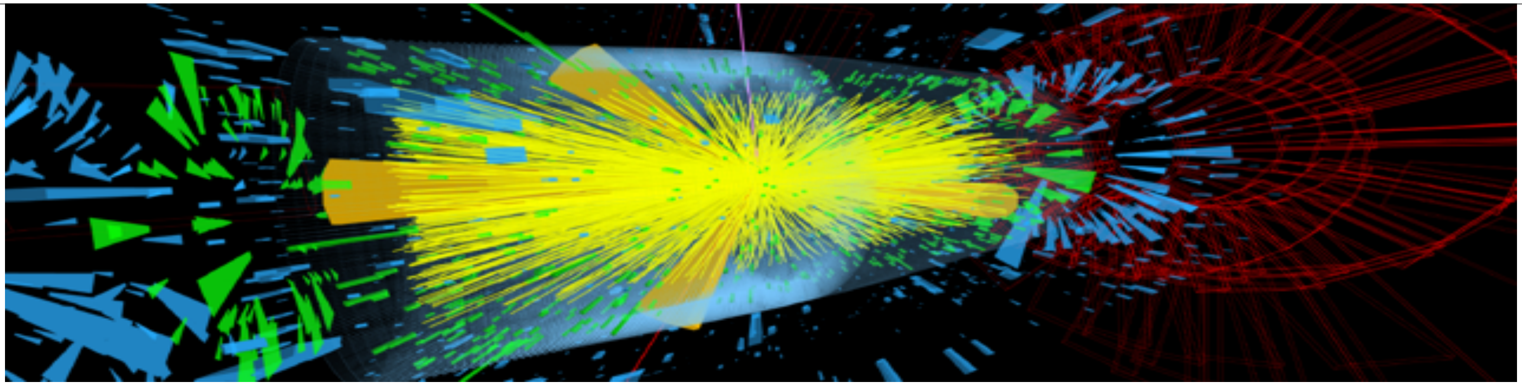






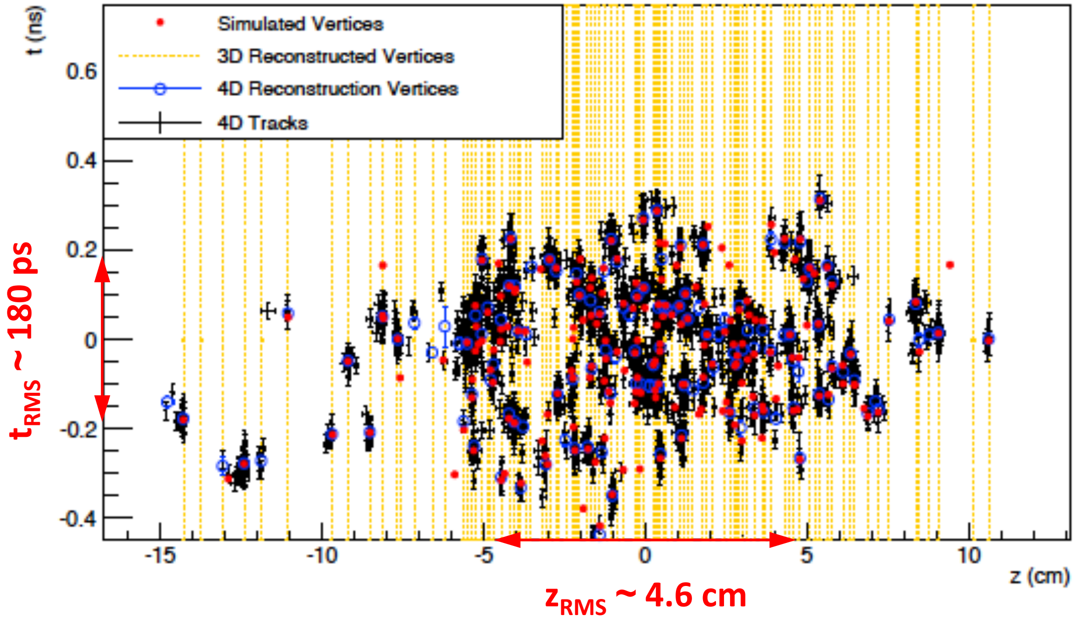
First UFSD installation in High Energy Physics

A HERMETIC MIP TIMING DETECTOR FOR CMS



Simulation of a VBF H → ττ in 200 pile-up pp collisions

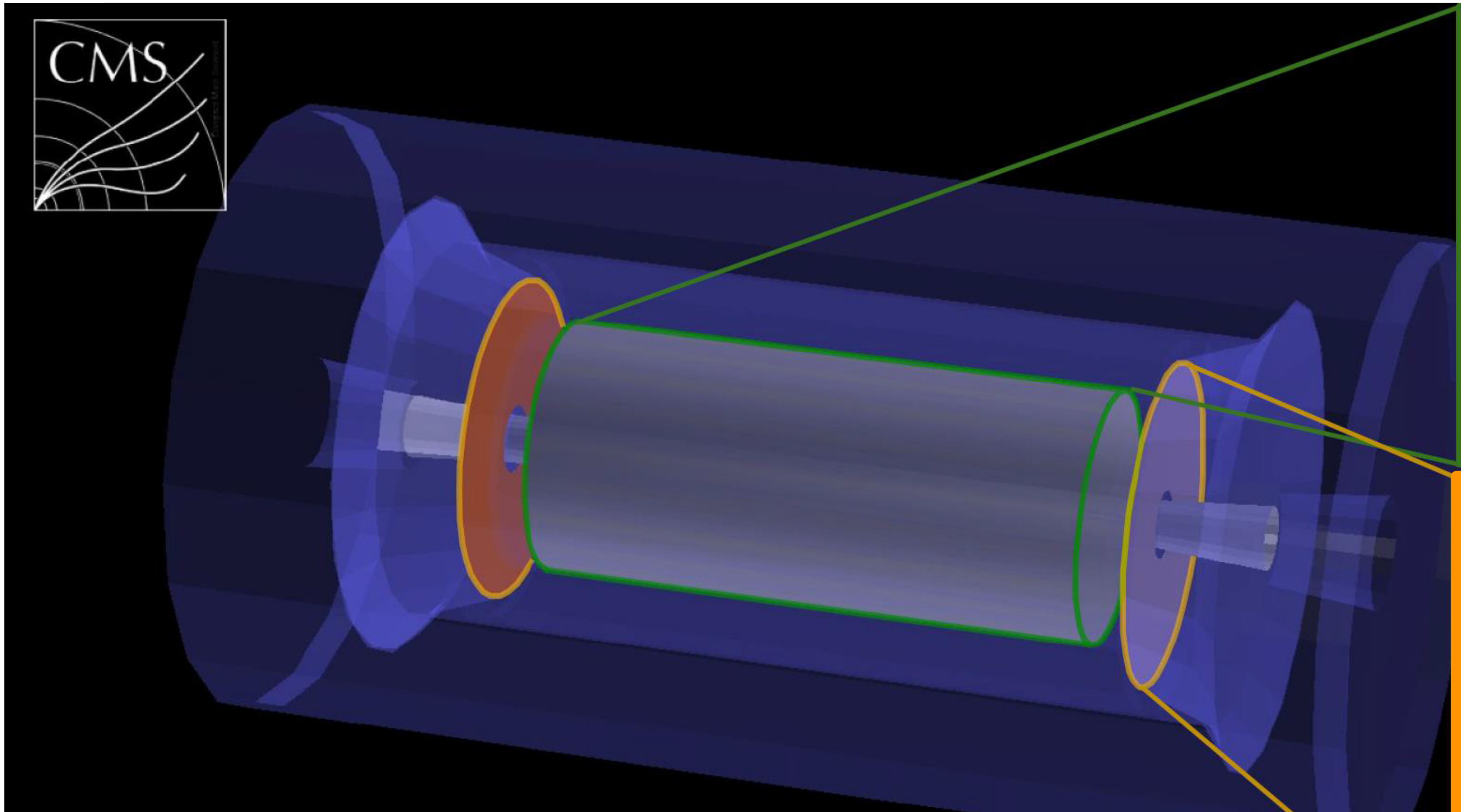
200 pp vertices



- Must reduce pile up to level of the current CMS detector, to preserve data quality
- Slice beam spot into consecutive 30-50 ps time exposures

  → **Results in ~ 40 pile-up events per slice**

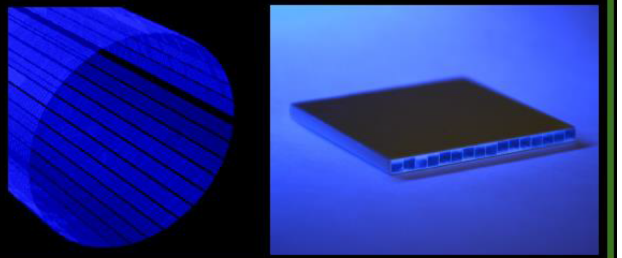
MIP TIMING DETECTOR IN A GLANCE



BARREL

Surface	~ 40 m²
Number of channels	~ 332k
Radiation level	~ $2\times10^{14}\ n_{eq}/cm^2$

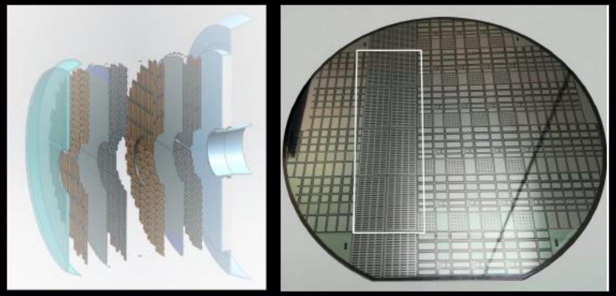
Sensors: LYSO crystals + SiPMs



ENDCAPS

Surface	~ 15 m²
Number of channels	~ 6M
Radiation level	~ $2\times10^{15}\ n_{eq}/cm^2$

Sensors: Low gain avalanche diodes



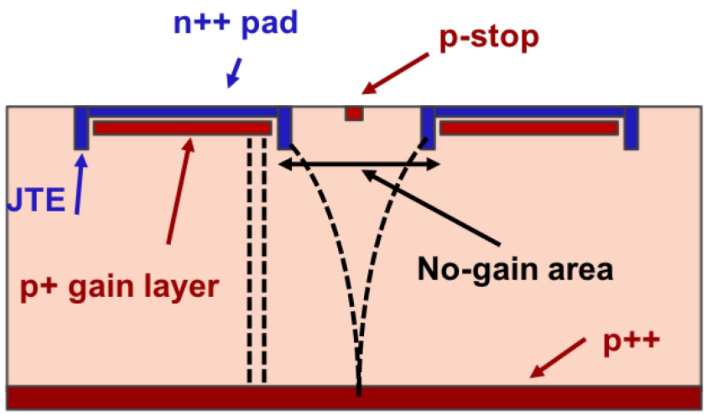
- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for $|\eta|<3.0$

ETL SENSOR REQUIREMENTS

- Ultra-Fast Silicon Detectors (UFSD)
  - Highly doped p^+ region just below the n-type implant
  - Low and controlled gain (10-30)
  - Good radiation tolerance
- Specifications
  - Thin detectors (~50 µm)
    → maximize signal slew rate
  - Small pixel size (1.3 x 1.3 mm^2)
    → minimize capacitance
  - Optimize no-gain region between pixels
    → maximize fill factor while maintaining pad isolation to maximize efficiency

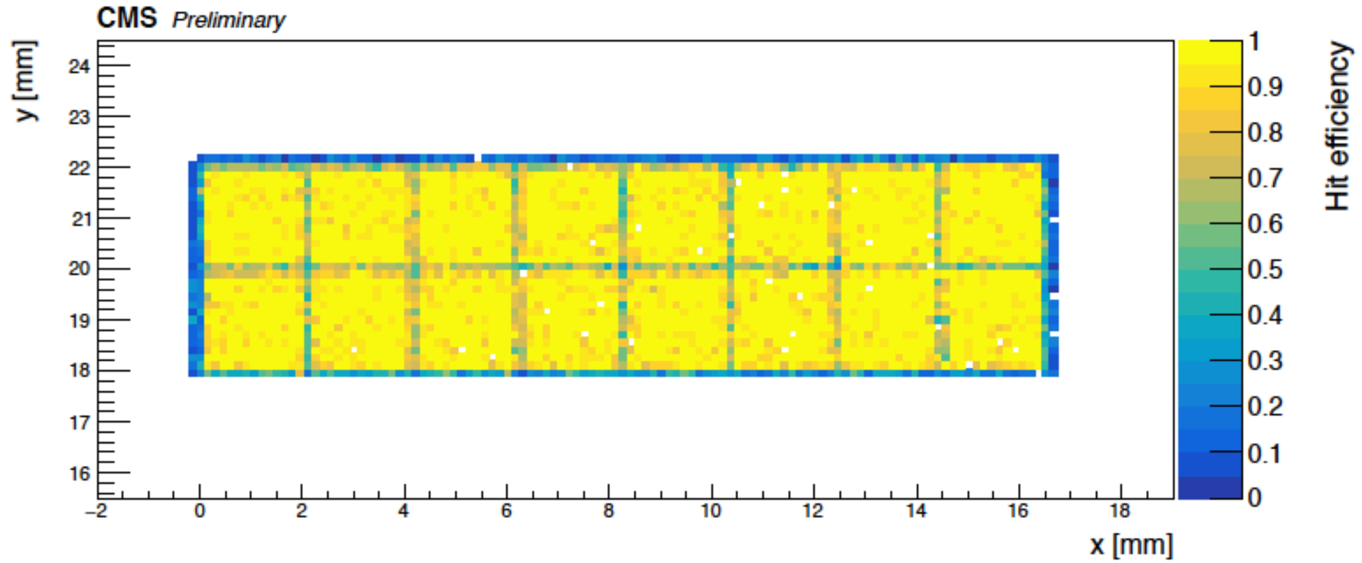
ETL = Endcap Timing Layer

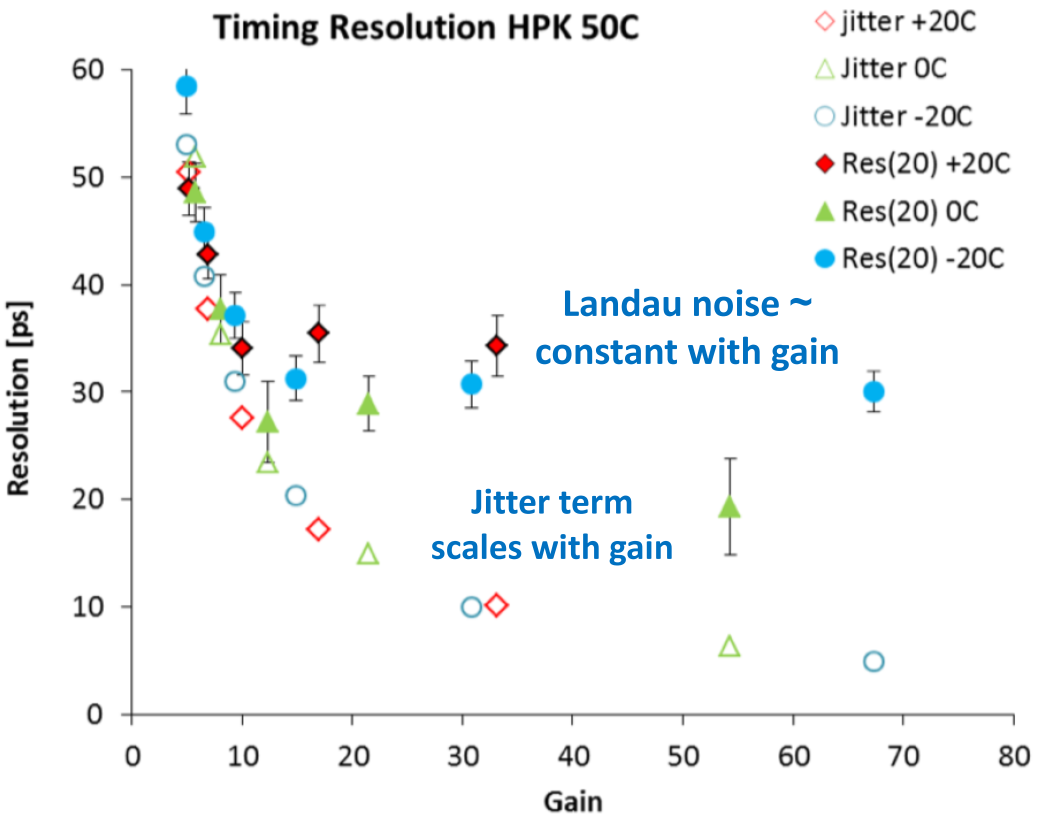
First large scale application of the UFSD in a high energy physics experiment



