# Characterization of CMS-ETL HPK2 LGAD samples before irradiation

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RD50

The 37th RD50 Workshop
(Zagreb -- online Workshop)
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(1) Also visiting scientist at CERN-SSD

# Outline

Samples

Electrical characterization overview

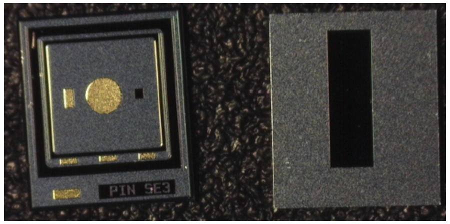
TCT scans and timing

Timing with $\beta$ source

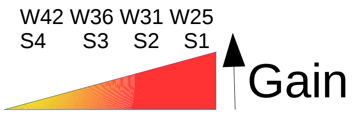
Behavior of samples at breakdown

# HPK2 samples at CERN-SSD

- HPK **LGAD** samples for CMS-ETL "HPK2 samples" arrived **10th July 2020** to CERN: 6"-wafers, 50 µm EPI (SiSi) on 150 µm wafer, Slim Edge 300 µm



- 4 splits: from S1 (highest gain) to S4 (smaller). Legend:




- Samples requested by **CERN-SSD** are single pads (LGADs and PiNs), 1.3×1.3 mm²

48 PiNs (12 of each gain split)
77 LGADs (**W25-S1**:18, **W31-S2**:20, **W36-S3**:20,**W42-S4**:19)

- Sensors first measured in **CVIV** setup, then glued to a single PCB for **TCT** and **RS** measurements
- **Irradiation** path for these samples (@Lbj). Sent in August…. received this week!

There are four irradiation points:

- 4E14 $n_{eq}/cm^2$ → 16 LGADs plus 8 PINs (4 LGADs plus two PINs per split)
- 8E14 $n_{eq}/cm^2$ → 16 LGADs plus 8 PINs (4 LGADs plus two PINs per split)
- 1.5E15 $n_{eq}/cm^2$ → 16 LGADs plus 8 PINs (4 LGADs plus two PINs per split)
- 2.5E15 $n_{eq}/cm^2$ → 16 LGADs plus 8 PINs (4 LGADs plus two PINs per split)

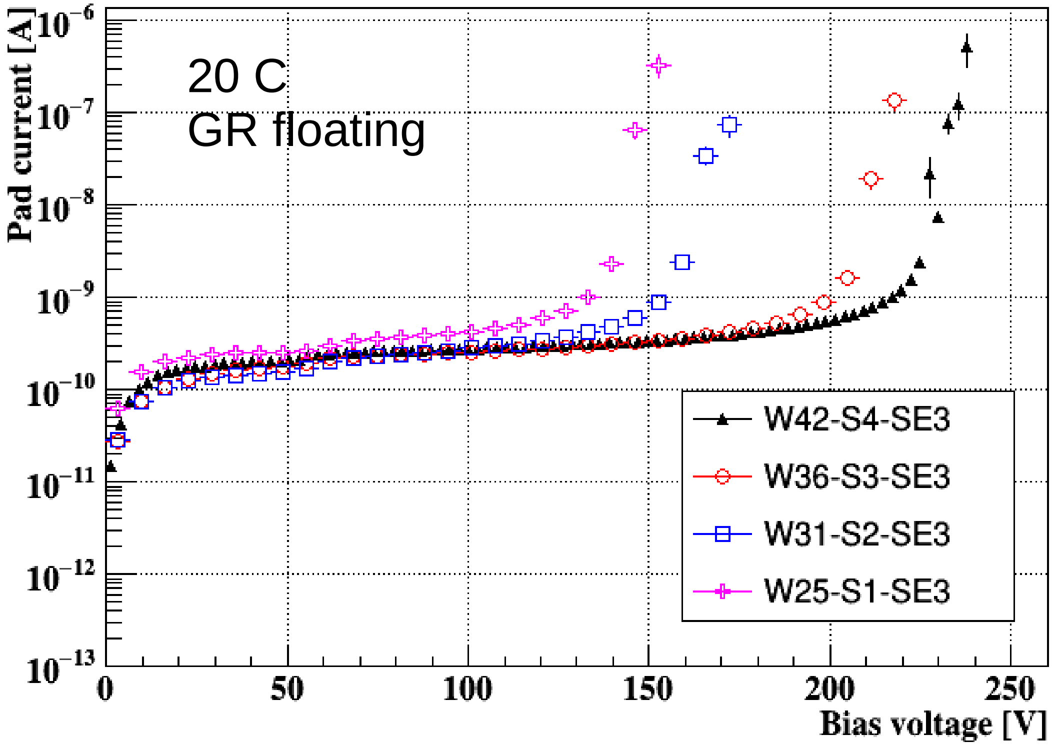
Then we have an extra irradiation point a low fluence for the FBK samples at: 1E13 $n_{eq}/cm^2$

