Measurements
on Ultra-Fast Silicon Detectors (UFSD)
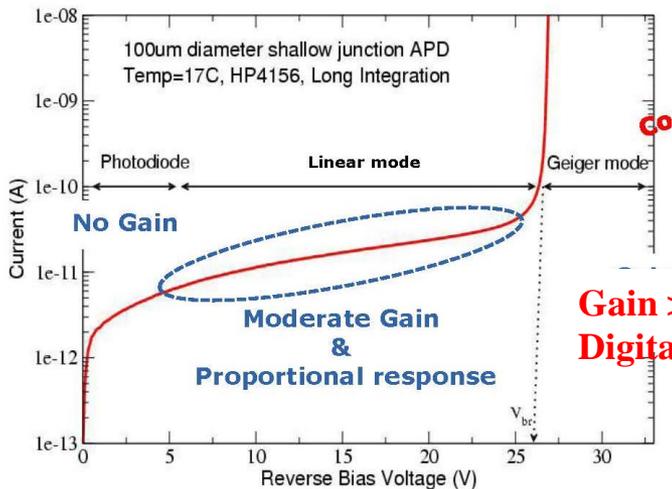
Hartmut F.-W. Sadrozinski
SCIPP, UC Santa Cruz

- Timing
- Beam test results
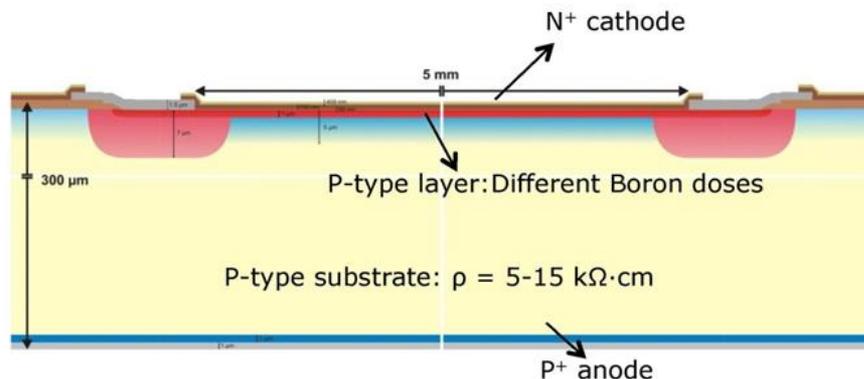- Effect of doping profile on time resolution
- Landau fluctuations

UFSD = thin Low-Gain Avalanche Detectors (LGAD)

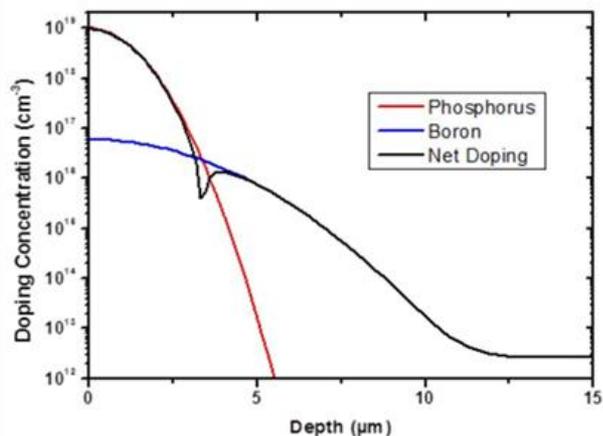Hartmut F.-W. Sadrozinski "Time Resolution of UFSD", RD50 CERN 2016

Principle:

An extra p-layer increases the E-field so that charge multiplication with **moderate gain** of 10-20 occurs without breakdown.

100um diameter shallow junction APD
Temp=17C, HP4156, Long Integration

Photodiode — Linear mode — Geiger mode

No Gain

Moderate Gain & Proportional response

Gain > 10^4 Digital response

V_{br}

Reverse Bias Voltage (V)

[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006

N$^+$ cathode

5 mm

300 μm

P-type layer: Different Boron doses

P-type substrate: ρ = 5-15 kΩ·cm

P$^+$ anode

High Doping Concentration: High Field

Phosphorus
Boron
Net Doping

Doping Concentration (cm^{-3})

Depth (μm)

As part of a RD50 Common Project, CNM Barcelona fabricated about 10 runs of LGAD, with thickness 300μm -> 50 μm. The INFN project at FBK Trento has produced 300μm LGAD, will deliver soon 50μm devices. HPK will deliver thin LGAD to UCSC in the beginning of December 2016.

**The beam tests were performed with 45 μm LGAD from CNM**

Prediction of Timing Resolution

$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$
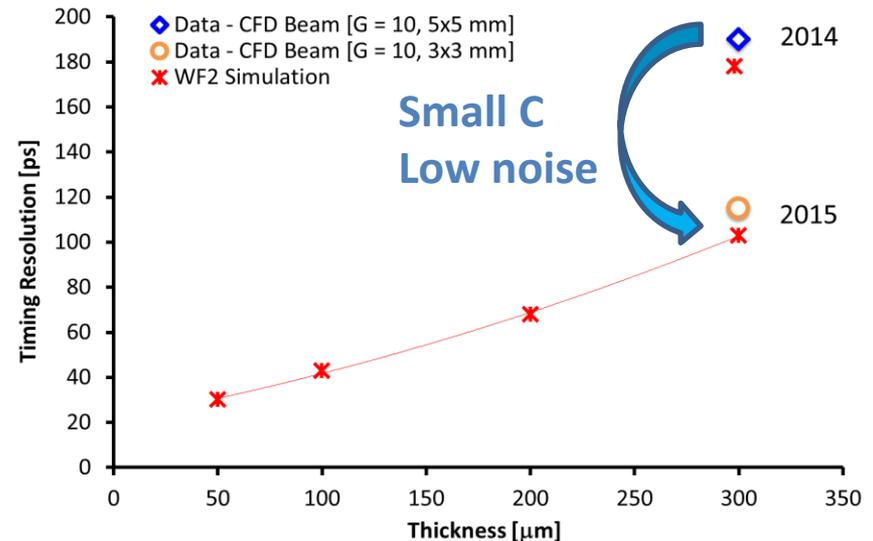
$$\sigma_{TimeWalk} = \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS} \propto \left[\frac{N}{\frac{dV}{dt}}\right]_{RMS}, \quad \sigma_{Jitter} = \frac{N}{dV/dt} \approx \frac{t_{rise}}{S/N}$$

- ➢ **Maximize slope dV/dt (i.e. large and fast signals)**
- ➢ **Correct time walk with constant-fraction discriminator (CFD)**
- ➢ **Minimize noise N**