ETL SENSOR PERFORMANCES

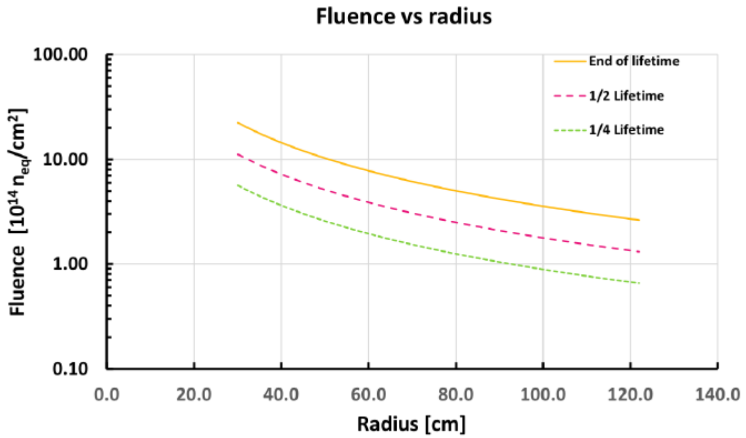
- Time resolution: 30 ps achieved
- 120 GeV proton beam test at FNAL
  - Signal uniformity of sensors: 2% spread
  - Efficiency: 100%
  - Fill factor with 50 um no-gain distance: 90%

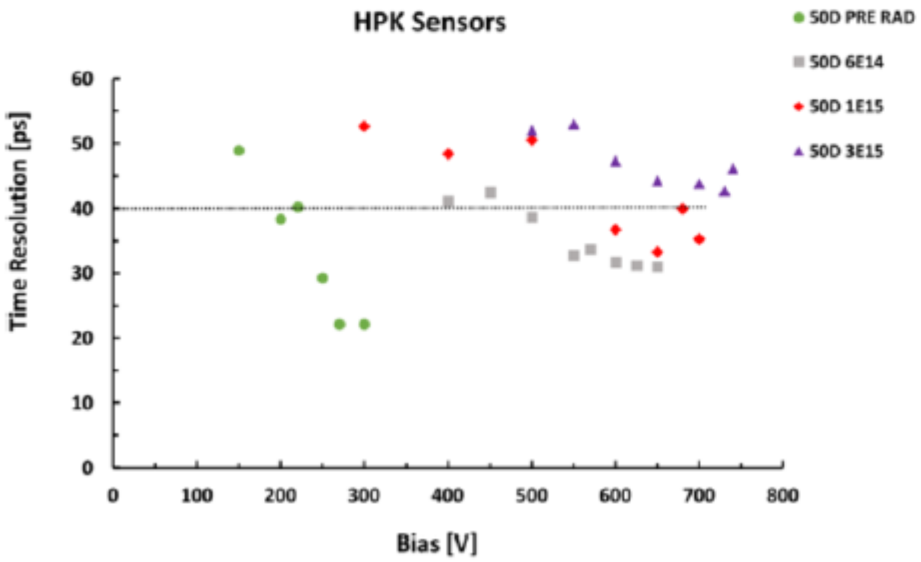


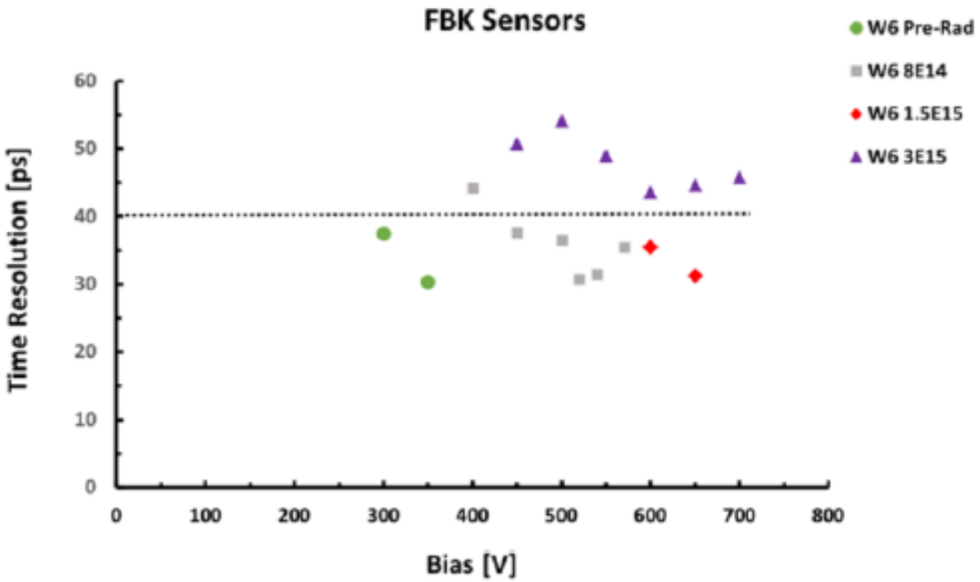


ETL RADIATION TOLERANCE

- ✎ Time resolution < 40 ps achieved with up to $1.5x10^{15}$ n_{eq}/cm^2
- ✎ Increasing bias voltage to compensate for loss of gain from radiation damage
- ✎ Leakage current mitigated by cooling to -30°C



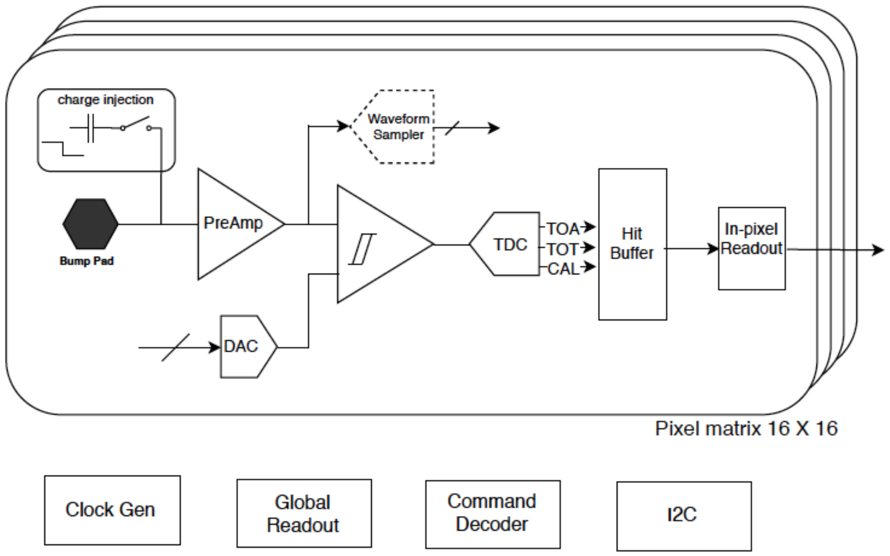




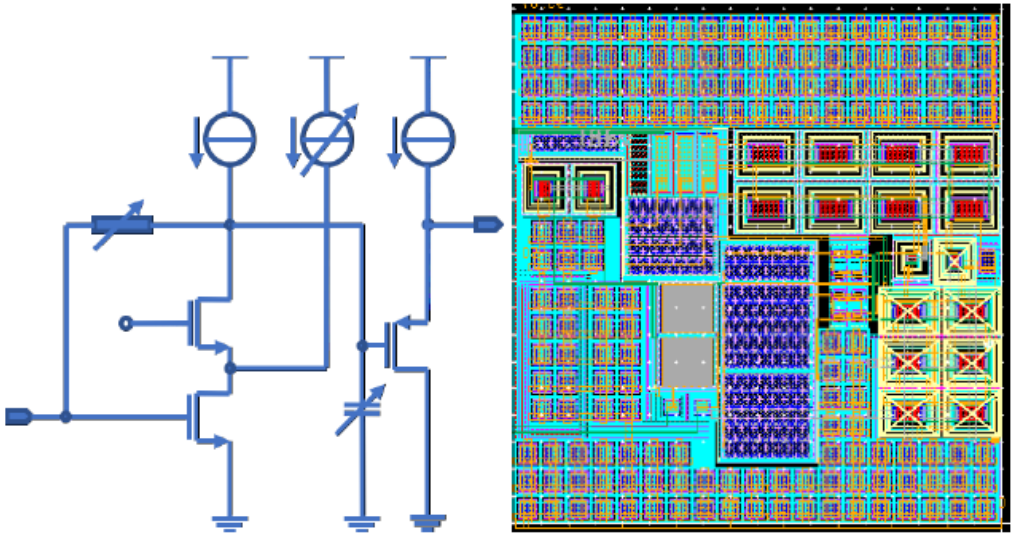
ETL READ-OUT ELECTRONICS

- Design goal: 50 ps per hit ⟶ 35 ps per track
- ETROC process based on TSMC 65 nm technology
- ToT used for time-walk corrections
- Trigger rate up to 1 MHz
- Power consumption < 215 mW/cm^2

ETROC schematic



Simplified schematic and layout of ETROC preamplifier



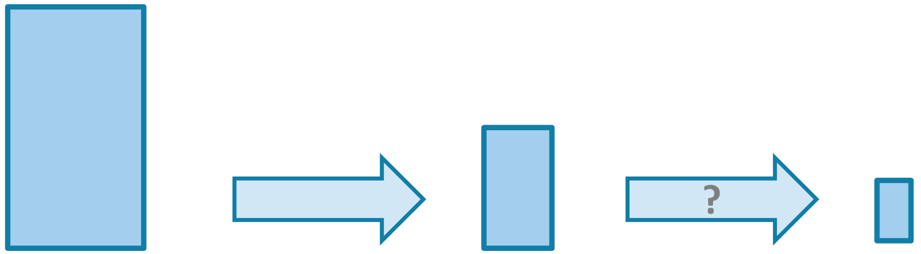
ELECTRONICS TOWARDS 4D TRACKING

Let’s consider a pixel size ~ $100\times100\ \mu m^2$

➢ Can we produce a sensor with small pixel and high fill factor?

➢ Can we fit the electronics?
$\longrightarrow$ the preamplifier does not scale with the technological node
$\longrightarrow$ memory and TDC do

Example: TDC evolution



130 nm
$70\times150\ \mu m^2$

65 nm
$40\times60\ \mu m^2$

28 nm
~ $20\times30\ \mu m^2$

$\Rightarrow$ **HR 4D Tracking requires either 65 nm or 28 nm electronics**

READ-OUT & ALGORITHMS

If we succeed in having the sensors and the read-out chip, still lot of work needed

Taking advantage of HR 4D Tracking requires a very complex back end:

- Very fast data transfer
- Real time tracking requires the development of specific 4D tracking
  $\longrightarrow$ sometimes called *retina*, being pursued by several groups

SUMMARY

- ➢ A new generation of detectors able to measure both time and space with high accuracy are being developed
  - ▻ UFSD are the proposed technology for CMS ETL High-Luminosity upgrades
  - ▻ Still R&D ongoing to exploit the full 4D capabilities
- ➢ ETL of CMS will represent the first large scale attainment of a Silicon based detector for 4D tracking
- ➢ There is no ‘*one technology fits all*’
  - ▻ depending on segmentation, precision, radiation levels and other factors the best solution changes

⇒ The path towards new detectors for the forthcoming high-density, high-energy collider era has started

ACKNOWLEDGEMENTS

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- INFN, Gruppo V
- Ministero degli Affari Esteri, Italy, MAE, “Progetti di Grande Rilevanza Scientifica”
- U.S. Department of Energy, grant DE-SC0010107
- RD50, CERN

BACKUP

POSSIBLE TECHNOLOGIES FOR 4D TRACKING

Silicon Sensors
▻ GigaTracker NA62: σ_t ~ 150 ps
▻ Silicon detector + SiGe HBT amplifier[1]: σ_t ~ 105 ps
+ Fine segmentation easy
+ Known technology
- Small signal
➻ Intrinsic resolution: **σ_t ~ 100 ps**

Diamond Detectors
▻ TOTEM Diamonds for CT-PPS ToF: σ_t ~ 100 ps
+ No leakage current
+ Radiation hard
+ Small capacitance, high mobility
- Small signal
➻ Intrinsic resolution: **σ_t ~ 100 ps**