Here we are going to include 6 LGADs plus two PINs, that are:

- W42-PIN-L14P5 and W42-PIN-L14P6
- W42-LGAD-L15P6 and W42-LGAD-L15P7
- W36-LGAD-L15P5 and W36-LGAD-L15P6
- W31-LGAD-L15P5 and W31-LGAD-L15P6

- In this talk: characterization of these samples **before** irradiation !

# Electrical characterization summaries: IV



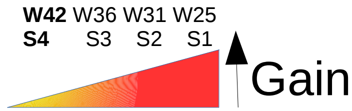

- Criteria to tag breakdown: compliance reached (10 μA)

| | Wafer Layout | Split | Target Vbr | Vbr_start | Vbr_compl |
|---|---|---|---|---|---|
| No25 | Small | 1 | 160V | 140 V | 160 V |
| No31 | Small | 2 | 180V | 160 V | 180 V |
| No36 | Small | 3 | 220V | 200 V | 220 V |
| No42 | Small | 4 | 240V | 230 V | 240 V |

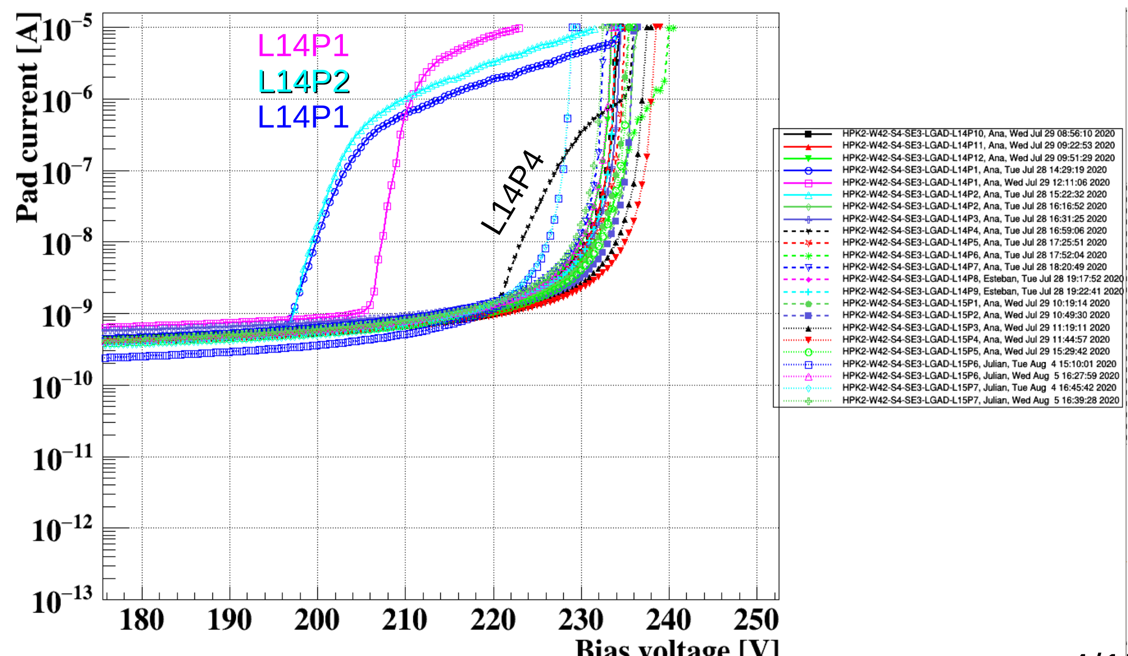
Torino data

**IV outliers** removed:
**W42:** 5/23, **W36:** 2/24, **W31:** 0/25, **W25:** 1/24
Some samples measured more than once

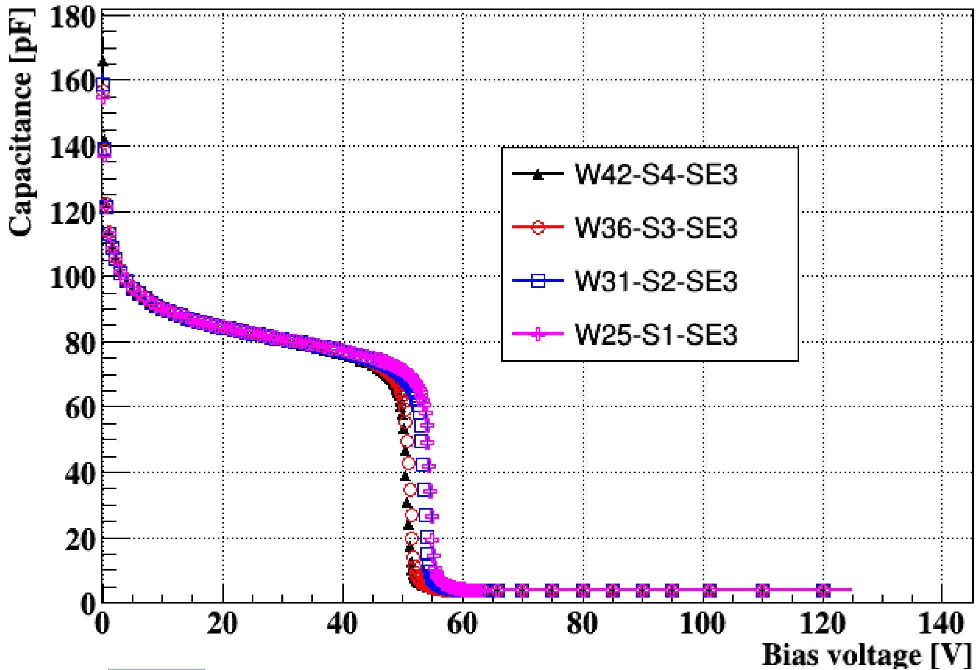
- Examples of "**outliers**". Here W42 (S4)