**WF2 Prediction of slope dV/dt:
use thin sensors with internal gain**
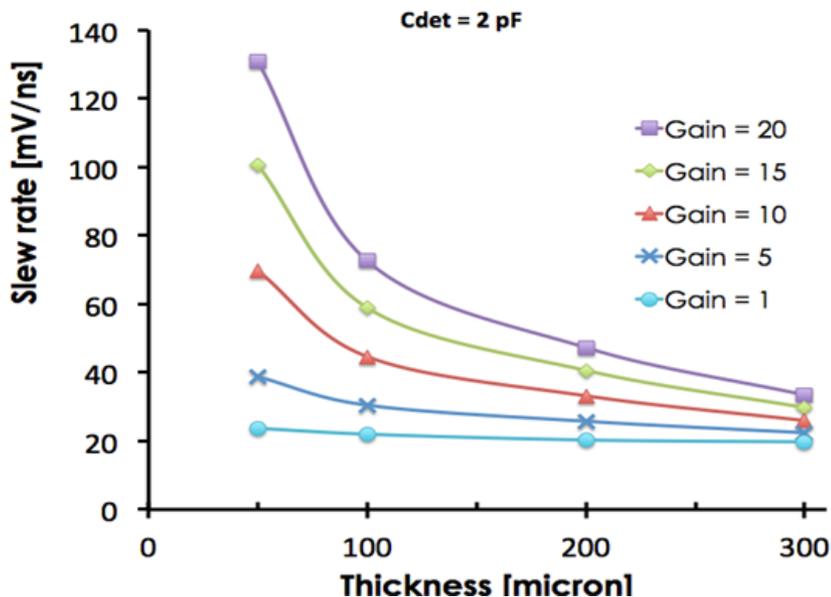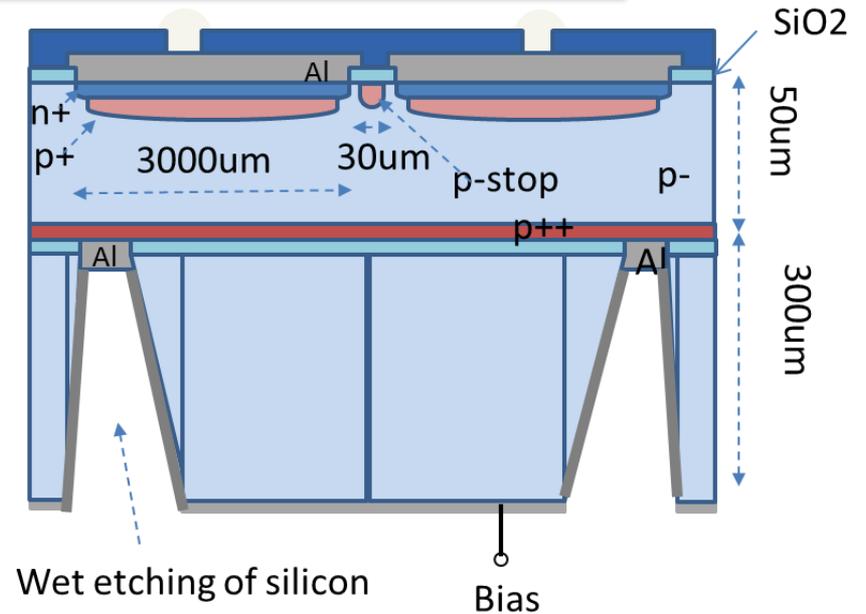
Beam test results extrapolated to 50µm UFSD

**Small C
Low noise**

3

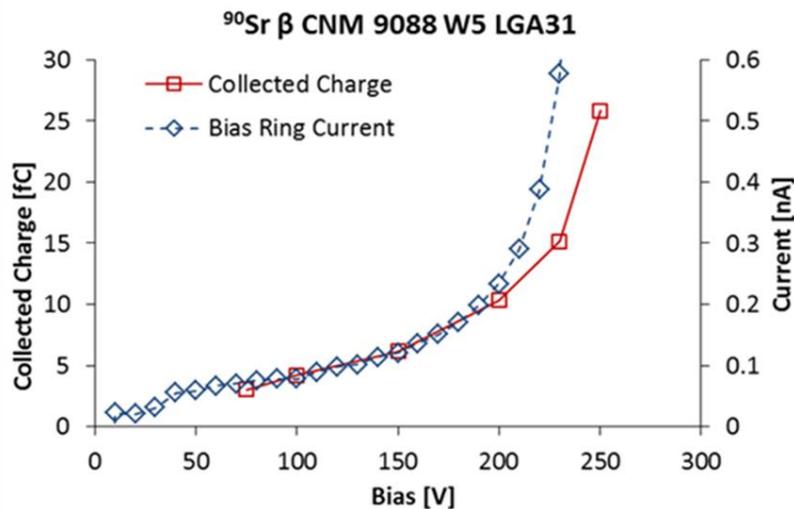# 45μm LGAD detectors on SoI (CNM)

N-on-p FZ on 300 handle wafer
Wet-etched contacts on the backside
to permit bias contact.
1.3x1.3 mm² single pad LGAD

SiO2
Al
n+
p+   3000um   30um
p-stop   p-
p++
Al
Al
50um
300um
Wet etching of silicon
Bias

Measurement of current and gain in the UCSC 90Sr β-source

⁹⁰Sr β CNM 9088 W5 LGA31
— Collected Charge
-◇- Bias Ring Current

Very low currents
Stable guard ring > 300V
Break-down at ~ 250V

Bias [V]	Gain
150	10
200	20
240	40

4

# Beam Test of a UFSD timing system

Beam Test CERN H8 Aug 17-25 2016, 180GeV π

Results from **3 stacked UFSD** & Č trigger counter

UFSD

$1.3\times1.3mm^2$ 45μm thick SoI LGAD, from the RD50 Common Project Run 9088 at CNM.

Amplifier board developed at UCSC (2 GHz BW)

Analog readout into 4 GHz – LeCroy WaveRunner Zi digital scope, at a sampling rate of 20 GS, (time discretization of 50 ps)

Č Trigger (M. Albrow et al.)

10mm long, $3\times3mm^2$ quartz radiator + $3\times3mm^2$ SensL SiPM on evaluation board (σ ≈ 15ps)
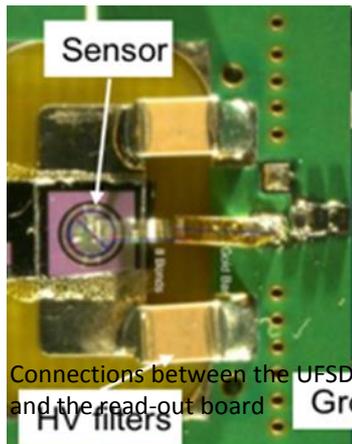
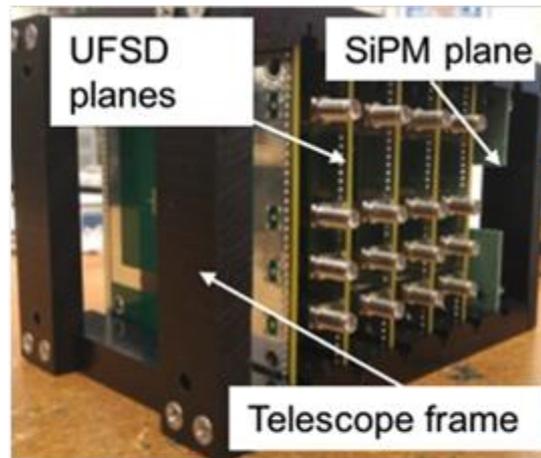Connections between the UFSD and the read-out board