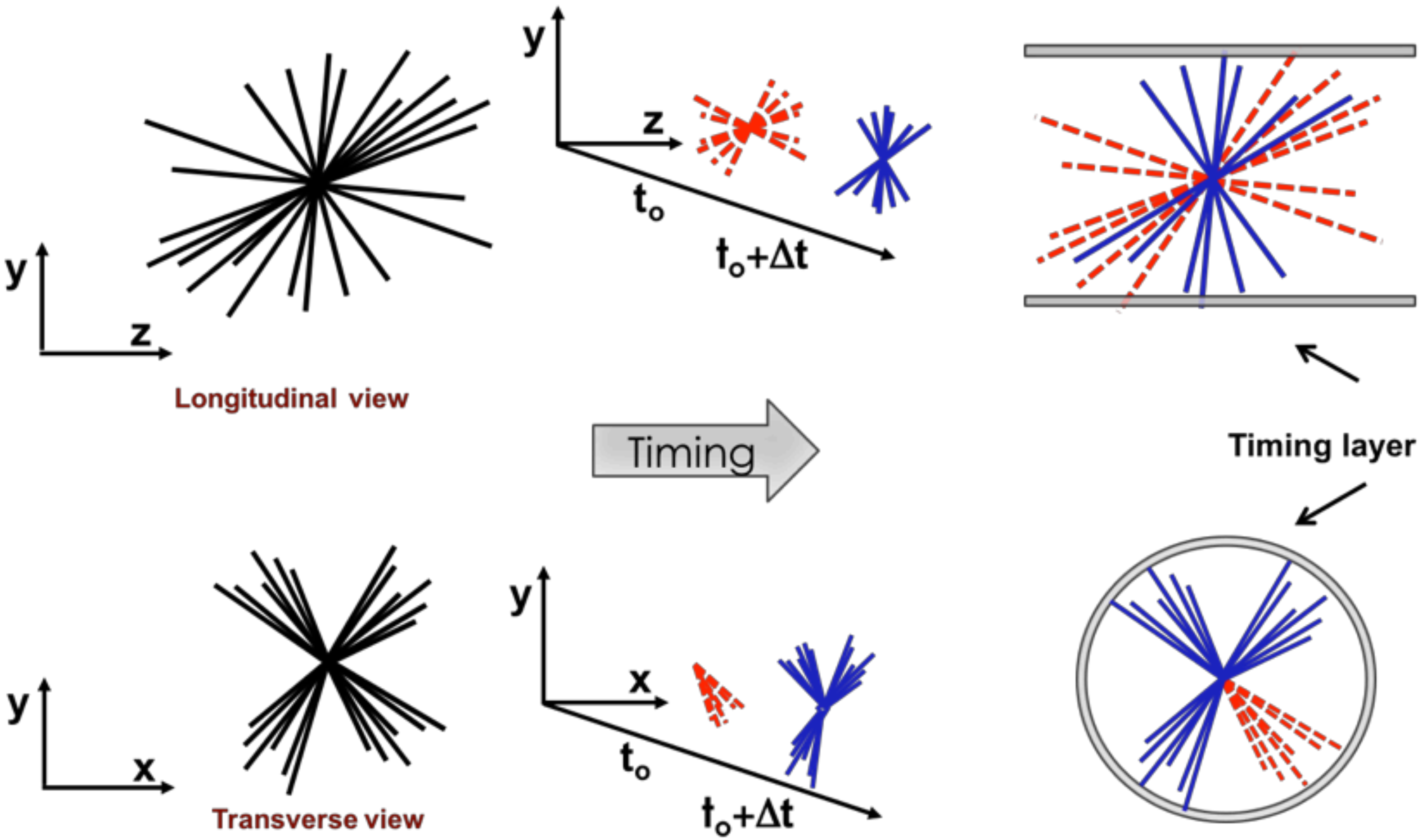
APD (Avalanche PhotoDiodes)
+ Thin sensors (30-50 μm)
+ High signal (gain 50-500)
- Sensitive to shot noise
- Radiation resistance up to 10^{14} n_{eq}/cm^2
- Fine segmentation difficult
➻ Intrinsic resolution: **σ_t ~ 30 ps**

LGAD (Low-Gain Avalanche Diodes) - UFSD
+ Thin sensors (50 μm)
+ Medium-high signal (gain 10-20)
+ Shot noise under control
+ Radiation resistance up to ~ $3 10^{15}$ n/cm^2
- Possible fine segmentation (TBD)
➻ Intrinsic resolution: σ_t ~ 30 ps

[1] M. Benoit et al., arXiv:1511.04231

TIMING IN THE EVENT RECONSTRUCTION

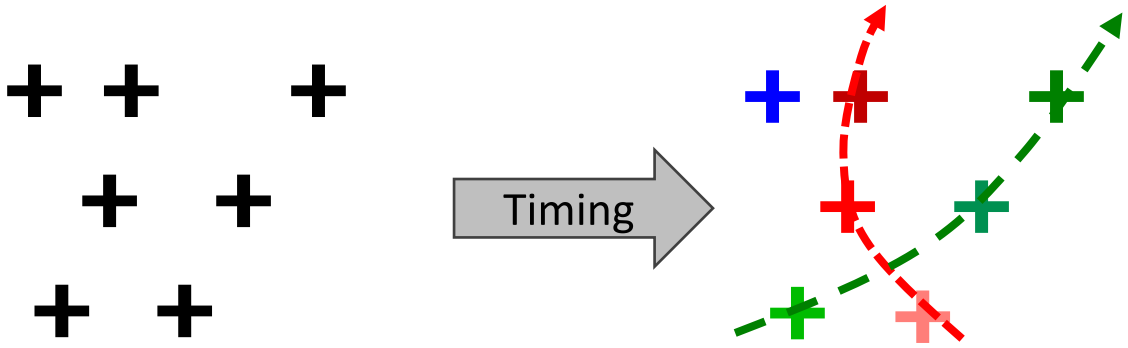
✏ Timing allows distinguishing overlapping events by means of an extra dimension

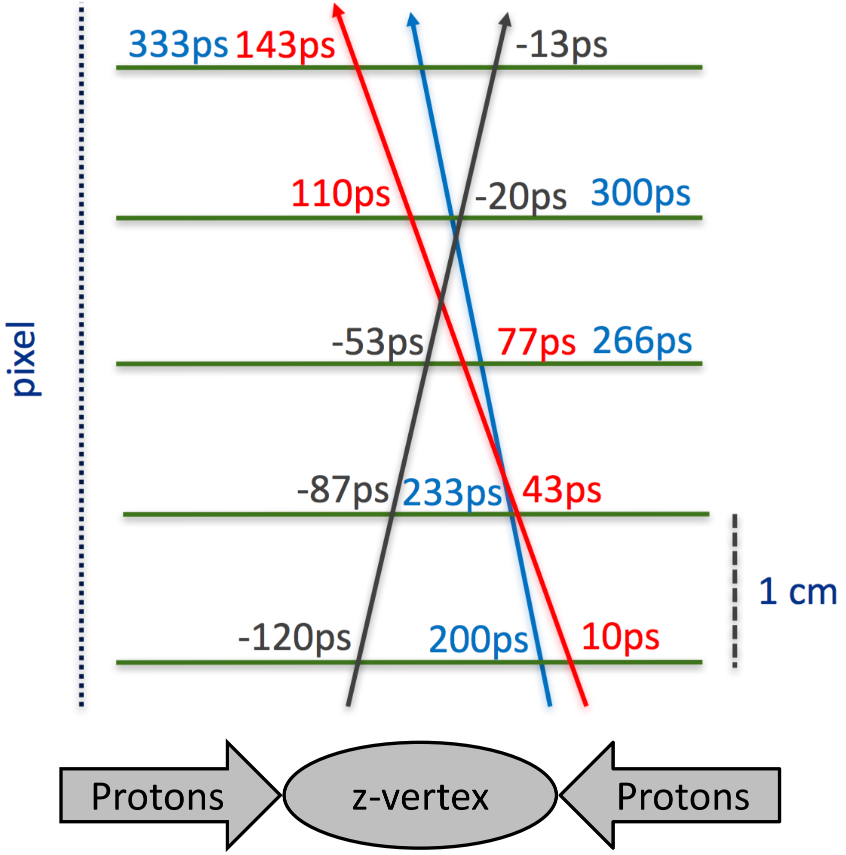


ATLAS and CMS Timing Layer concept

TIMING AT EACH POINT ALONG THE TRACK

- ✏ Massive simplification of pattern recognition, new tracking algorithms will be faster even in very dense environments
- ✏ Use only *time compatible points*

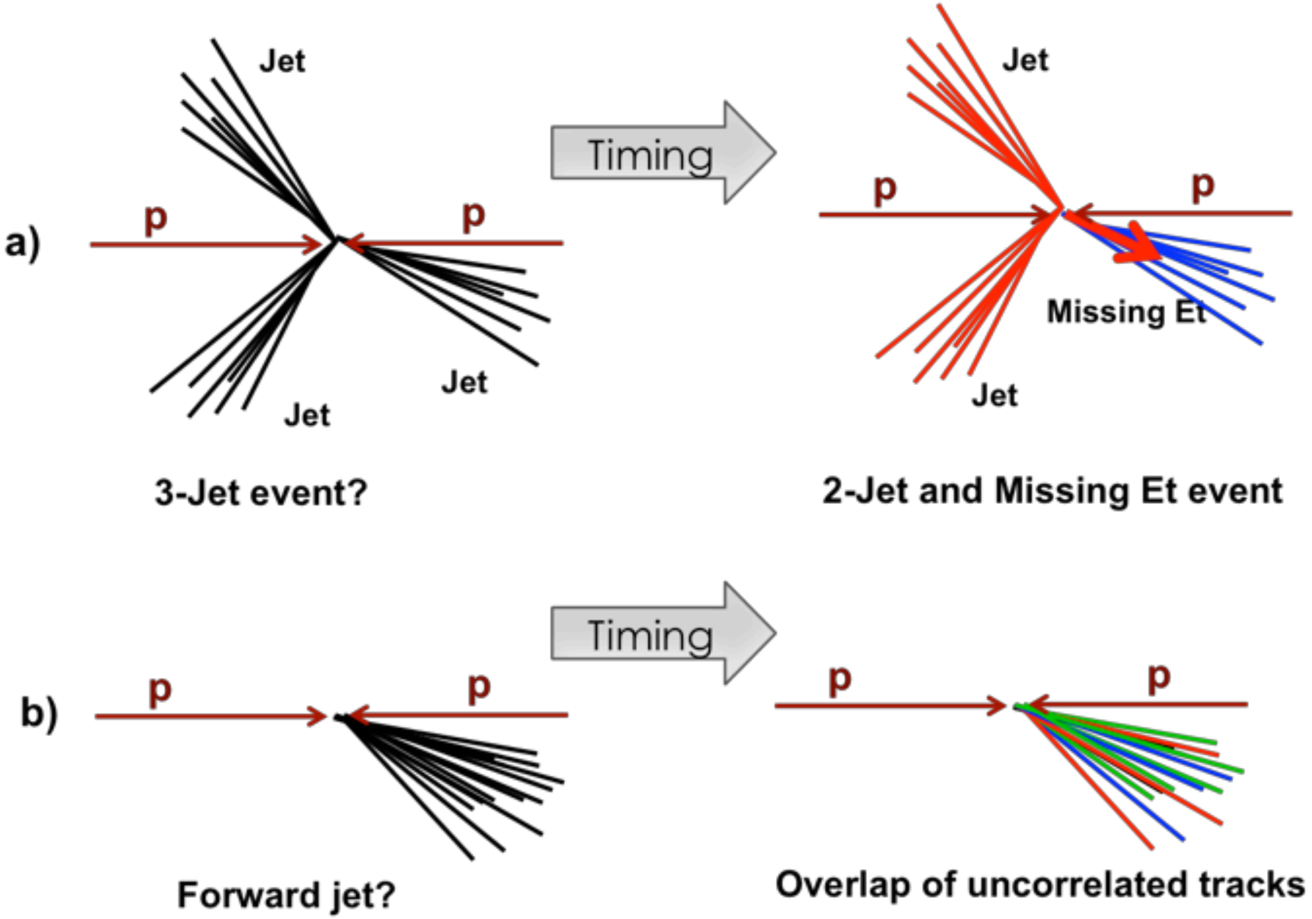




LHCb VeLo Upgrade 2035

TIMING AT THE TRIGGER LEVEL

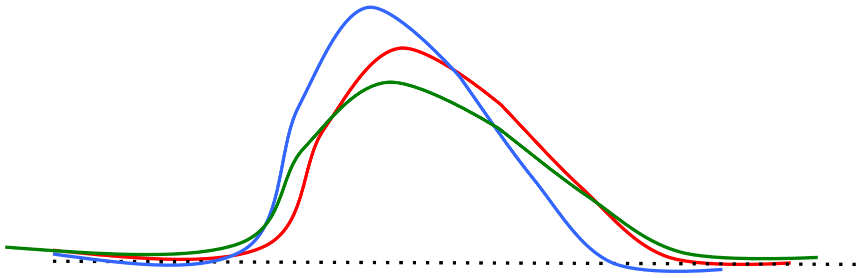
✏ Timing at the trigger decision allows reducing the trigger rate rejecting topologies that look similar



EIC
FCC-hh
???

POSSIBLE GEOMETRIES

Signal shape is determined by Ramo's theorem



$$\boldsymbol{i \propto q \cdot v_{drift} \cdot E_w}$$

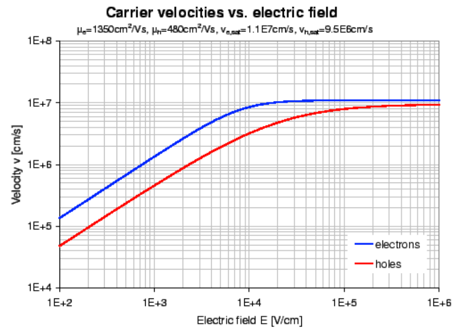
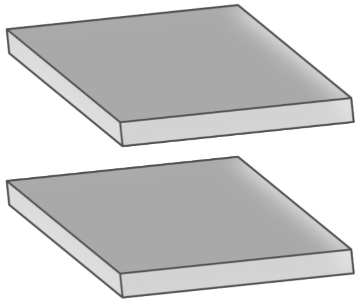
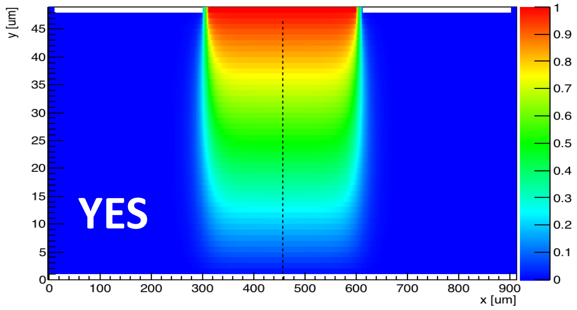
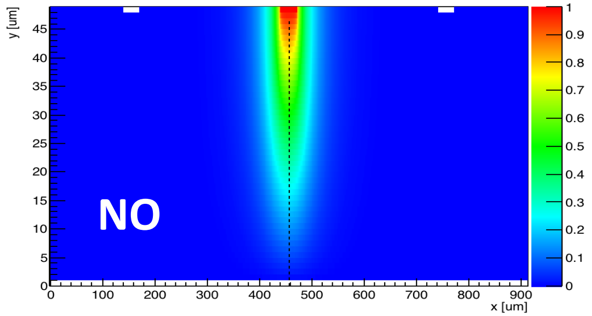


Figure: Electron and hole velocities vs. the electric field strength in silicon.