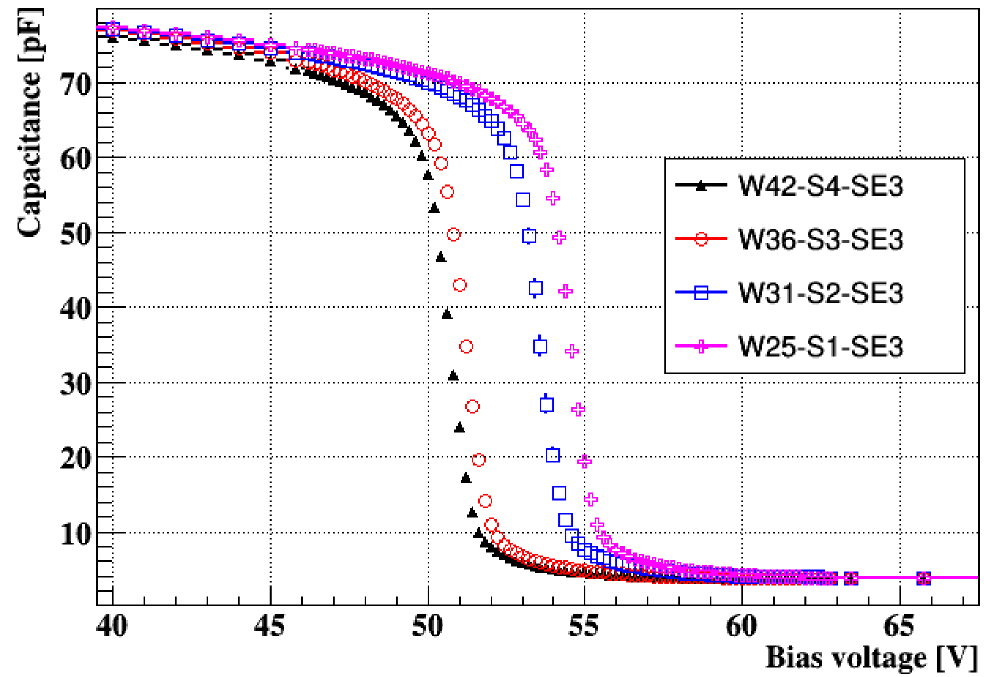


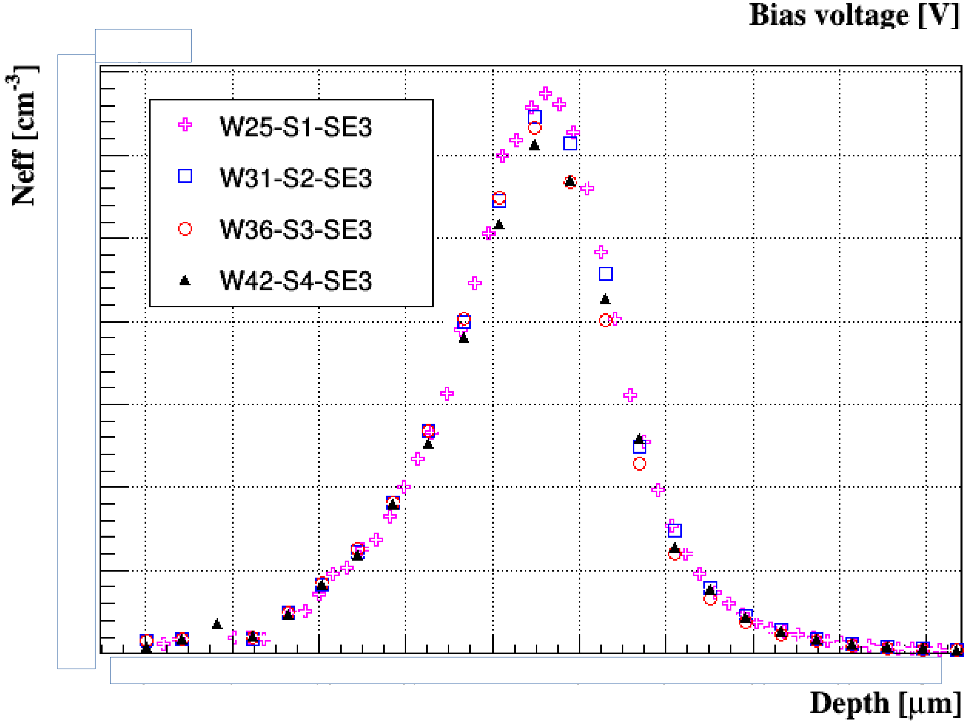

Outlier here does not mean bad quality, but performance slightly different from the rest