Figure 1 Beam Test frame showing four UFSD and the trigger counter. Alignment was assured with four rods (not shown) aligning holes in the four corners of the boards and the trigger counter holder and the frame.
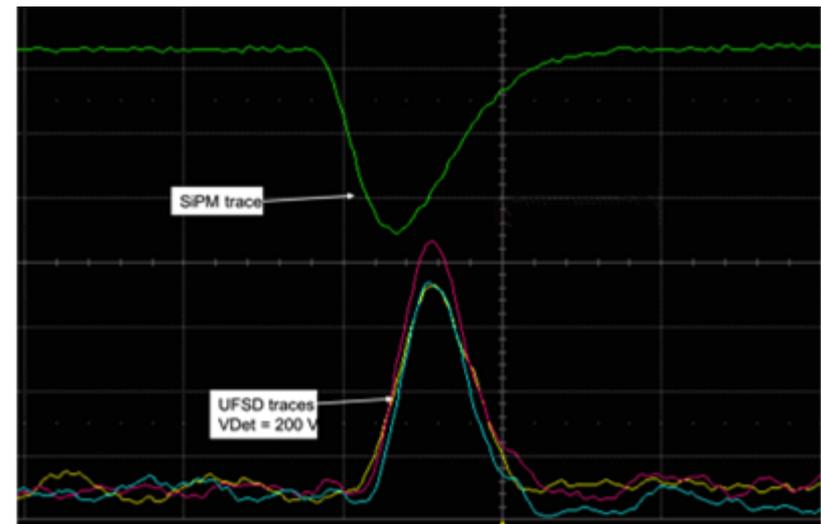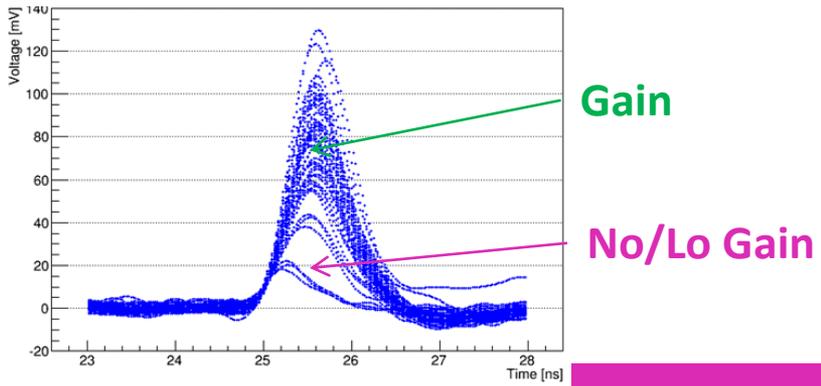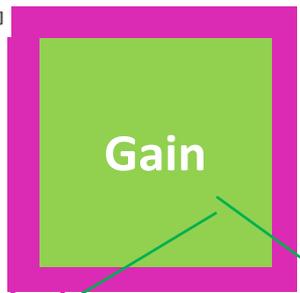

Figure 1 Screenshot of one event, showing the signals of 3 LGAD biased at 200 V and the SiPM at 28 V. Each horizontal division corresponds to 2 ns, while each vertical division is 100 mV.
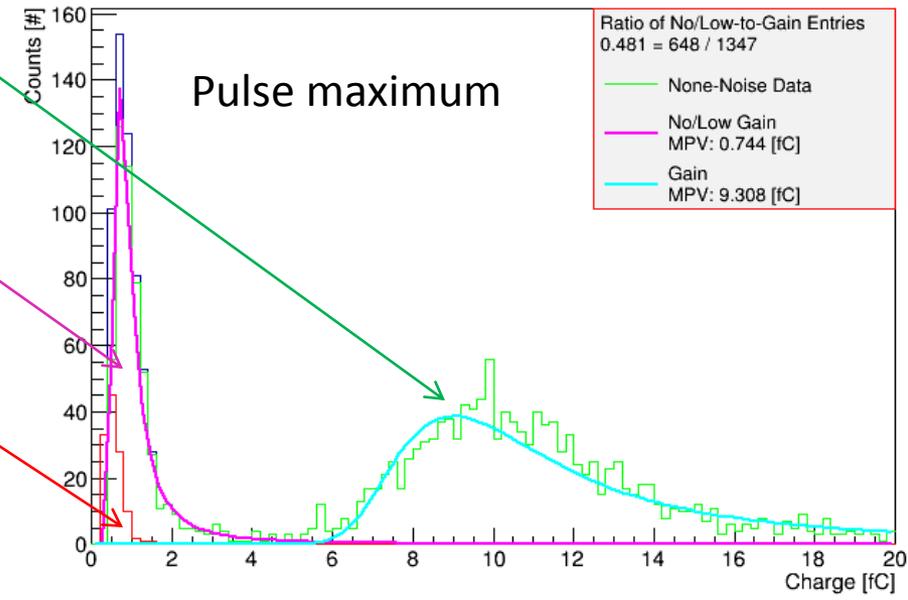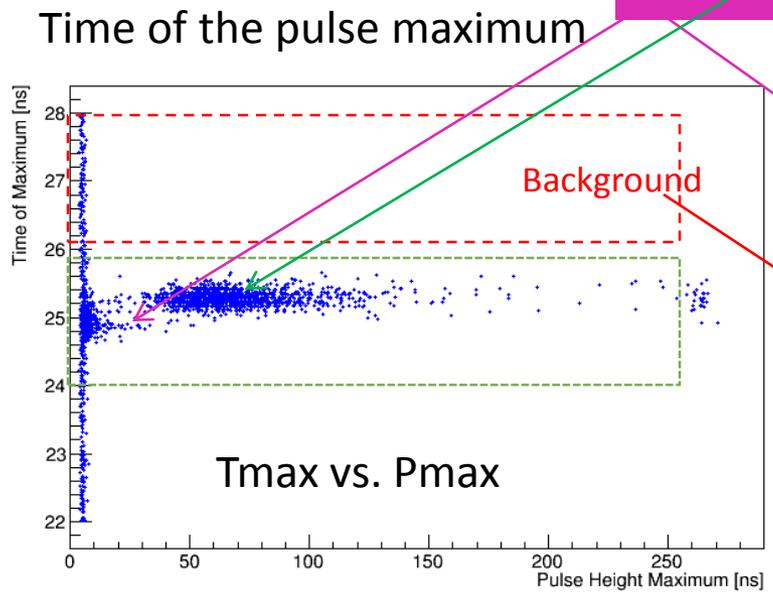
Beam Test Signals 45µm UFSD (1.3x1.3 mm²)

Pulse shapes have two distinct populations:
"Gaussian", large = gain
Triangular, small = no/lo –gain

Gain

No/Lo Gain

Clear separation gain vs. no/lo gain
Excellent S/N

Gain

No-Lo Gain

Time of the pulse maximum

Background

Pulse maximum

Ratio of No/Low-to-Gain Entries
0.481 = 648 / 1347

None-Noise Data

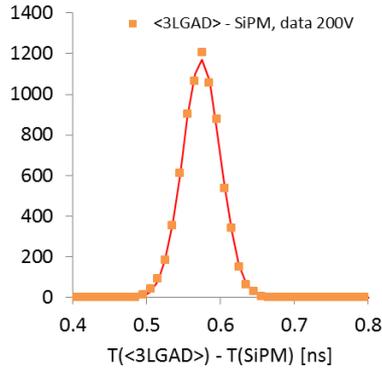No/Low Gain
MPV: 0.744 [fC]

Gain
MPV: 9.308 [fC]

Tmax vs. Pmax

Time Differences with 3 UFSD and 1 SiPM (examples)

subtract SiPM resolution in quadrature

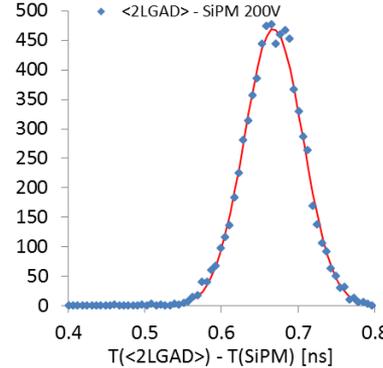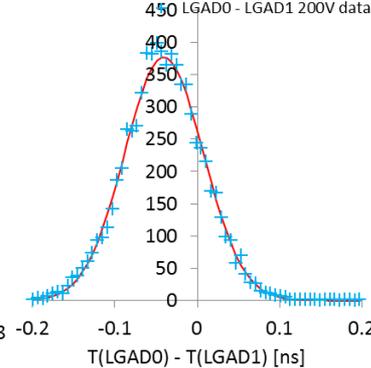| $(T_0+T_1+T_2)/3-T_{SiPM}$ (1 measurement)	$(T_i+T_k)/2-T_{SiPM}$ (3 measurements)	T_i-T_k (3 measurements)	T_i-T_{SiPM} (3 measurements)

200V (Gain ≈ 20)

σ = 25.6 ps   σ = 29.1 ps   σ = 48.1 ps   σ = 37.0 ps

240V (Gain ≈ 40)