Drift velocity, $\boldsymbol{v_{drift}}$, and weighting field, $\boldsymbol{E_w}$, need to be **as uniform as possible**
Basic rule: **parallel plate geometry**







⇒ strip implant ~ strip pitch >> thickness

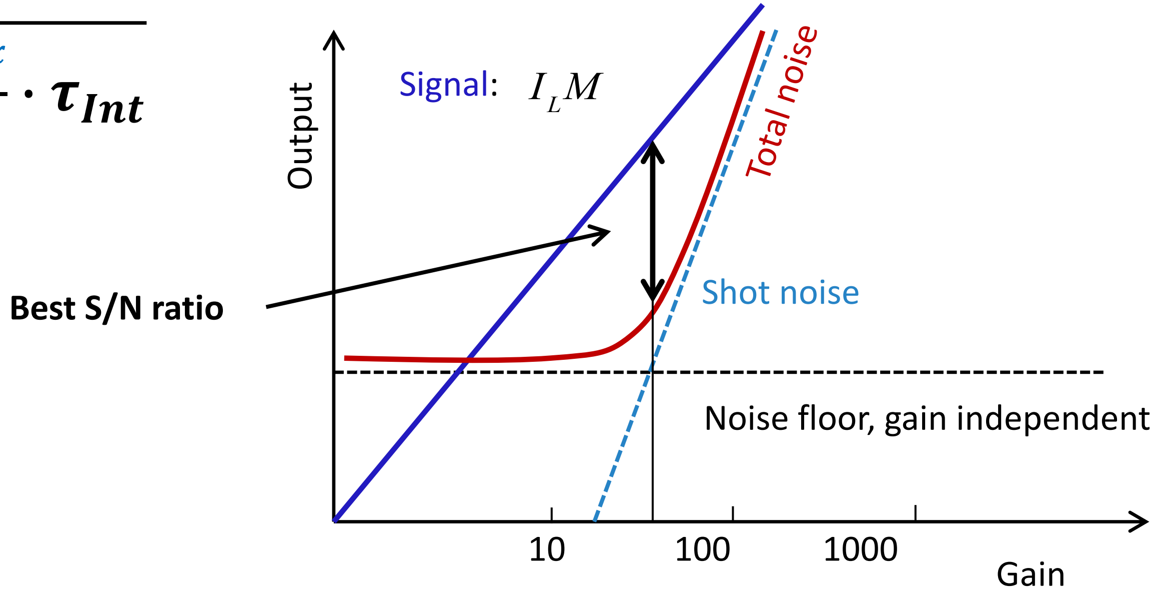
SHOT NOISE

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

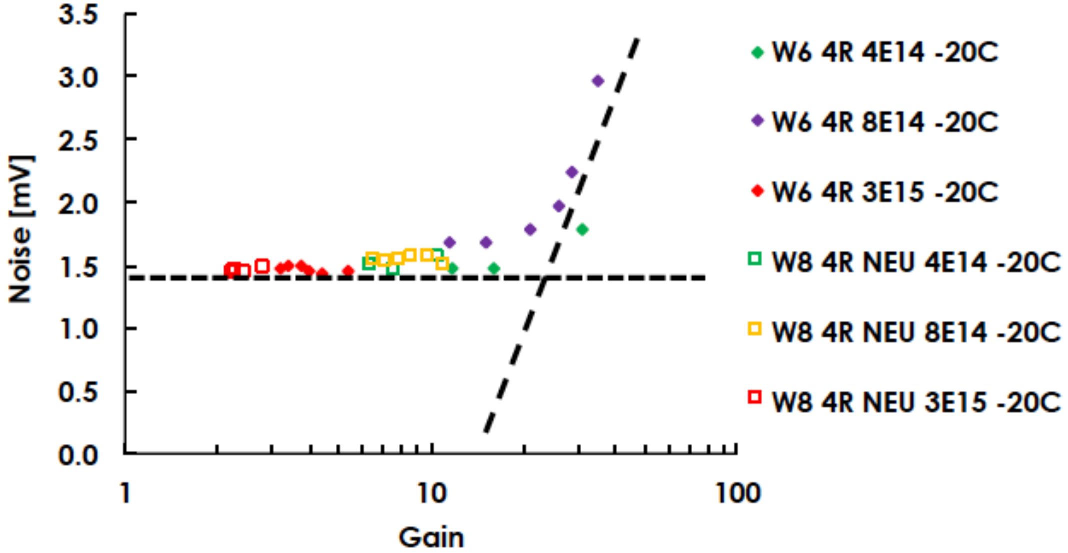
Shot noise increases faster than the signal
→ the ratio S/N becomes worse at high gain

To minimize the shot noise

- ➢ **Low gain (G = 10-20)**
- ➢ **Cool the detector**
- ➢ **Use small pads to have less leakage current**

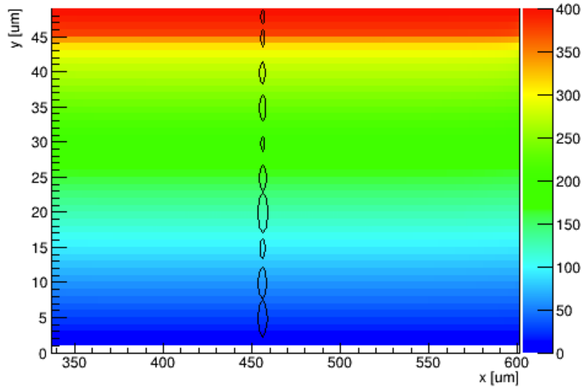


It has been measured that the values of Shot Noise are below the Current fluctuations

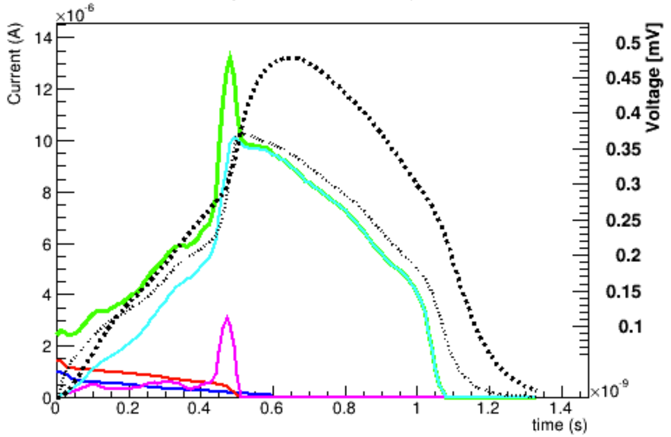


ELECTRONICS - THE PRE-AMP CHOICHE

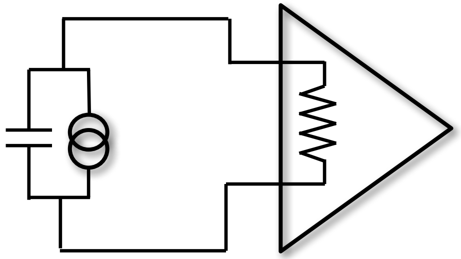
Energy deposition in a 50 µm sensor



Current signal in a 50 µm sensor

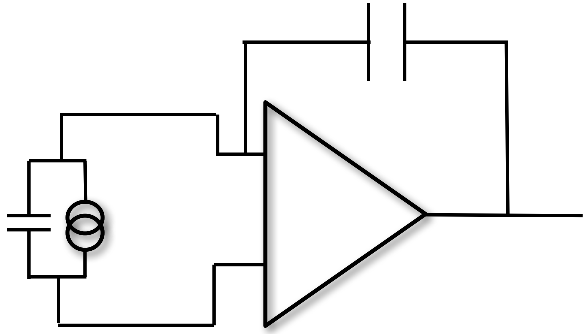


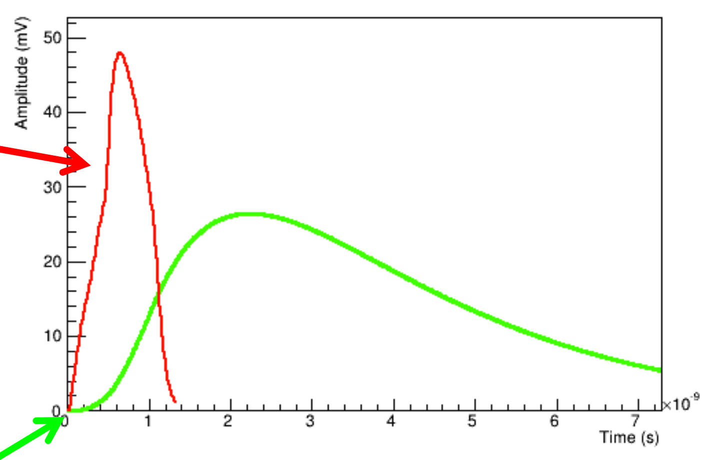
Current Amplifier



- Fast signal steepness
- Higher noise
- Sensitive to Landau bumps
- More power

Charge Sensitive Amplifier



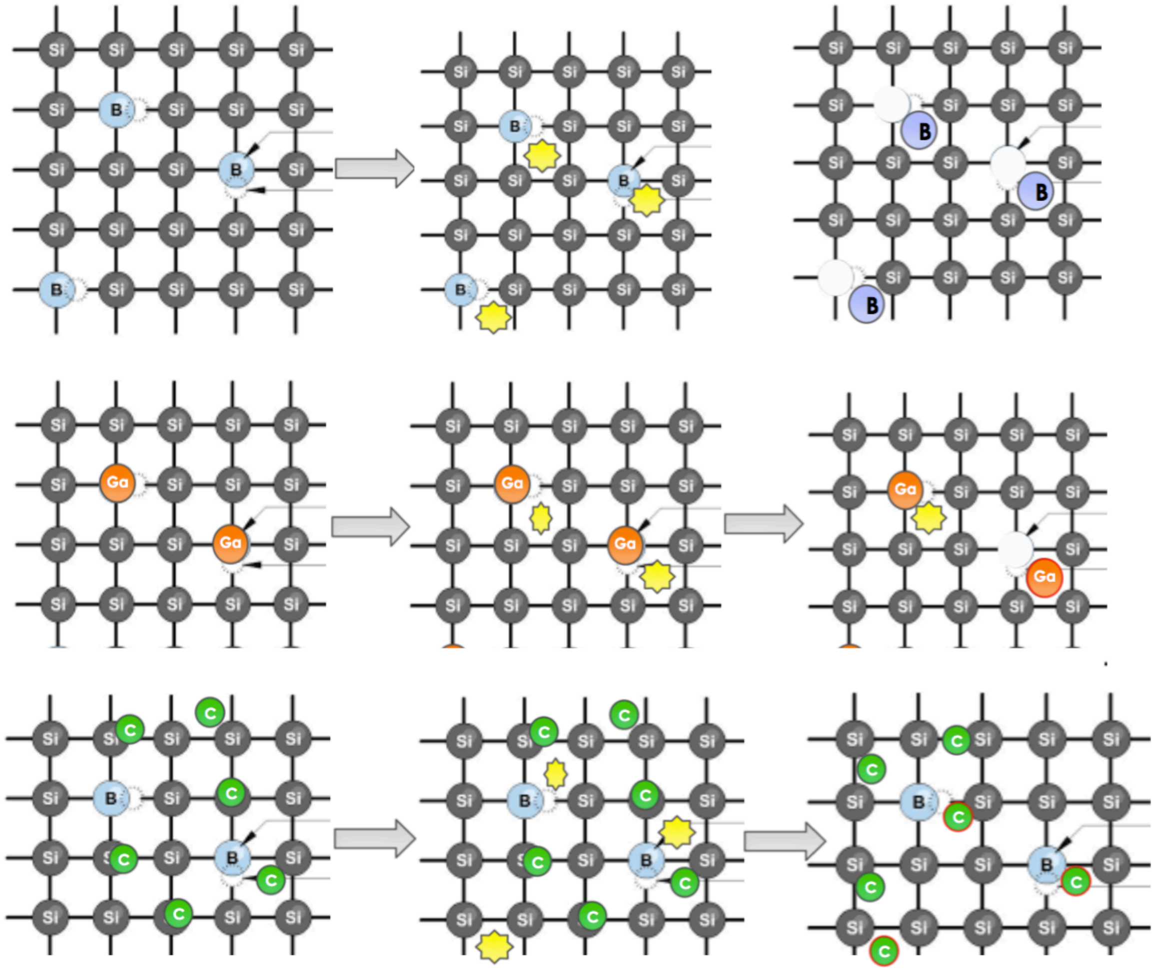


- Slower signal steepness
- Lower noise
- Signal smoothing
- Less power

DOPING STRATEGY MOTIVATION

From RD50 Collaboration

Different types of gain layer implant to study the radiation effects on the gain layer



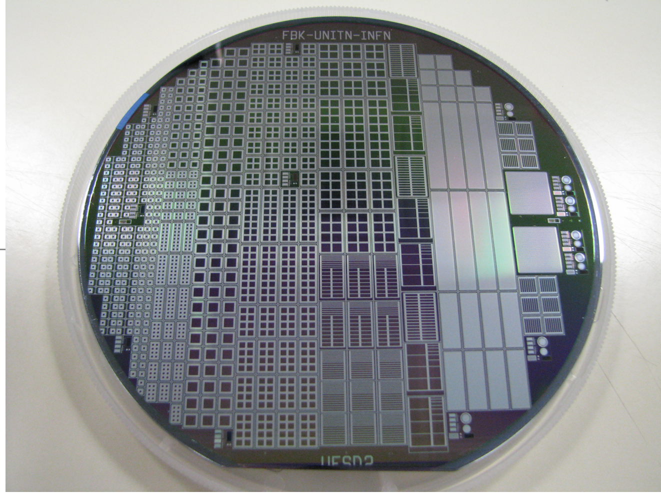
Boron
Radiation creates interstitial defects that inactivate the Boron

Gallium
From literature, Gallium has a lower possibility to become interstitial

Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium

50µm UFSD2 PRODUCTION

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
14	Gallium	1.04		Low
15	Gallium	1.04	Low	Low
16	Gallium	1.04	HIGH	Low
18	Gallium	1.08		Low



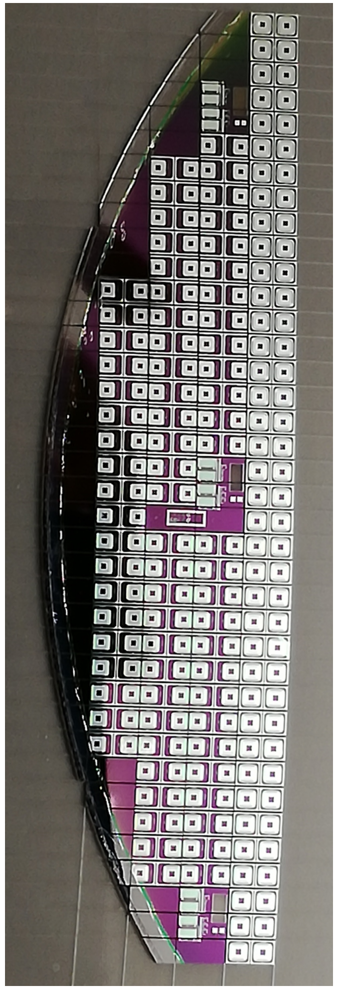
Production:

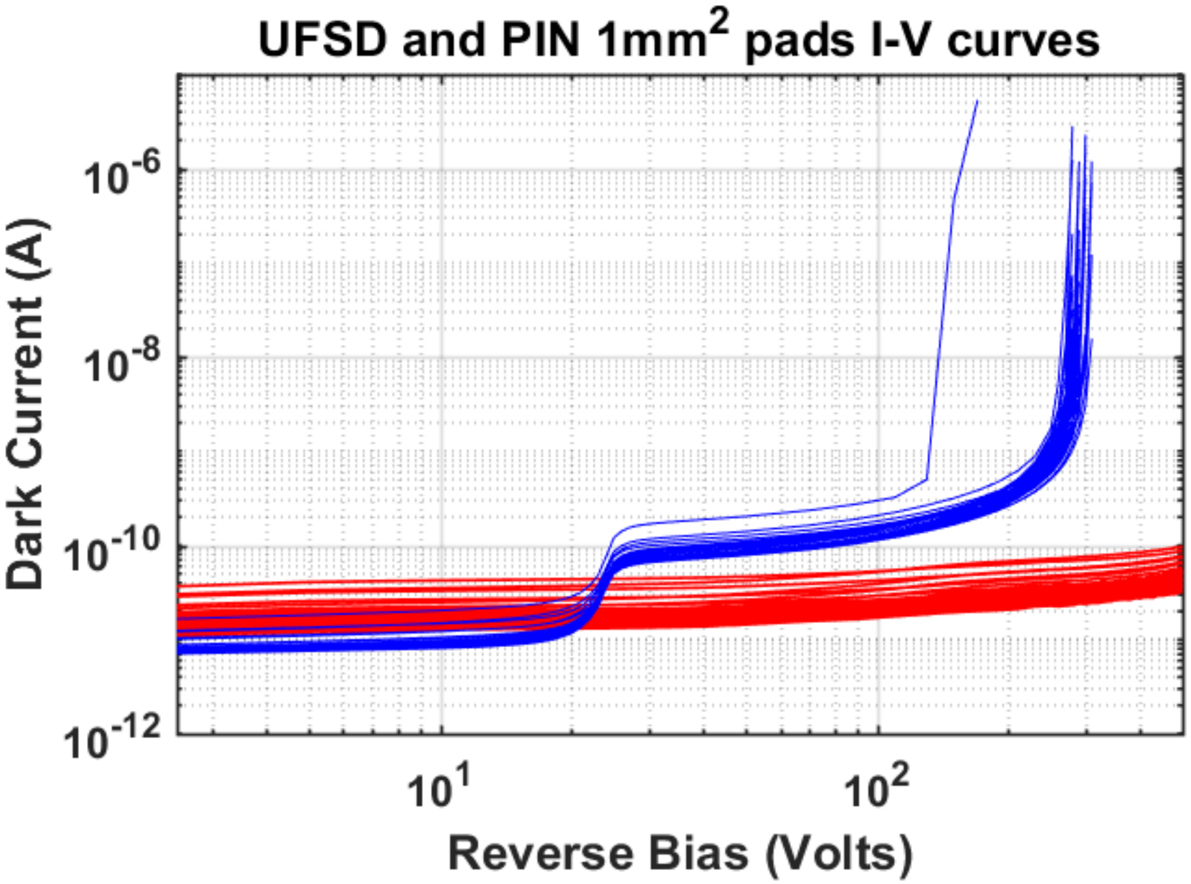
- 18 Silicon-on-Silicon wafers
- 4 different gain layer strategies:
  - Boron (Low & High diffusion)
  - Carbonated Boron (B High diffusion)
  - Gallium (Low diffusion)
  - Carbonated Gallium (Ga Low diffusion)
- 4 different doping concentration for Boron implants
- 2 different diffusion temperatures for Boron
- 3 different doping concentration for Gallium implants
- 2 carbon concentration (Low & High)

Carbonated Boron, Gallium & Carbonated Gallium implants to investigate radiation hardness

Gallium implant required a complete new simulation, because of implantation energy and diffusion very different from Boron

IV CURVES - WAFER UNIFORMITY





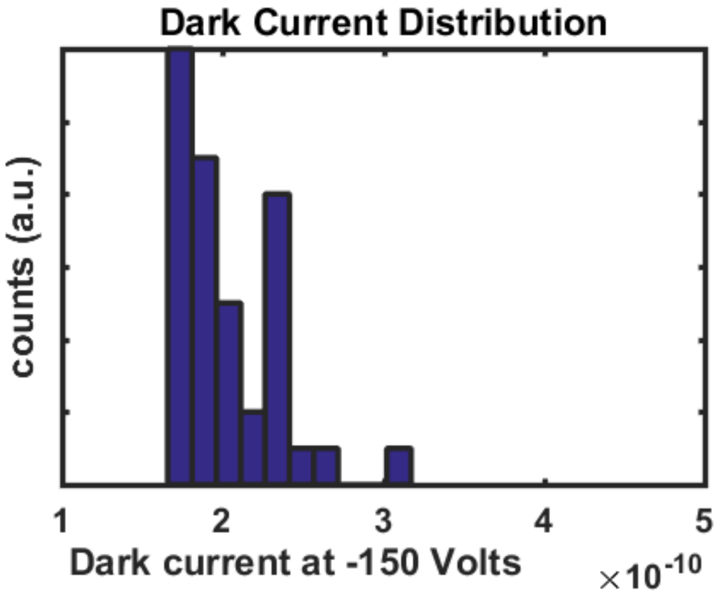
All the 1x1 mm² pads are plotted without any die selection

→ **Very high uniformity and low dark current**

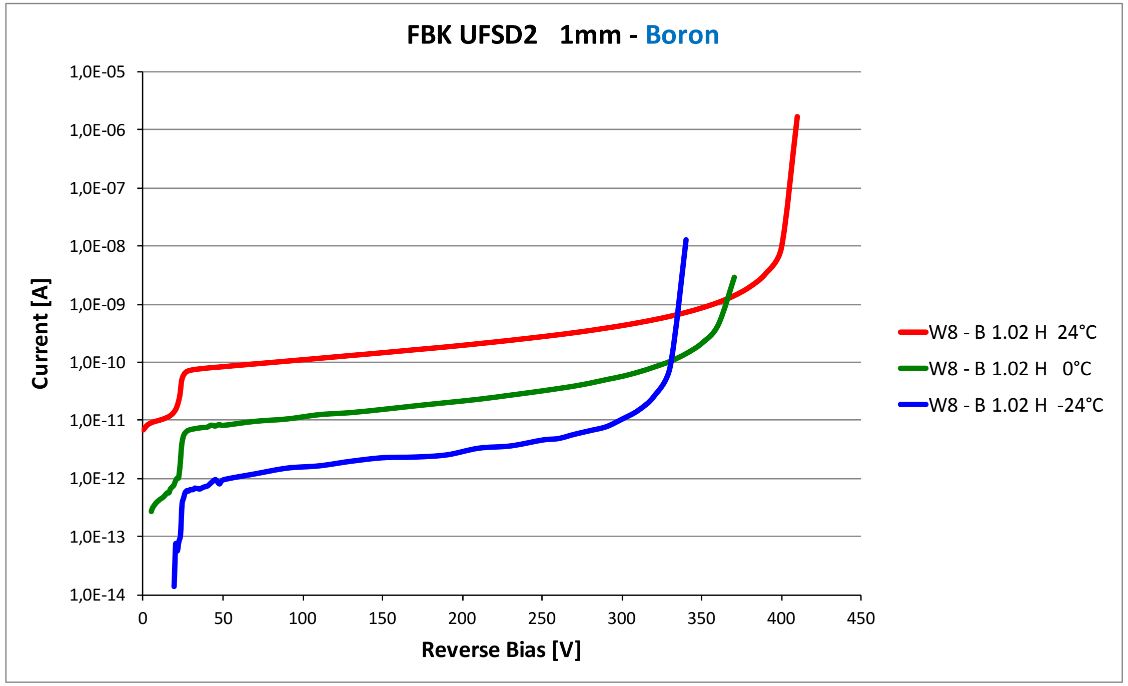
Data from Wafer 2

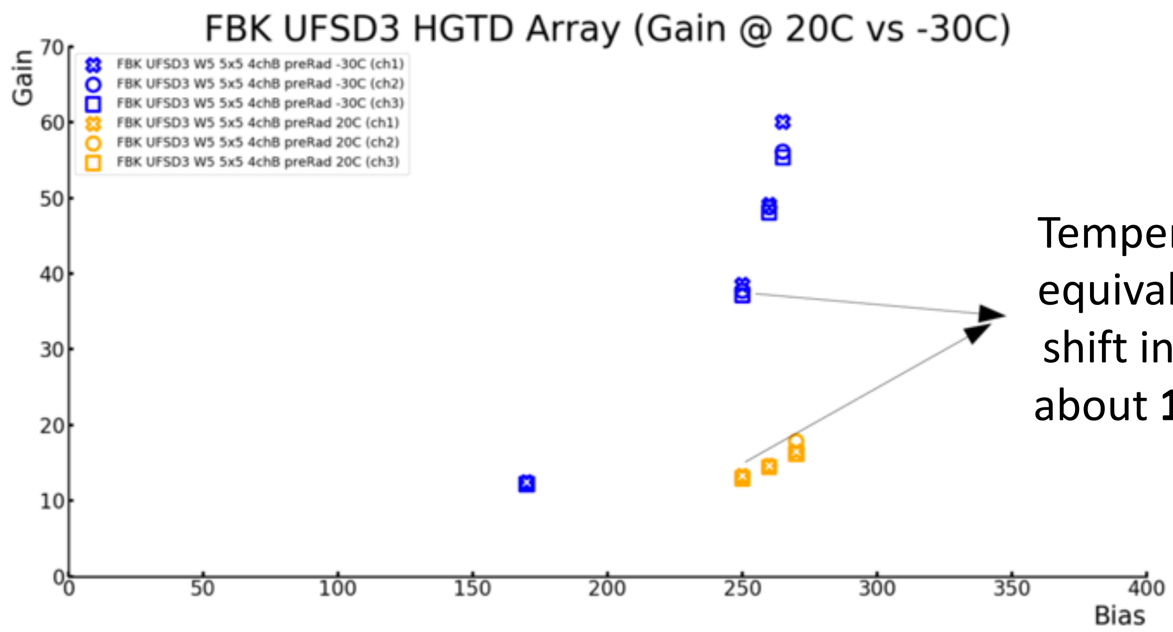
Boron LD Dose Factor = 1.0

Measurements on wafer



IV CURVES - TEMPERATURE DEPENDENCE



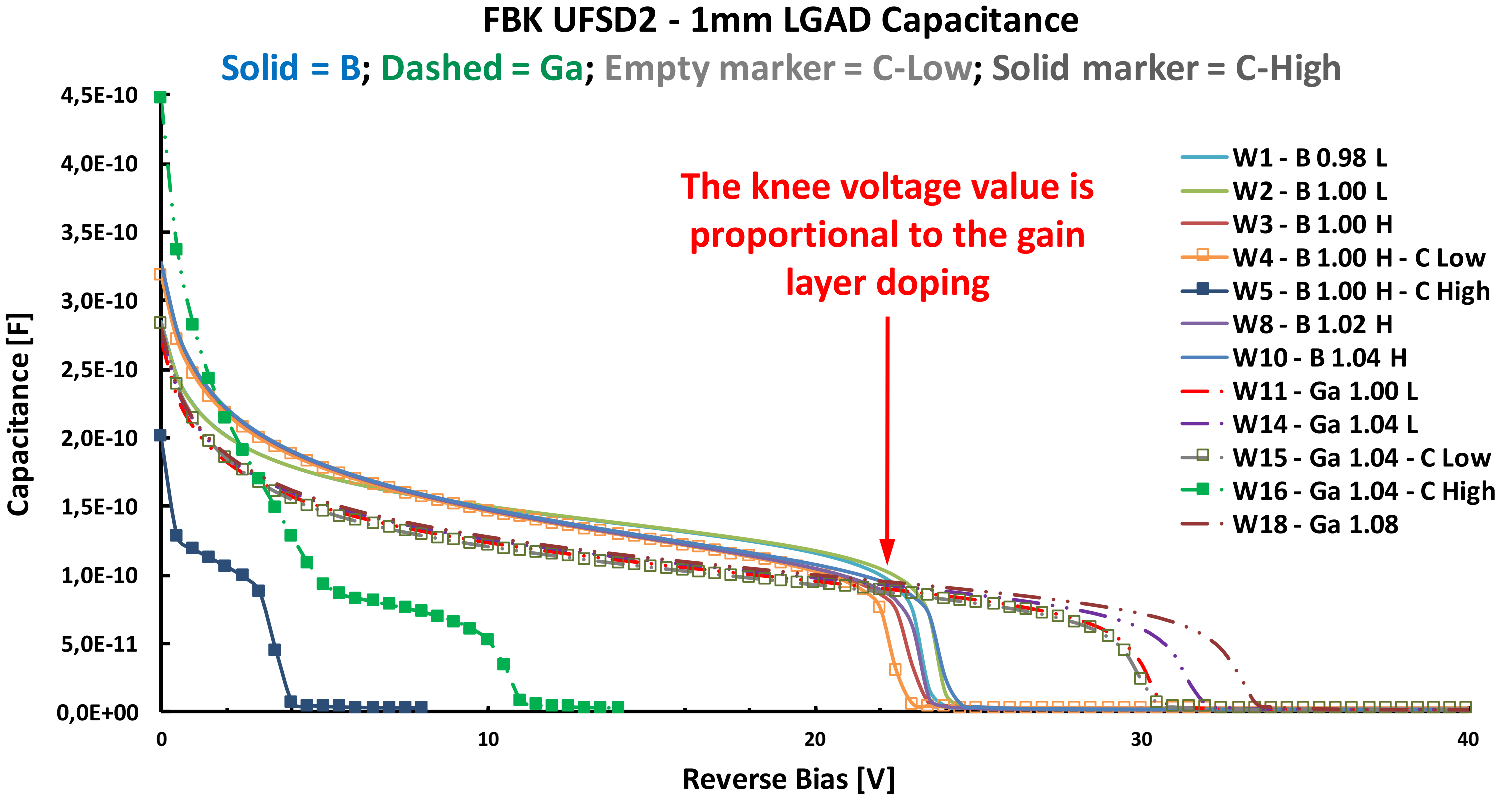


Temperature is equivalent to a shift in V_{bias} by about **1-1.5V/K**

- Leakage current scales with the temperature (expected a factor 2 for every 7°C)
- Expected a gain inversely proportional to the temperature
- Internal Breakdown shift towards lower voltage due to the temperature decreasing