σ = 19.8 ps   σ = 22.0 ps   σ = 35.6 ps   σ = 27.7 ps
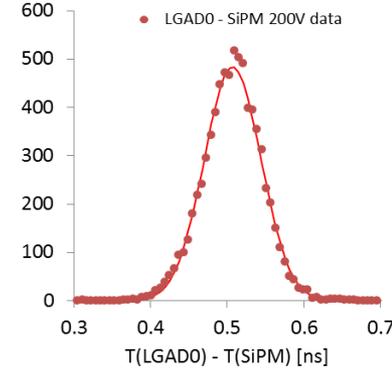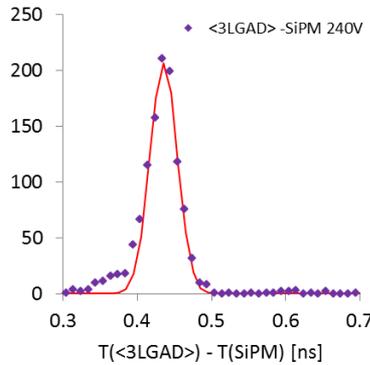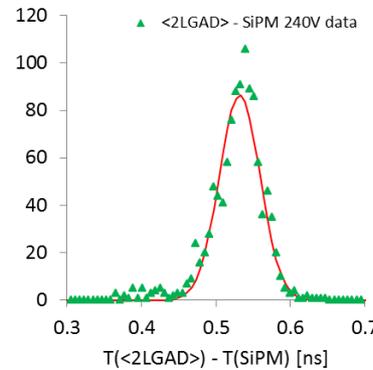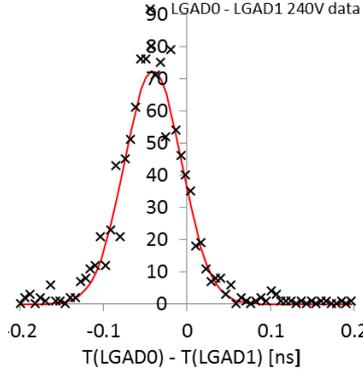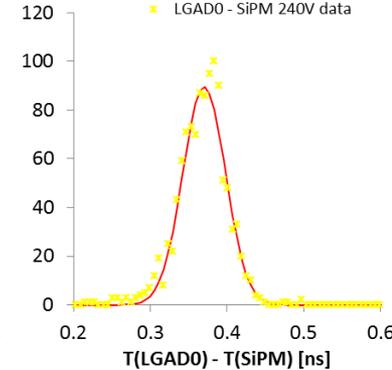
Beam test results of a UFSD timing system

Evaluate timing resolution (CFD ≈ 20%) for bias voltages 200V and 240V for different combinations of sensors and SiPM and fit for resolution of single UFSD and averages of double and triple UFSD.

Singles: UFSD-SiPM & UFSD-UFSD (6 measurements)
Doubles: <2 UFSD>/2 – SiPM (3 measurements)
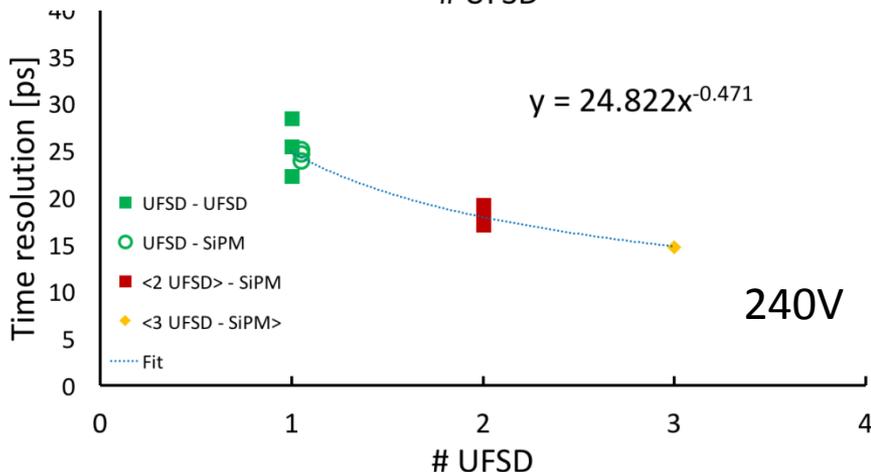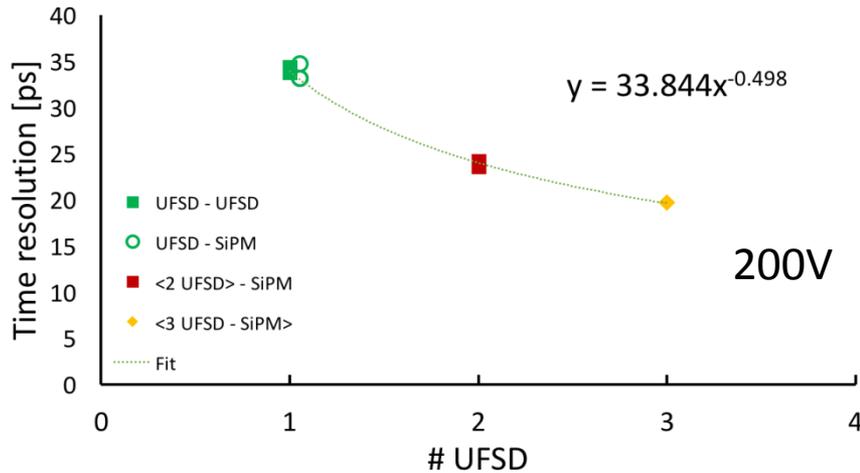Triplet: <3 UFSD>/3 – SiPM (1 measurement)

Timing resolution as a function of number N of UFSD averaged

Timing Resolution [ps]		
Vbias [V]	200V	240V
N=1 :	34.6	25.6
N=2 :	23.9	18.0
N=3 :	19.7	14.8

- Good matching of 3 UFSD sensors
- UFSD time resolution 26 ps - 35 ps
- Time resolution of average of 3 UFSD:
        20 ps (200V) & 15 ps (240V)
- Timing resolution agrees
        with expectation $\sigma(N) = \sigma(1)/N^{0.5}$
- Improvement expected from 130nm ASIC

N. Cartiglia et al, (INFN Torino, UC Santa Cruz, CNM Barcelona, IJS Ljubljana) https://arxiv.org/abs/1608.08681v2

Updated UFSD Timing Resolution from Beam Tests

Legend:
- ◆ Data - CFD Beam [G = 10, 5x5 mm]
- ○ Data - CFD Beam [G = 10, 3x3 mm]
- ▲ Data - beta (G=5, 1x1mm)
- □ Data CFD Beam (G=20, 1x1mm)
- ✖ WF2 Simulation

2014

2015
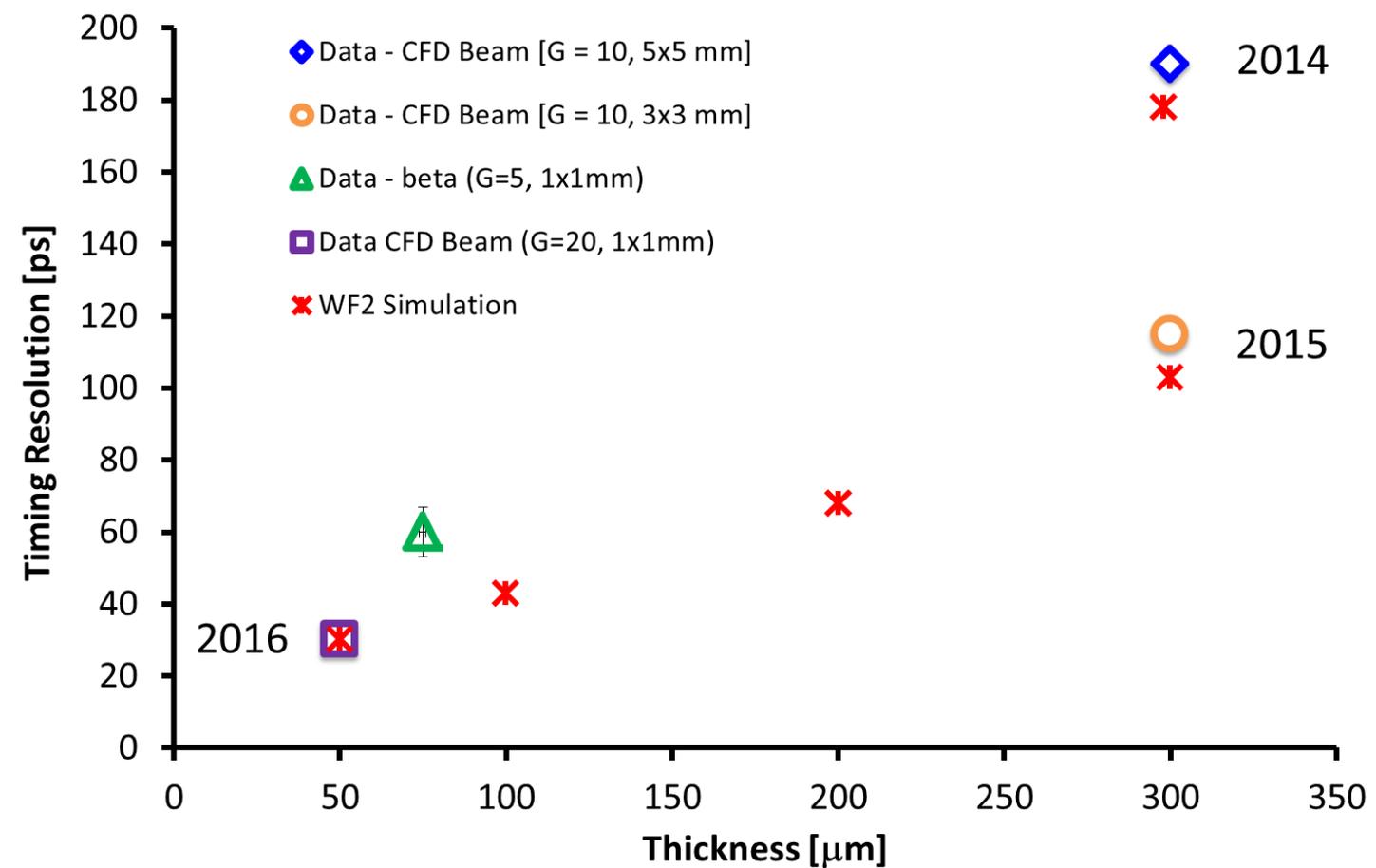
2016

Good agreement with WF2 prediction

Improvement due to
Thin sensors
Small capacitance
Low noise
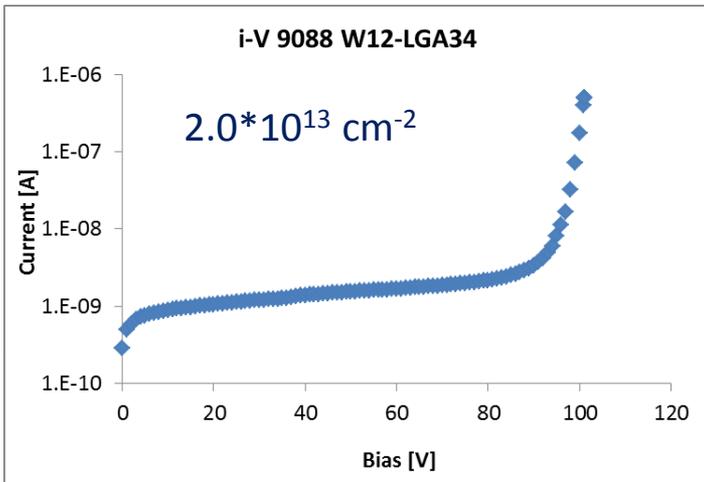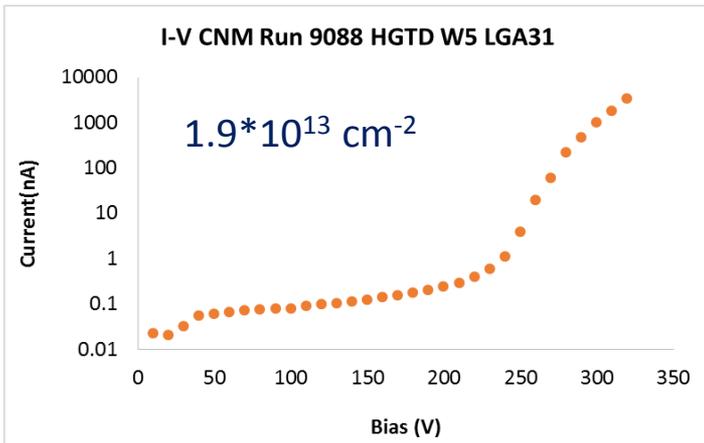
9

P+ dose dependence of Breakdown and Gain

Breakdown behavior is determined by the p+ dose

250V for $1.9*10^{13}$ cm^{-2} ,

100V for $2.0*10^{13}$ cm^{-2} ,

45 μm 1.3x1.3 mm^2 LGAD from CNM Run 9088

I-V CNM Run 9088 HGTD W5 LGA31

$1.9*10^{13}$ cm^{-2}

i-V 9088 W12-LGA34

$2.0*10^{13}$ cm^{-2}

Gain is determined by the p+ dose
is about the same at breakdown

W12 LGA34 470
W5 LGA31 1754
W5 LGA33 470
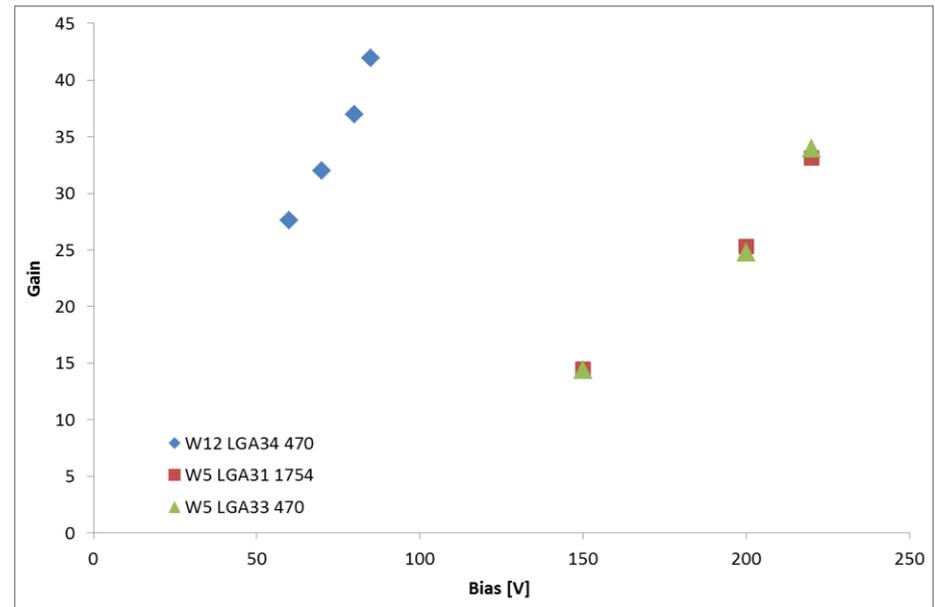
Setting the collected charge the same for the two preamps
yields 2 kΩ feedback resistor → 1754 Ω Trans-impedance