ΔT = 48°C → Current(24°C)/ Current(-24°C)~100 → Result expected

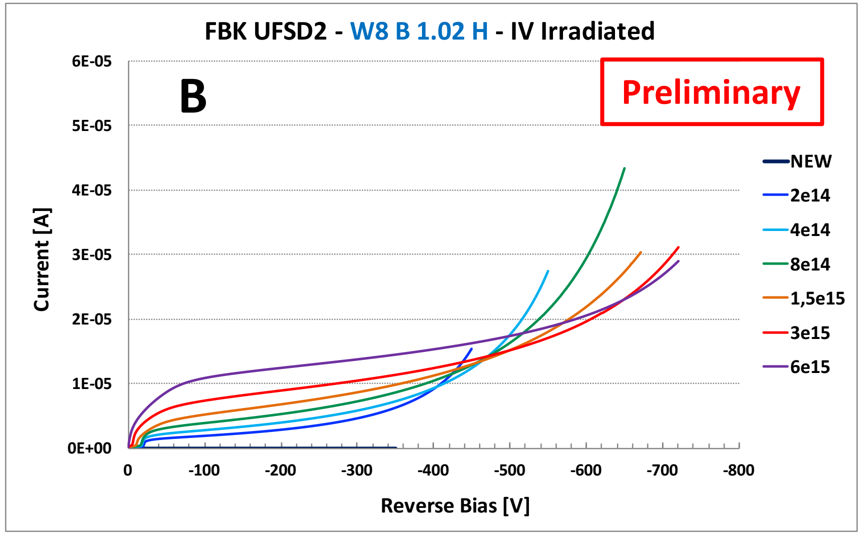
CV CURVES - ALL WAFERS

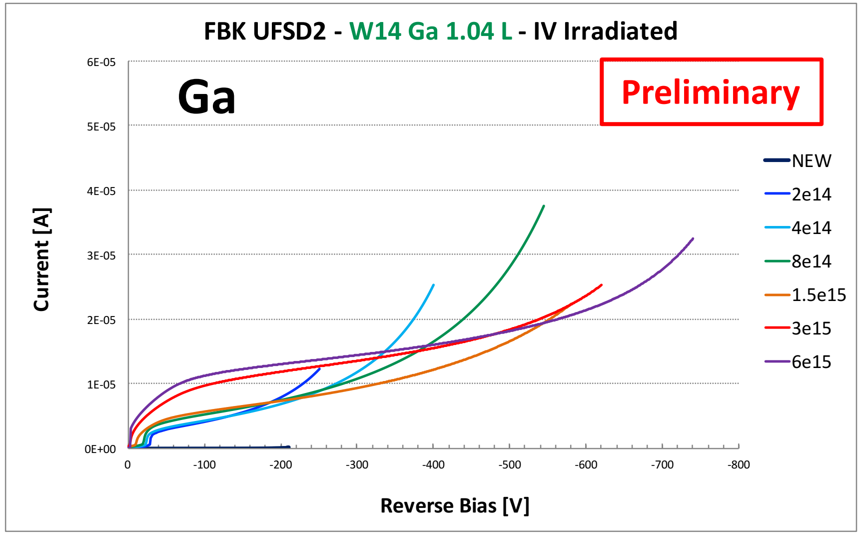


- The knee at ~30V indicates the the gain layer depletion voltage
- Boron & Gallium doped sensors show slightly different behavior due to different gain layer width
- Low Carbon: similar depletion voltage as in the case without Carbon
- High Carbon: depletion voltage occurs much earlier that in the case without Carbon

IV Measurements on Irradiated Sensors

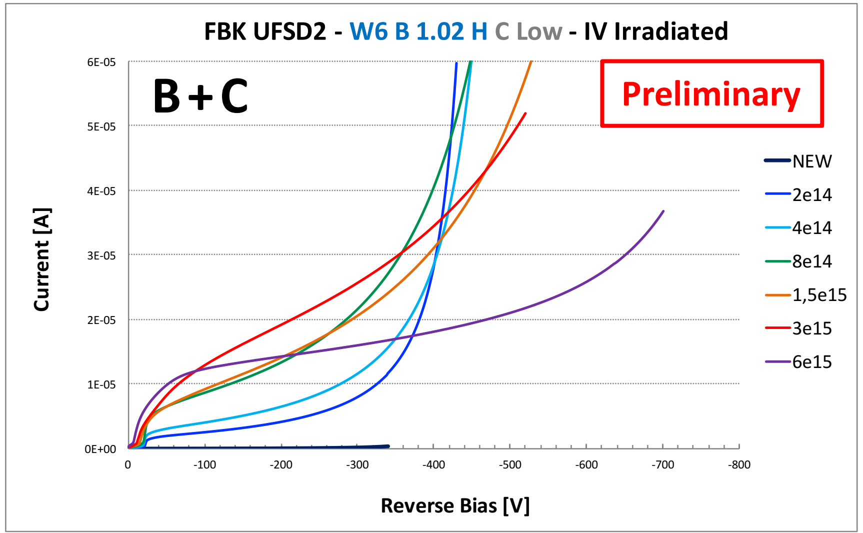
Standard

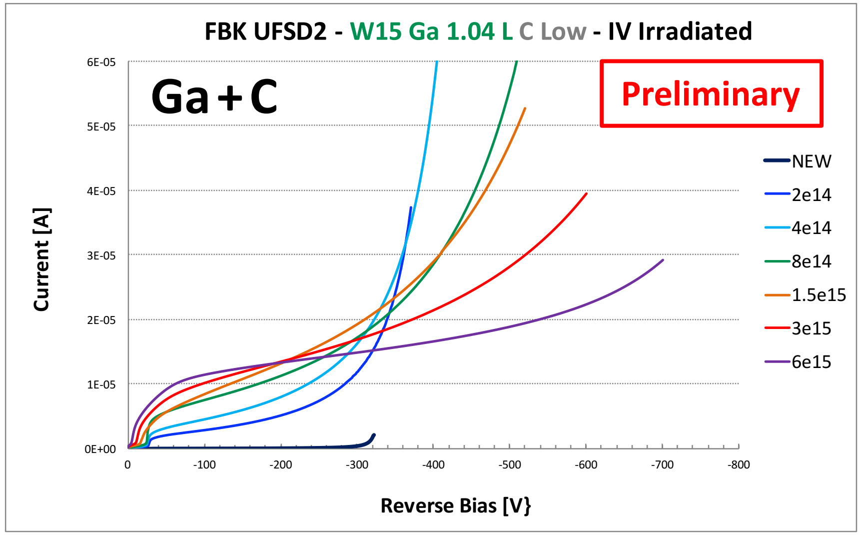




Curvature proportional to gain

Carbonated



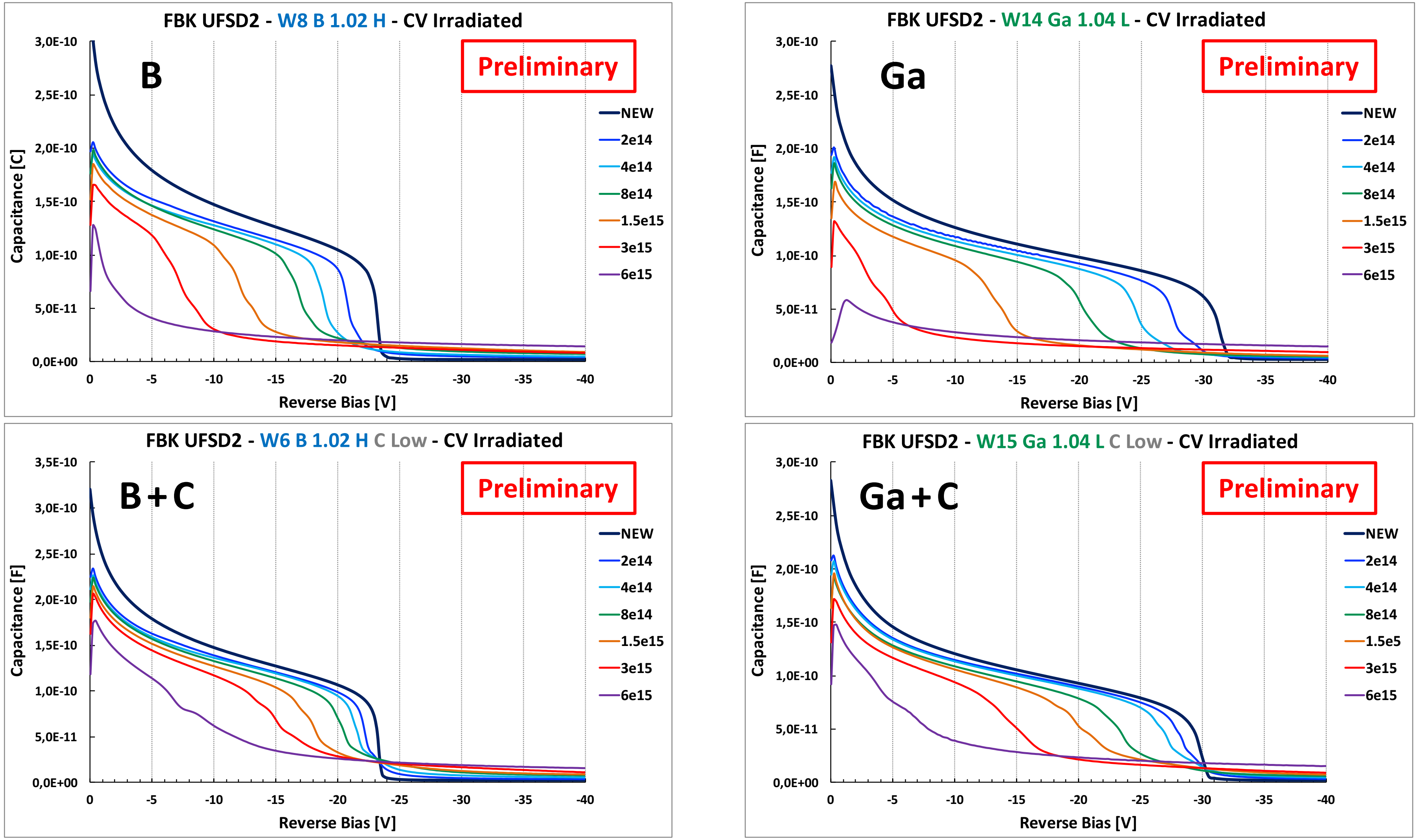


Irradiation extends the operating voltage of the sensors up to ~ 750 V

CV Measurements on Irradiated Sensors

Standard

Carbonated



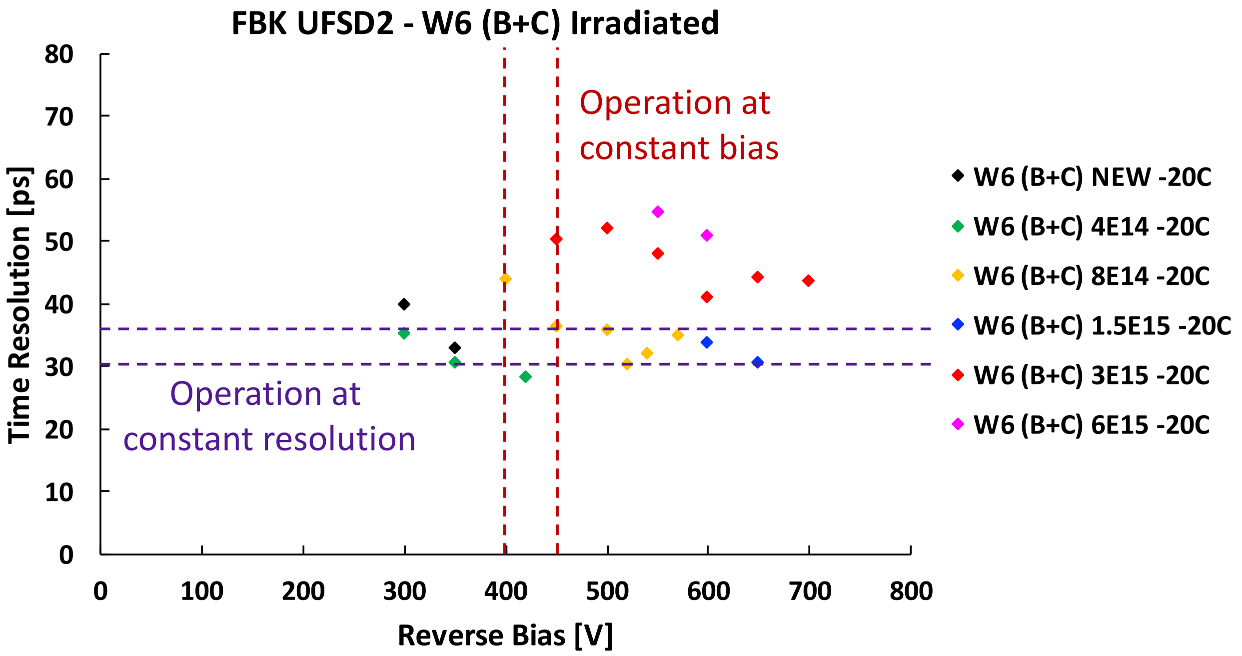
Reminder: fluence doubles at each step

The knee voltage value is proportional to the gain layer doping

TIME RESOLUTION WITH CARBON

FBK UFSD2 B+C:

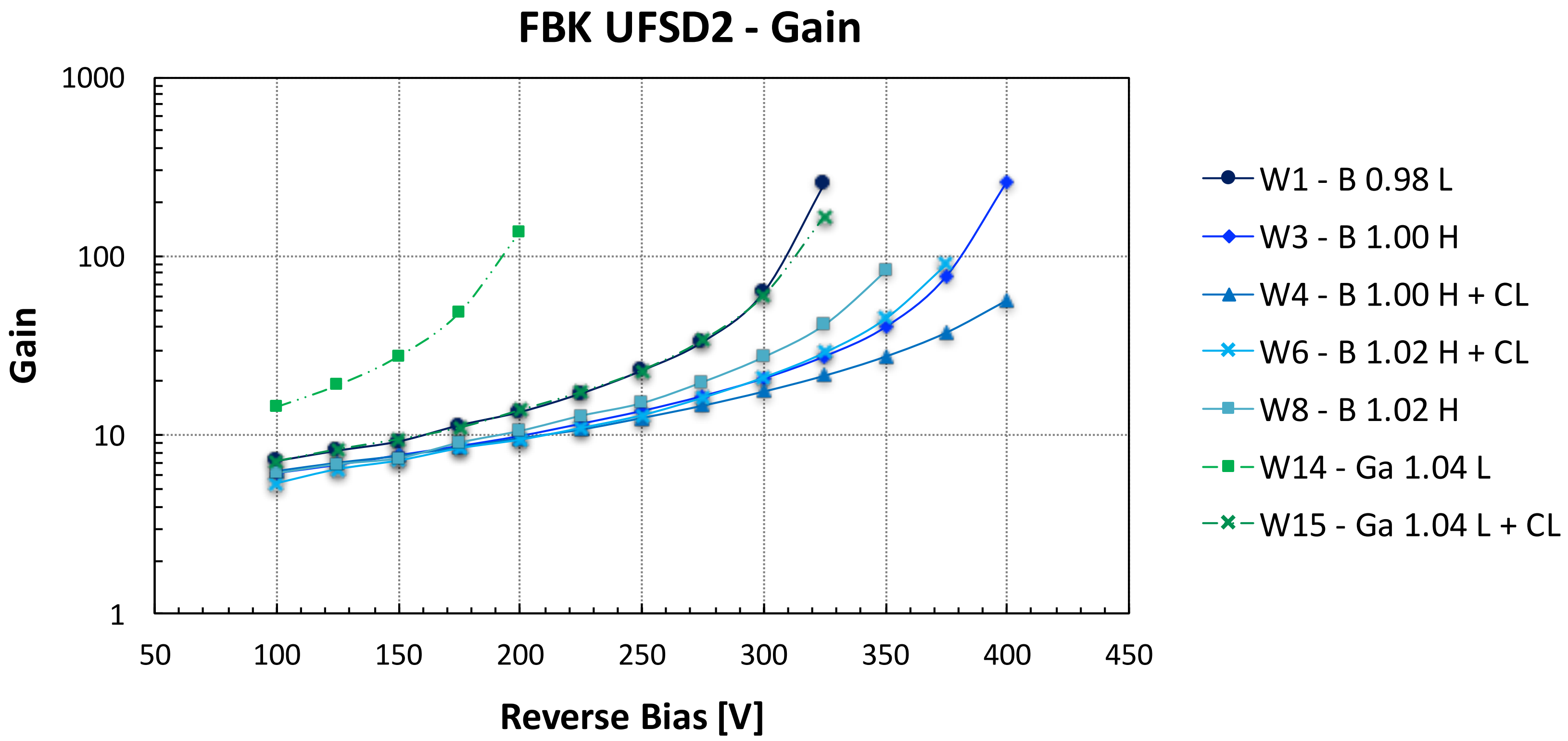
- ➢ Constant time resolution up to 1.5E15 n_{eq}/cm^2 increasing V_{bias} to 650
- ➢ Constant V_{bias} up to 1.5E15 n_{eq}/cm^2 with 30% degradation in time resolution

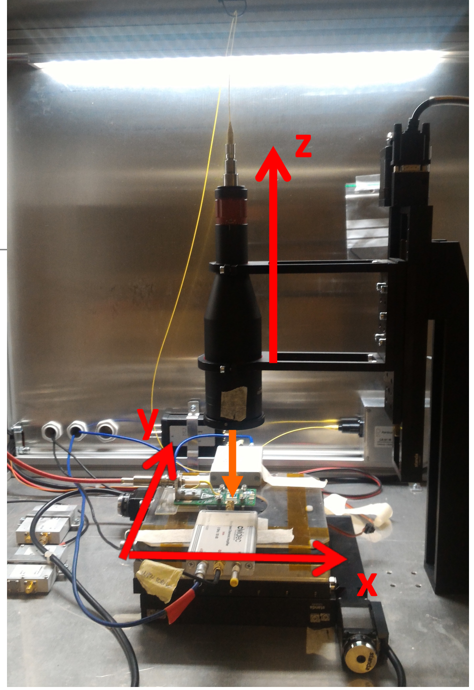


1.5E15 n_{eq}/cm^2 at HL-LHC correspond to 4000 fb^{-1} at $|\eta| = 3$

→ Current R&D focuses on reducing the need to increase the bias voltage

GAIN MEASUREMENT





TCT Setup from Particulars

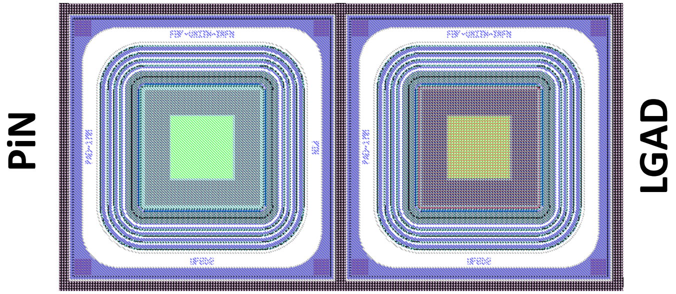
Pico-second IR laser at 1064 nm

Laser spot diameter ~ 50 µm

Cividec Broadband Amplifier (40dB)

Oscilloscope Lecroy 640Zi

Room temperature



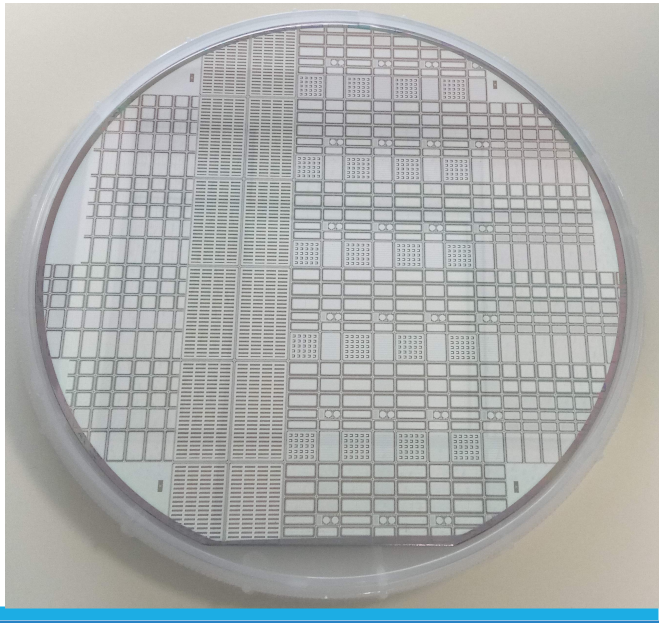
GAIN = (Signal area LGAD)/(Signal area PiN)

FBK UFSD3 Production

Wafer #	UFSD2	Dose Pgain	Carbon	Diffusion
1	W1	0.98		L
2	W1-Epi	0.96		L
3		0.96	A	L
4	Epi	0.96	A	L
5		0.98	A	L
6		0.96	B	L
7		0.98	B	L
8		0.98	B	L
9		0.98	C	L
10		1.00	C	L
11		1.00	D	L
12	W8	1.02		H
13	W8-Epi	1.00		H
14	W6	1.02	A	H
15	W6-Epi	1.00	A	H
16		1.02	B	H
17		1.02	B	H
18		1.04	B	H
19		1.02	C	H
20		1.04	C	H

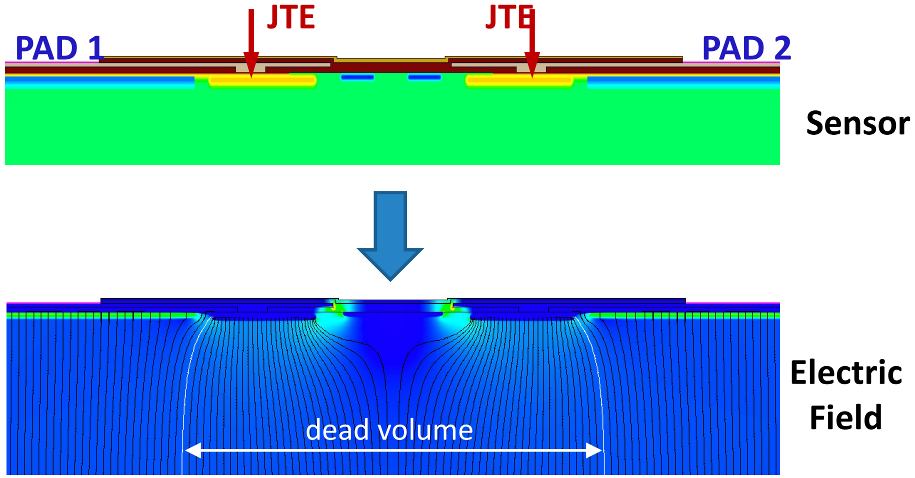
- 6” wafers processed - 55 µm thick active substrate
- 16 Float-Zone, 4 Epitaxial substrates
- 2 strategies of gain implant diffusion
- 5 splits of gain layer doses
- 4 splits Carbon co-implantation
- 4 inter-pad termination strategies

Strategy	Nominal width [µm]
Aggressive	15 µm
Medium	20 µm
Safe	30 µm
Super Safe	40 µm
UFSD2	70 µm

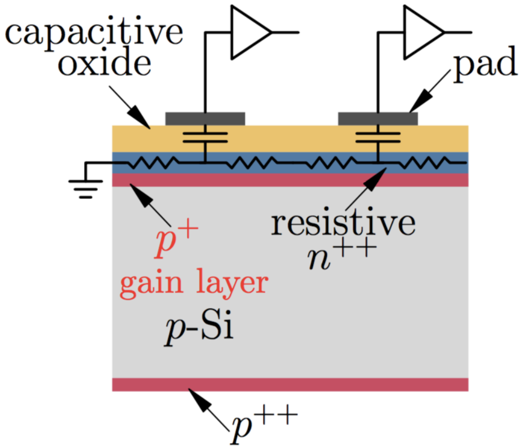


FILL FACTOR

Actual situation: 50 µm → 93% (for 1.7 mm^2 pad)

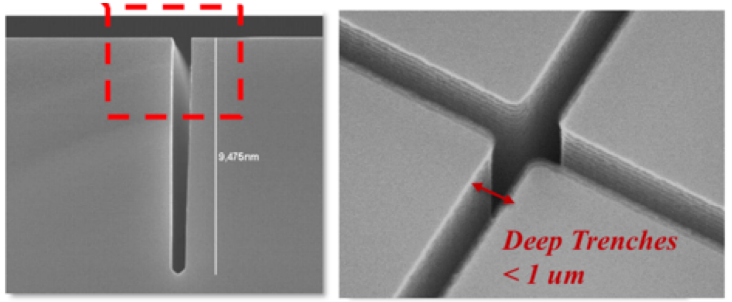


Future R&D



RSD (INFN+FBK) project, no segmentation in the active area → **100% fill factor by definition**

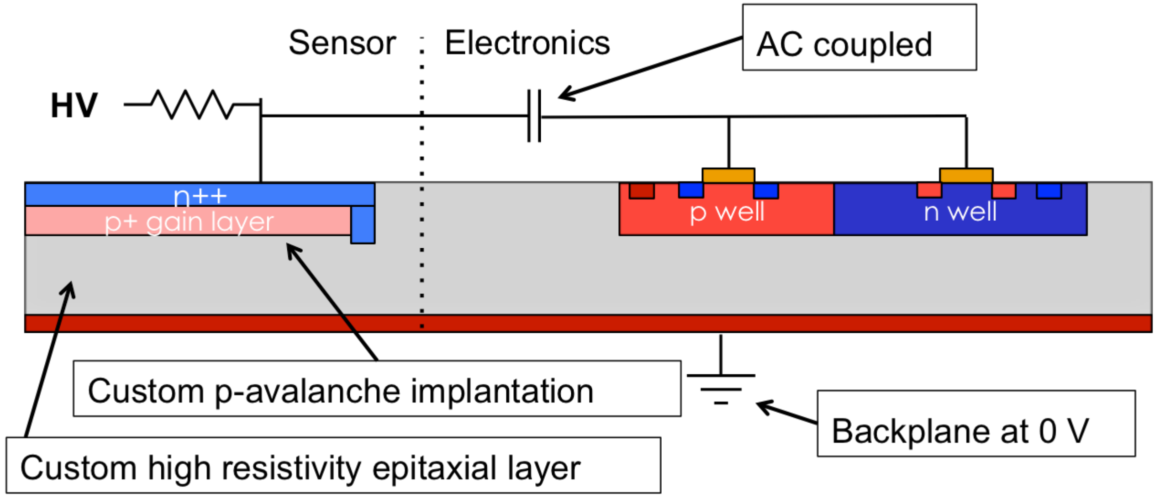
FBK + RD50 project, taking example from SiPM, using a trench design → **about 100% fill factor**



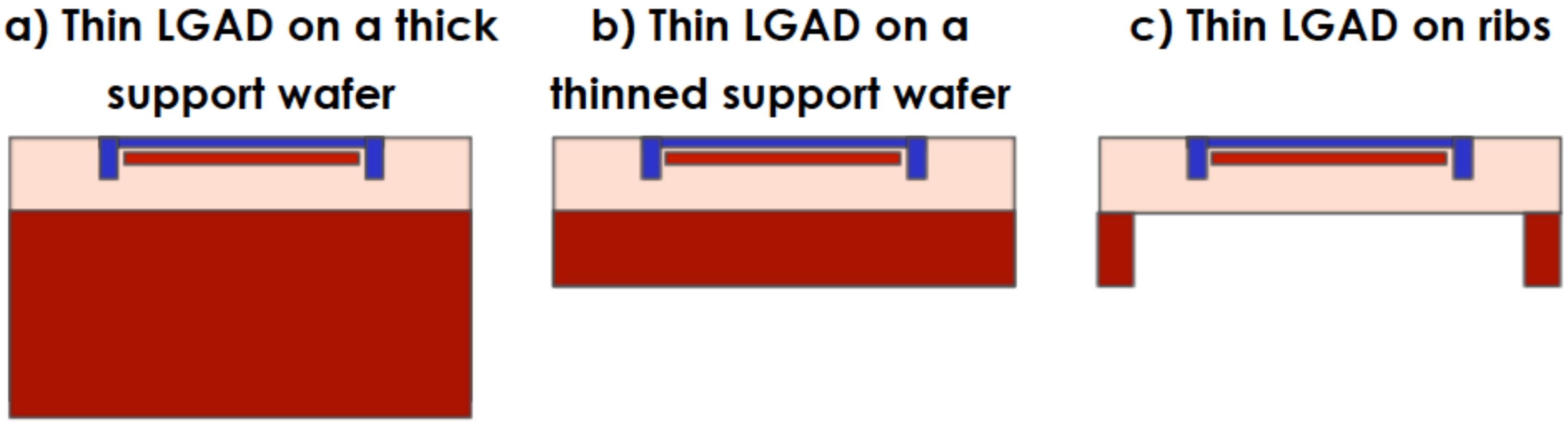
HD-LGAD

FUTURE R&D

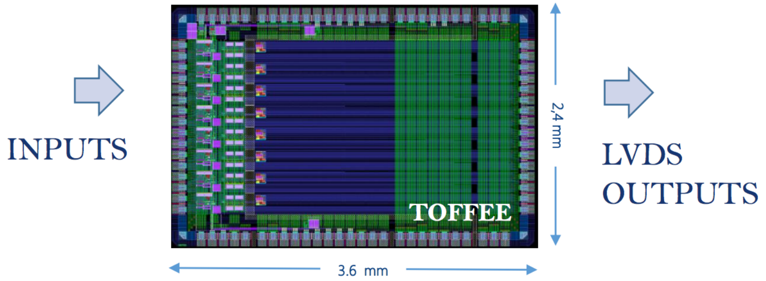
- **Monolithic detectors**



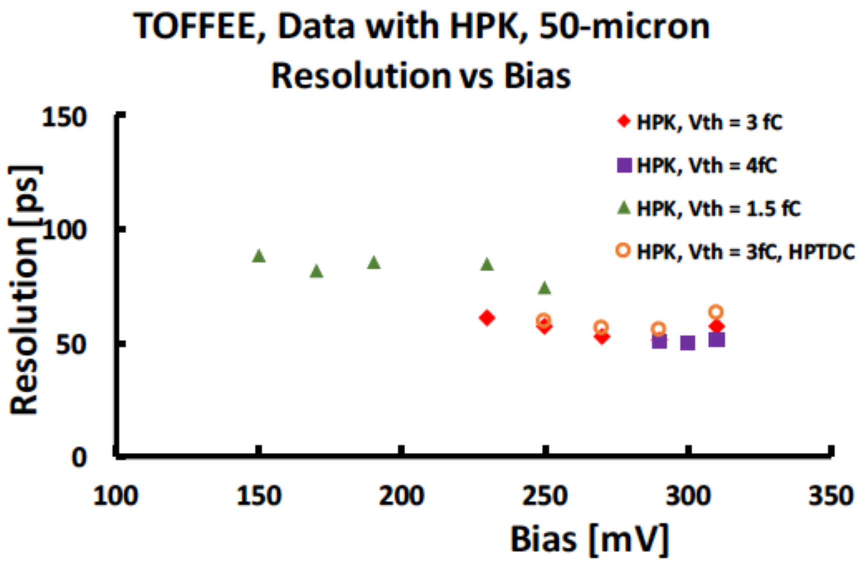
- **Lower material budget**



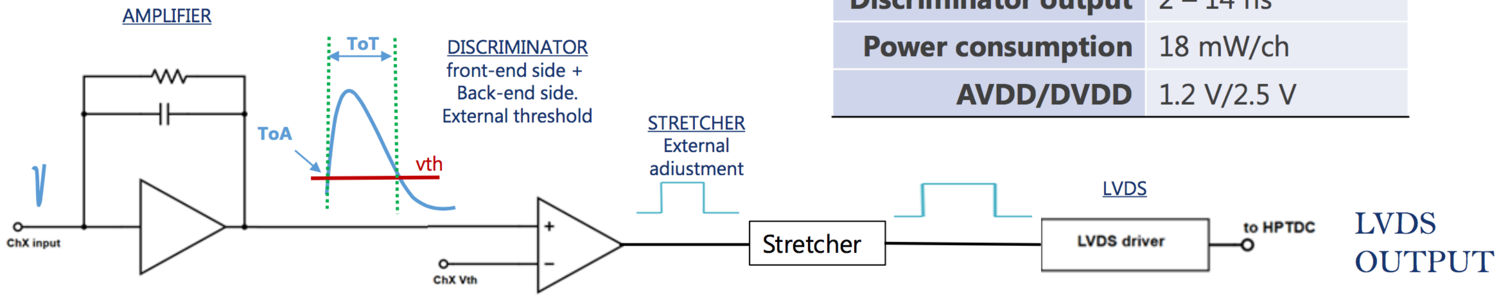
TOFFEE



Technology	CMOS 110 nm
Channels	8
Sensor capacitance	2-10 pF
Input dynamic range	3 fC – 60 fC
Analog gain	7 mV/fC
GBW	14 GHz
RMS noise (C=6pF)	800 μV
Discriminator output	2 – 14 ns
Power consumption	18 mW/ch
AVDD/DVDD	1.2 V/2.5 V



The channel architecture



The LVDS output is meant for time digitization with HPTDC (rising and falling edges). **A Strecher is required**.