Time Resolution vs. Bias and Gain

Oct HGTD BT Single Diode Timing

Oct HGTD BT Single Diode Timing
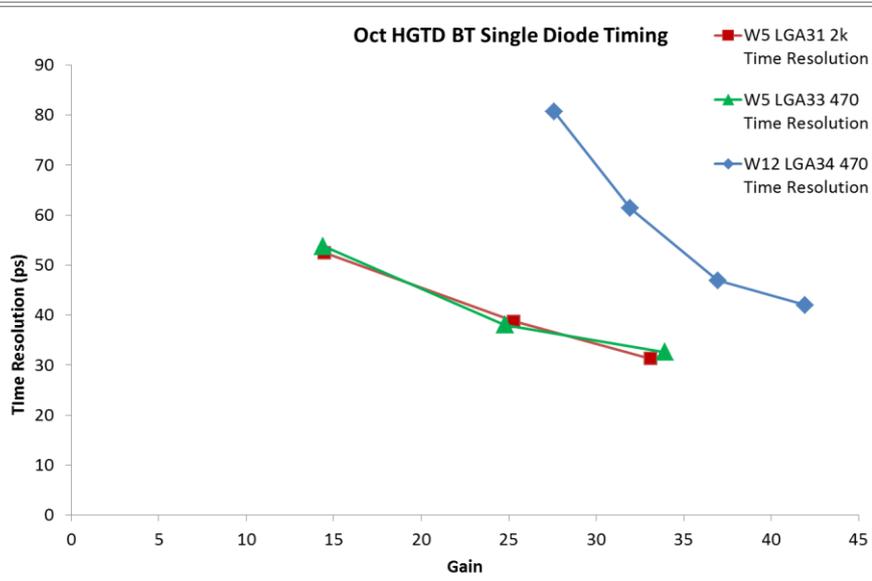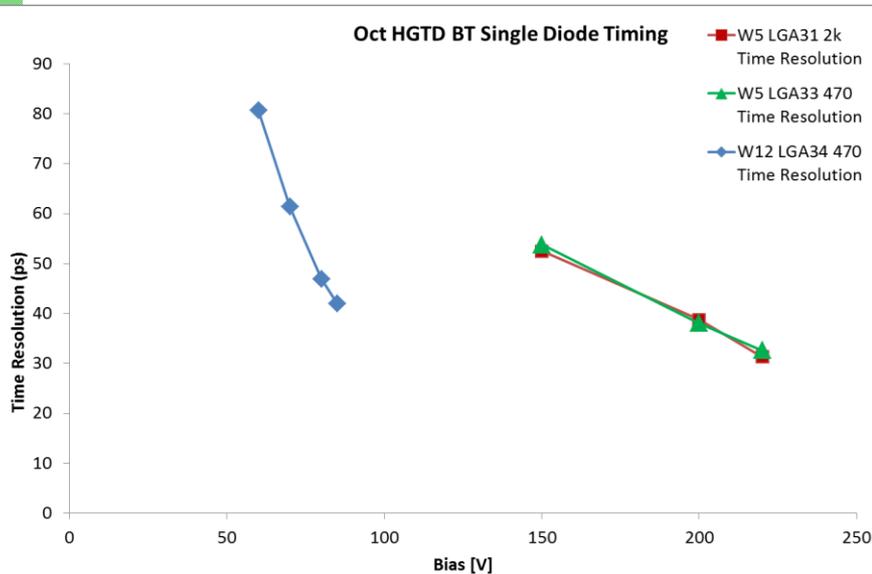
Pulse shapes governed by charge collection and by frontend electronics

W 12: Breakdown below 100V limits the drift field
Time resolution limited by collection time!.

Average Pulse Shapes
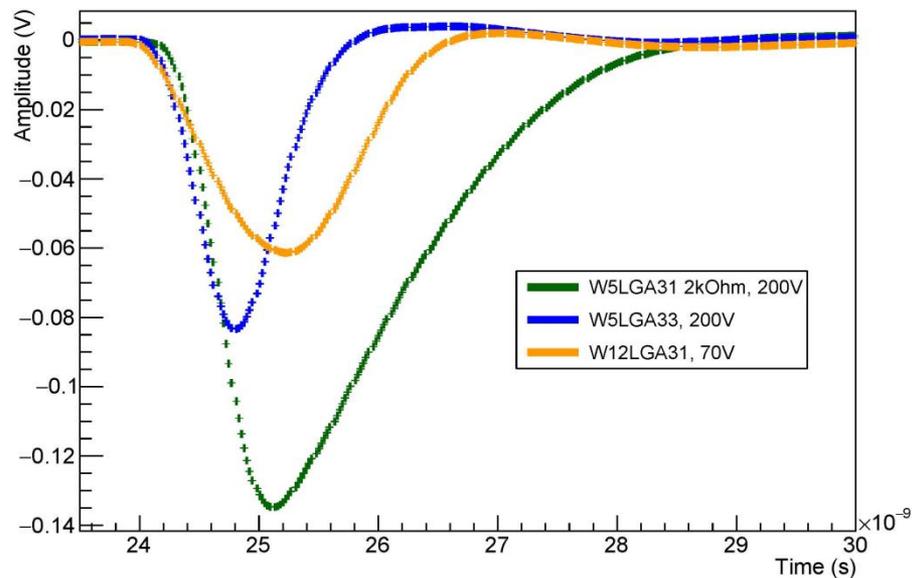
W 12: Slower electron drift leads to slower pulse. Higher input impedance amplifier leads to slower and longer pulse, but also less noise.

Slower amplifier has lower noise, leads in the end to almost identical jitter.

11

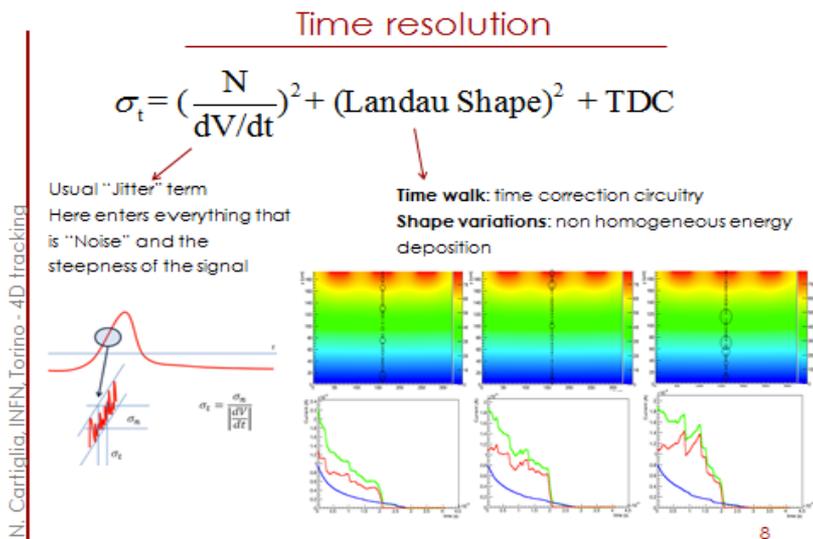# What is missing?: Landau Fluctuations

Hartmut F.-W. Sadrozinski "Time Resolution of UFSD", RD50 CERN 2016

N. Cartiglia, INFN, Torino - 4D tracking

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

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

Time walk: time correction circuitry
Shape variations: non homogeneous energy deposition

8

WF2 Simulation
Time uncertainty due to Landau non-uniform charge deposition
BBA amplifier, G ~ 20, various thicknesses

- 300 um
- 200 um
- 100 um
- 50 um
- 25 um

Contributions of Landau fluctuations to the time resolution as a function of the Constant Fraction Discriminator value for different detector thicknesses. Based on simulations.