TOFFEE is the first version of a multipurpose 8-channel chip with Time-over-Threshold time-walk correction

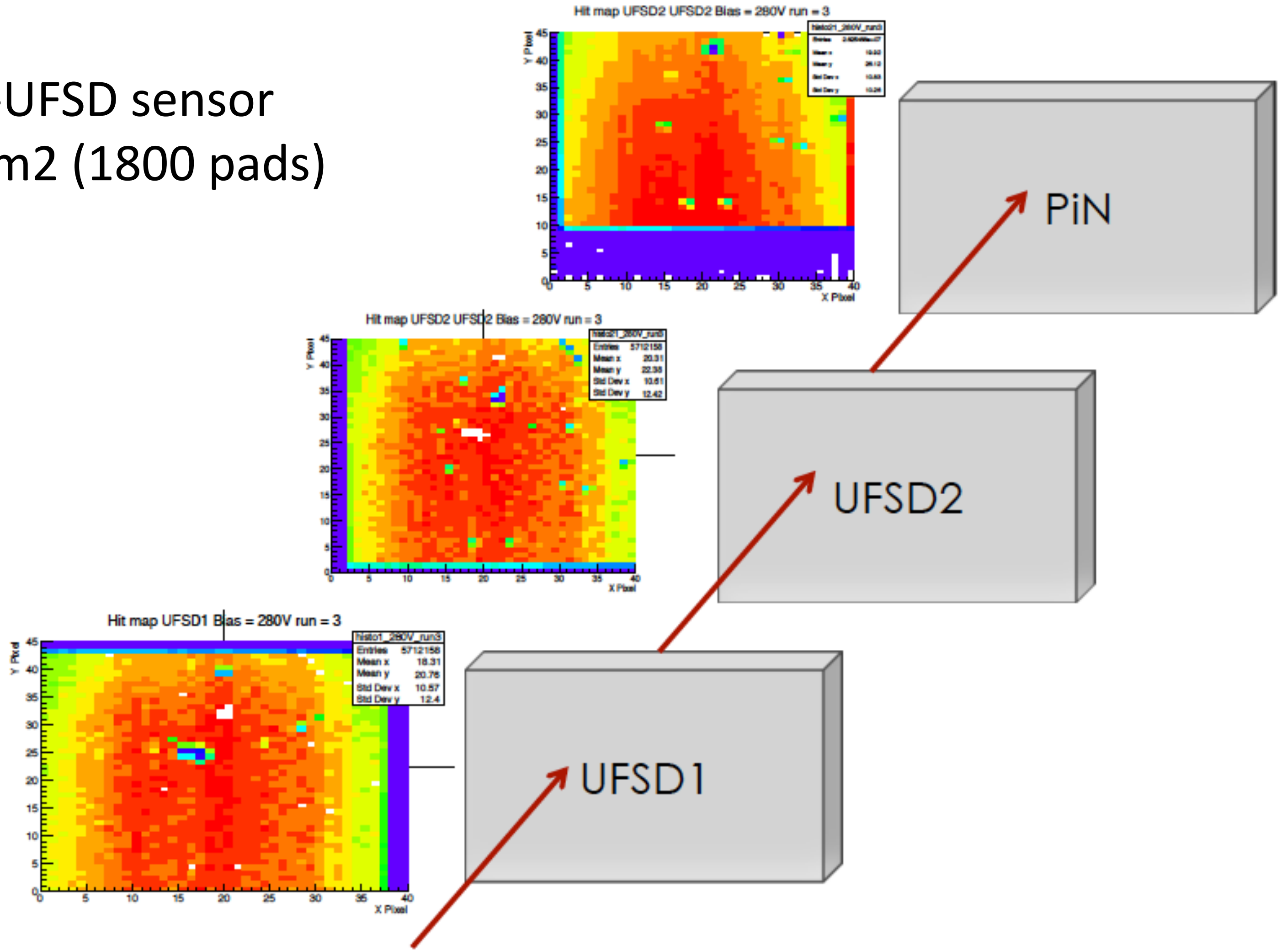
→ **At beam test, it achieves a resolution of 55 ps, including the digital part**

TDCpix

Bump-bonded NA62 TDCpix ROC to FBK-UFSD sensor
NA62 ROC: 40x45 pads, each 300x300 μm2 (1800 pads)

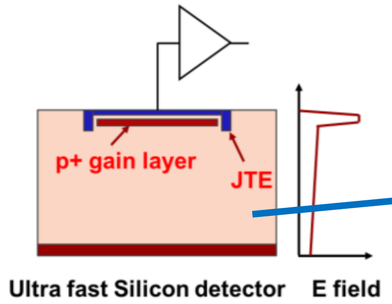
- ➢ More than 99% of pads working
- ➢ Same voltage behavior as single pad
  → breakdown above 280 V

⇒ **First example of 4D tracking!**

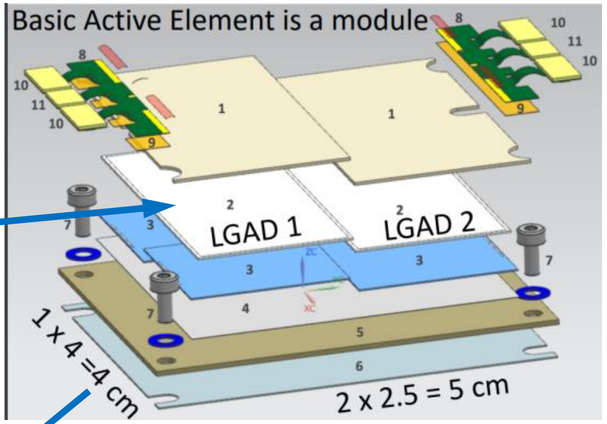


ETL LAYOUT

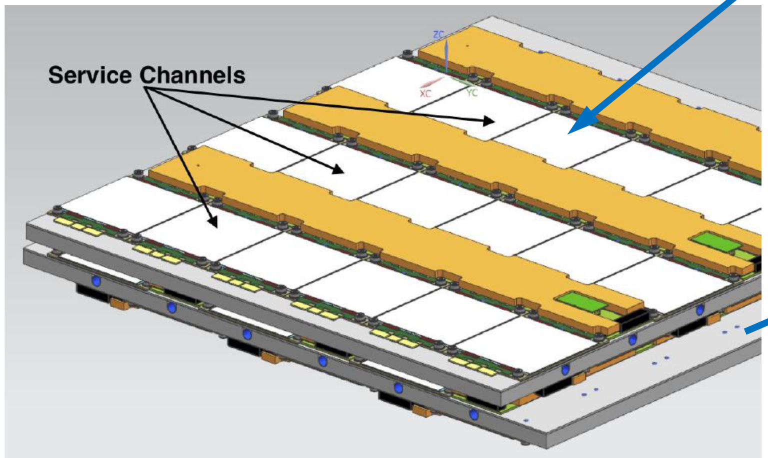
UFSD sensor with array of 16x32 1.3x1.3 mm^2 pixels

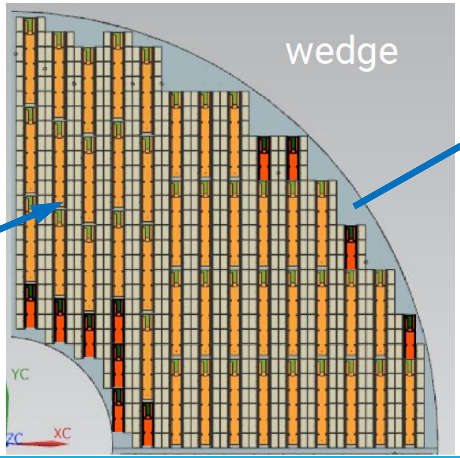


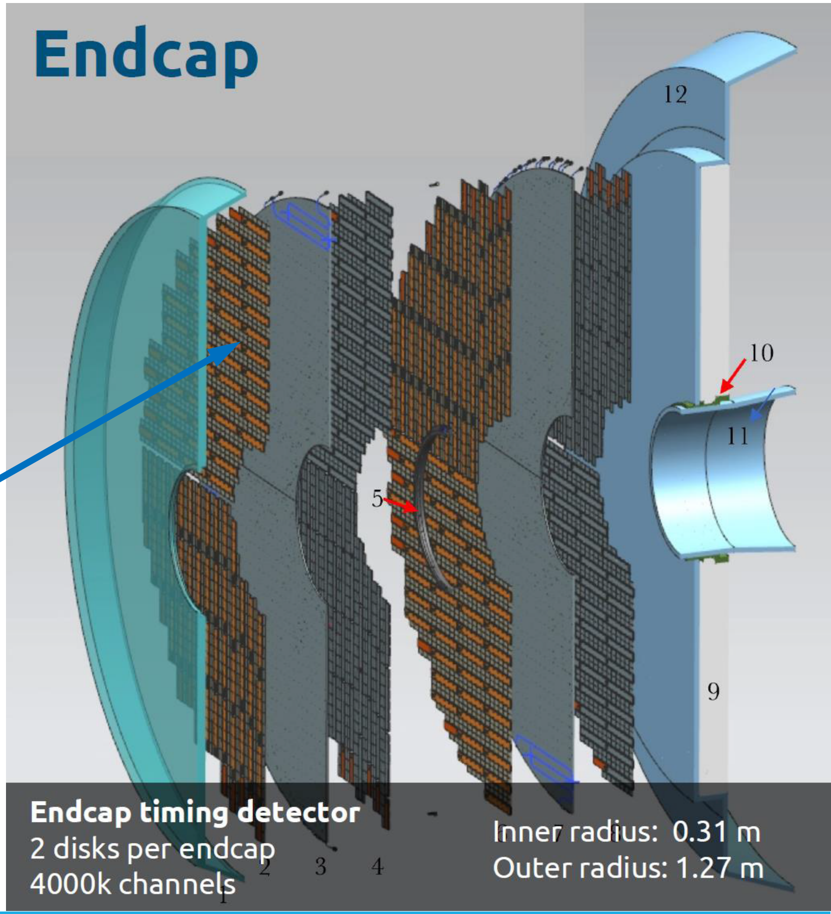
Module with 2 sensors



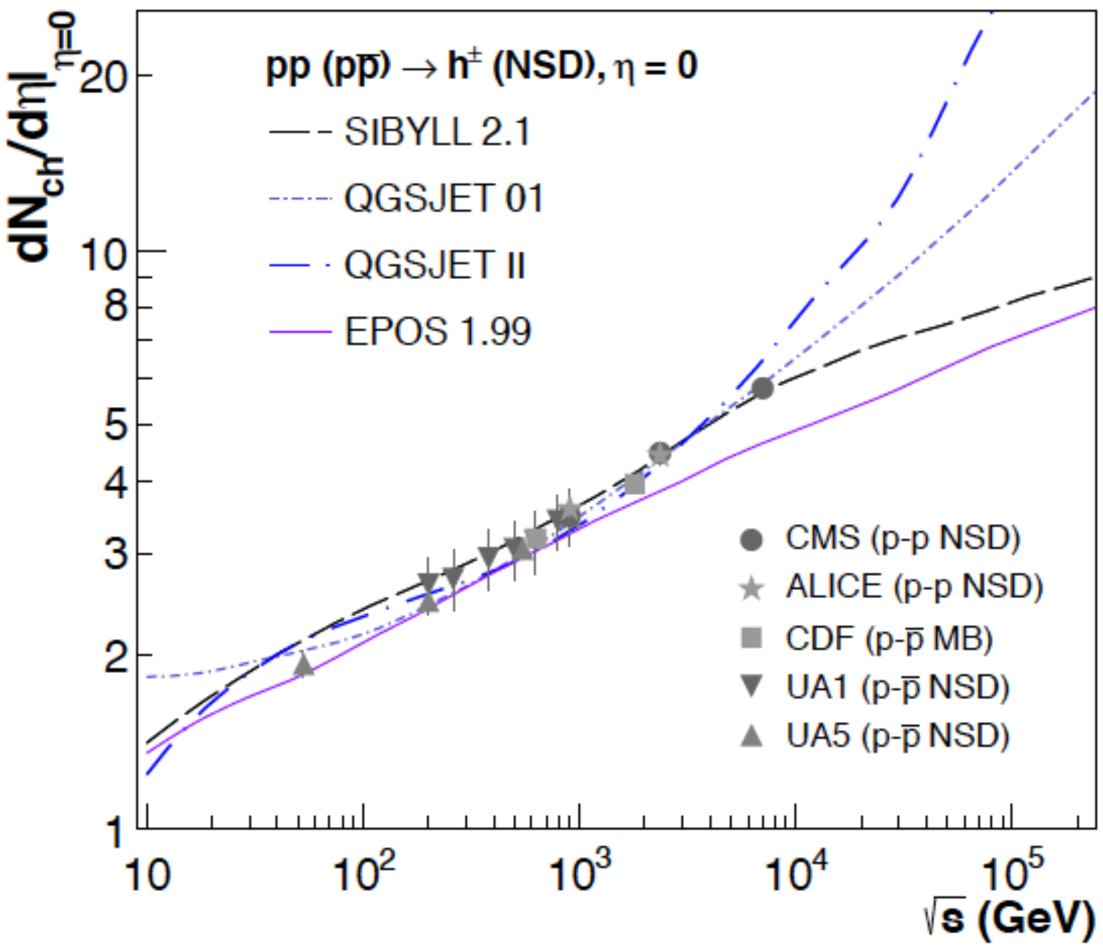
Support disk







Underlying events in high energy pp collisions



Scaling of the central charged multiplicity for the SIBYLL, QGSJET, and EPOS models compared to collider data for NSD events