Beam Tests show that we can correct for time walk.

So assuming we can beat the time jitter with lower noise and higher gain, Landau fluctuations become the time resolution floor which we can't go below. They depend on the sensors thickness, independent of the gain.
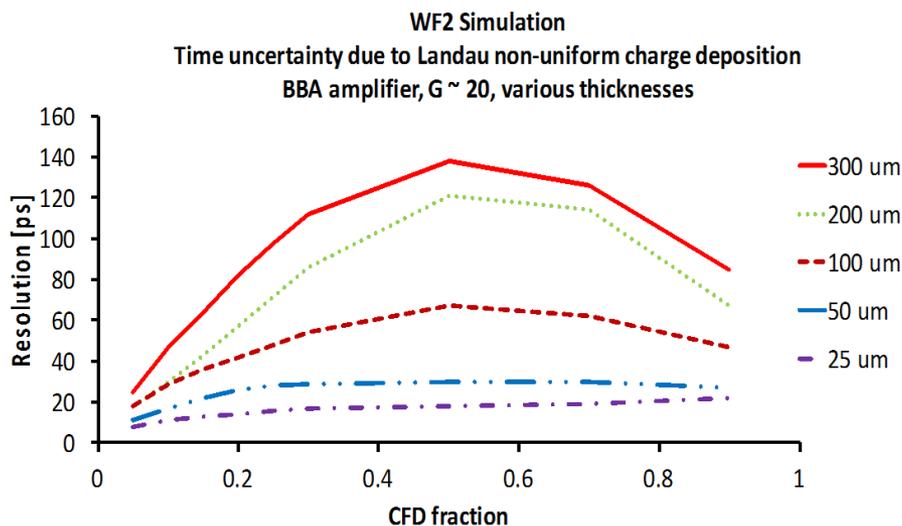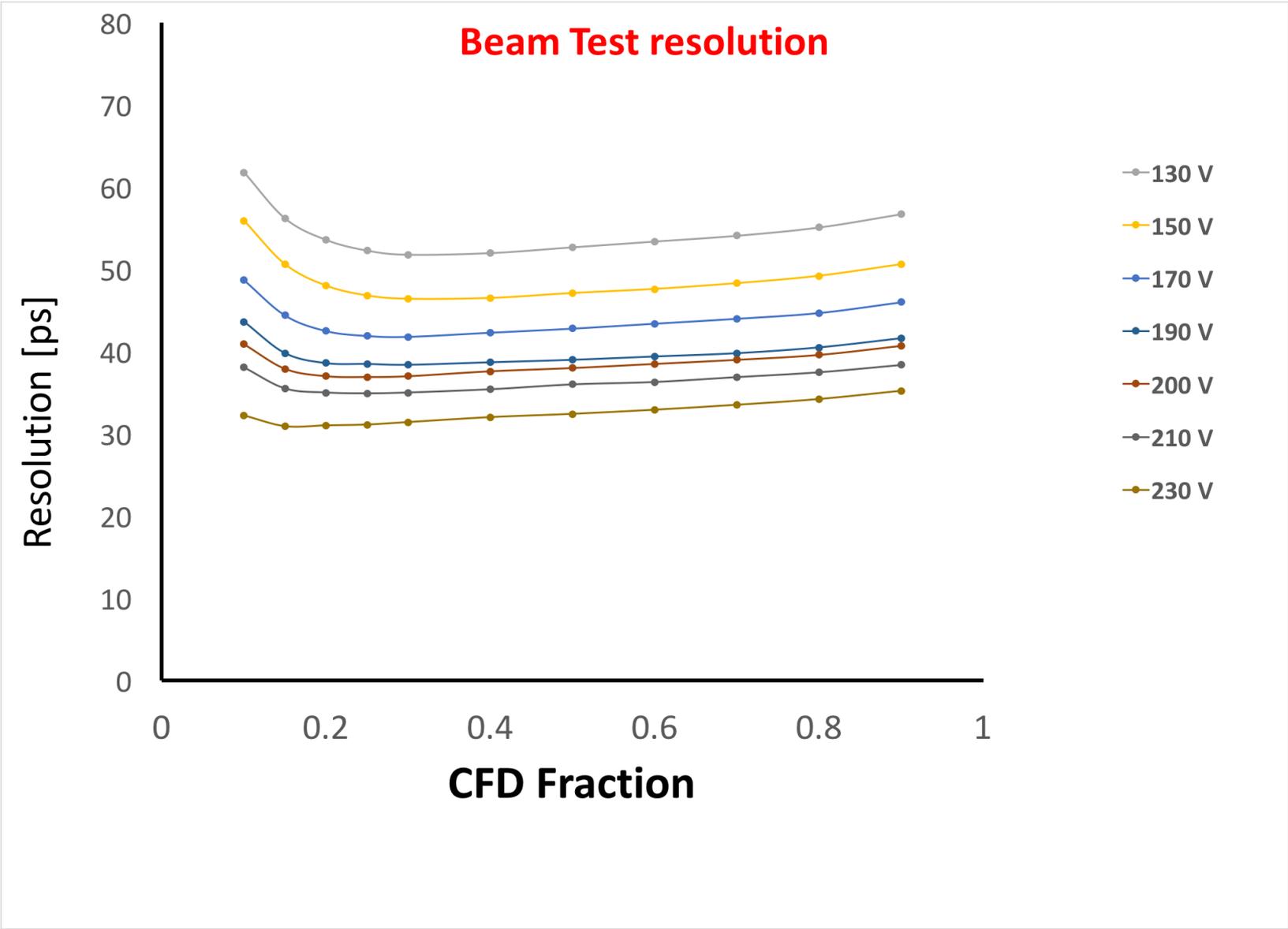
Both thin sensors, and low noise (for low threshold) are required for good timing resolution.

Beam Test resolution

Legend: 130 V, 150 V, 170 V, 190 V, 200 V, 210 V, 230 V

X-axis: CFD Fraction
Y-axis: Resolution [ps]

Hartmut F.-W. Sadrozinski "Time Resolution of UFSD", RD50 CERN 2016

Time Resolution, Jitter, Landau Fluctuations vs. Gain

Oct HGTD BT Single Diode Time Resolution & Jitter

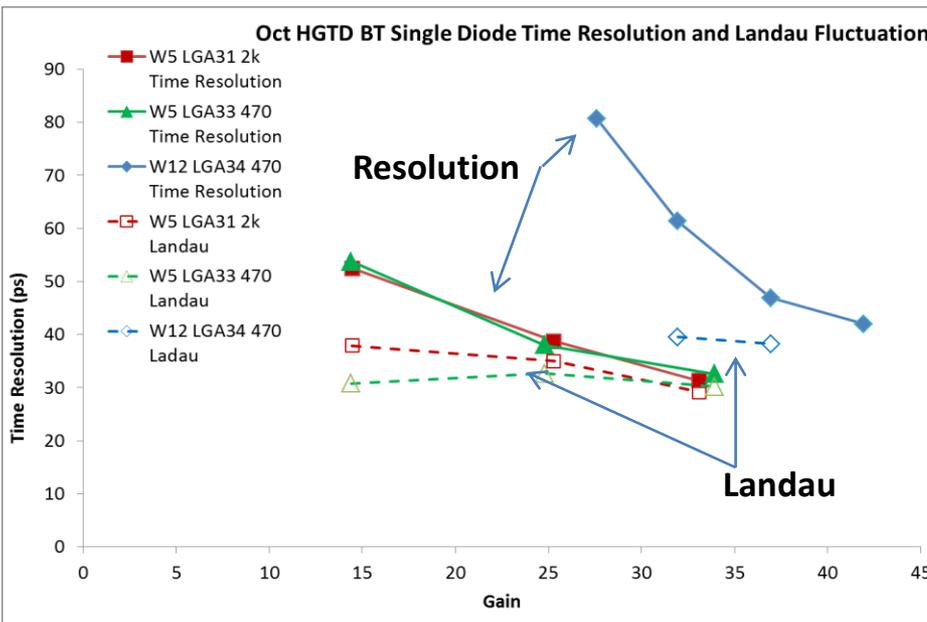Oct HGTD BT Single Diode Time Resolution and Landau Fluctuation
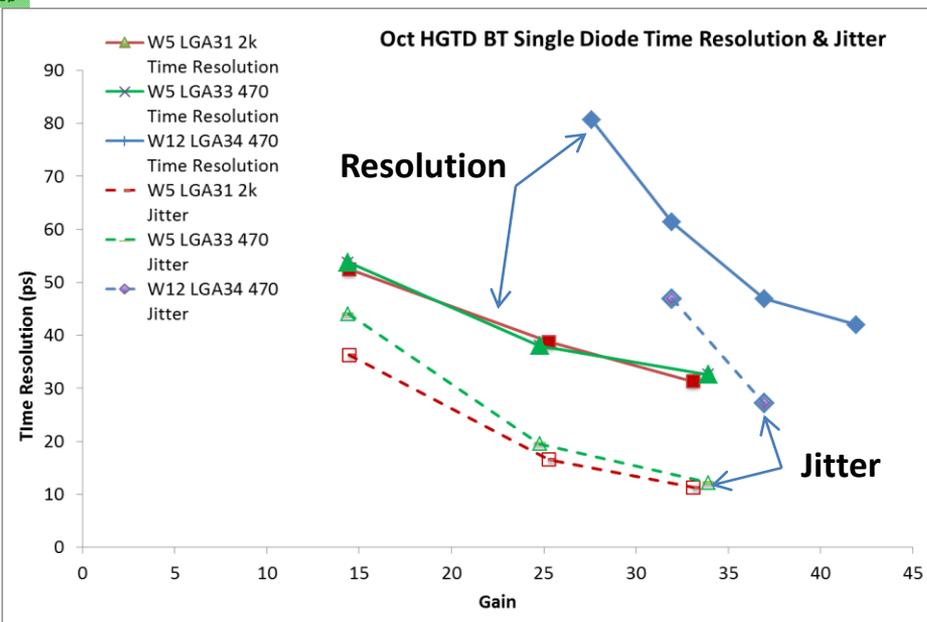
Time resolution σ_t governed
by Jitter σ_J and Landau Fluctuation σ_L:

$$\sigma_t^2 = \sigma_J^2 + \sigma_L^2$$

Time resolution > Jitter

The Jitter can be determined
from global parameters

$$\sigma_J = \frac{N}{dV/dt} \approx \frac{t_{rise}}{(\frac{S}{N})}$$

Landau Fluctuations $\sigma_L^2 = \sigma_t^2 - \sigma_J^2$
are approximately constant as expected
(independent of gain since due to
fluctuations of the initial ionization)

Evidence is mounting that Landau Fluctuations
are the limiting effect to the time resolution of
UFSD.

Conclusions

Since inception of 4D sensors in 2012,
we made giant steps forward:

- Fabrication of UFSD (= thin LGAD) by 3 manufacturers
- Development of fast current amplifiers with SiGe frontend
- Beam test results (both UFSD and HGTD) in agreement with WF2,
  ~35 ps for single 1.3x1.3 mm^2 UFSD, 20 ps for stack of three at gain = 20.

- Closing in on the time resolution limit in Landau fluctuations.
- For excessive gain (low breakdown voltage) time resolution is worsened by the slow charge collection.

Contributors

A. Anker, J. Chen, V. Fadeyev, **P. Freeman**, Z. Galloway, **B. Gruey**, H. Grabas,
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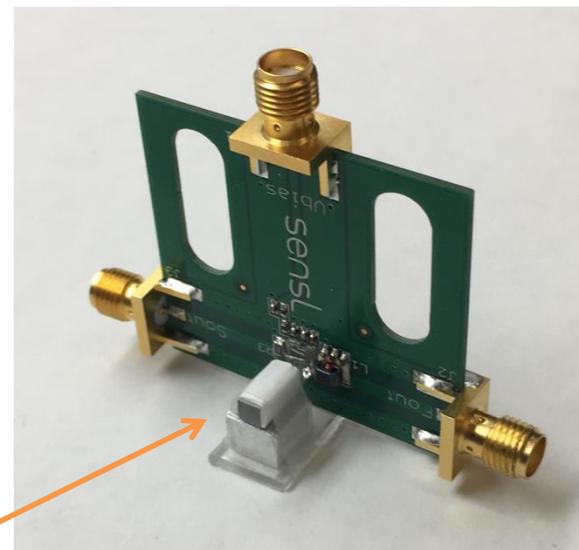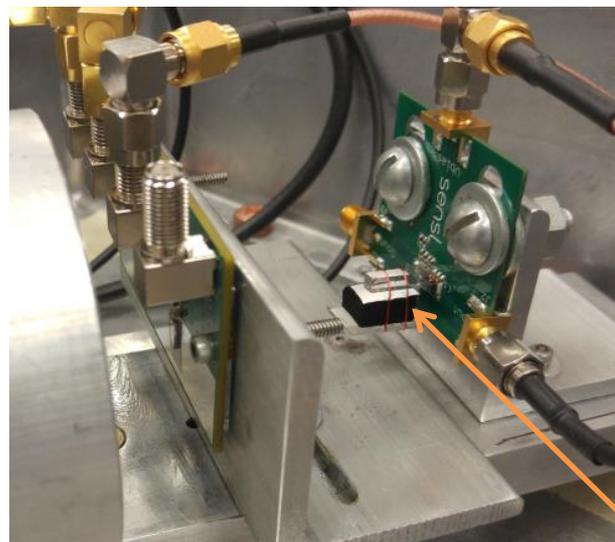V. Cindro, G.Kramberger, I. Mandić, M. Mikuž, M. Zavrtanik

Jožef Stefan Inst. and Dept. of Physics, University of Ljubljana, Ljubljana, Slovenia
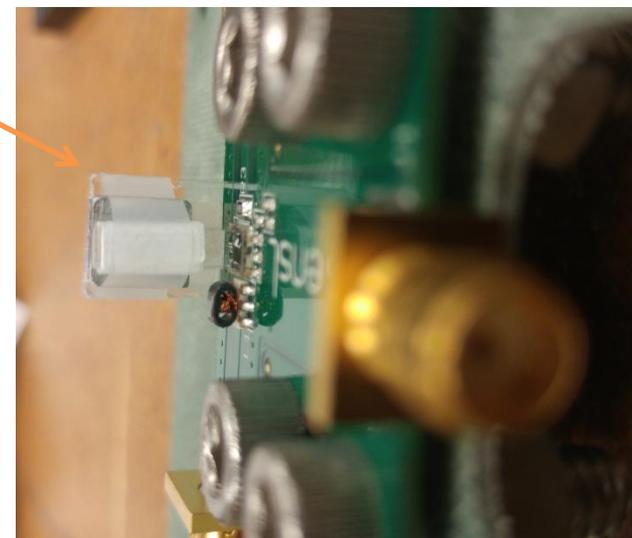
*Students in **bold***

Hartmut F.-W. Sadrozinski "Time Resolution of UFSD", RD50 CERN 2016

Backup

**3mmx3mmx10mm
quartz bar
read out by fast SiPM**

Sensl S-MicroC series evaluation board
http://sensl.com/downloads/ds/DS-MicroCseries.pdf
Trigger: 3x3x10 mm Quartz & SiPM
sensl MicroFC-SMA-30050r

M. Albrow et al.NIM . A 623 (2010) 931

Hartmut F.-W. Sadrozinski "Time Resolution of UFSD", RD50 CERN 2016