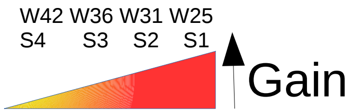
# Electrical characterization summaries: CV



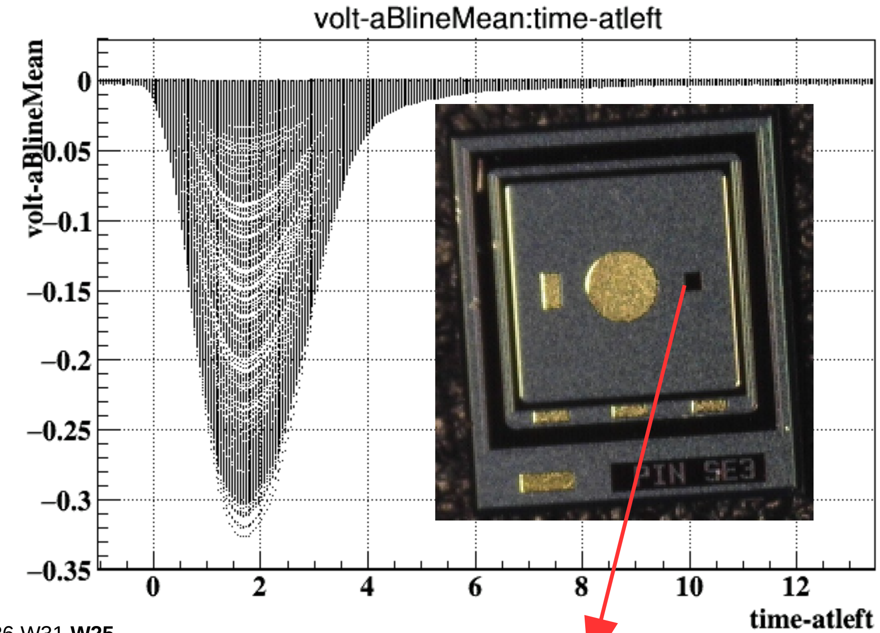



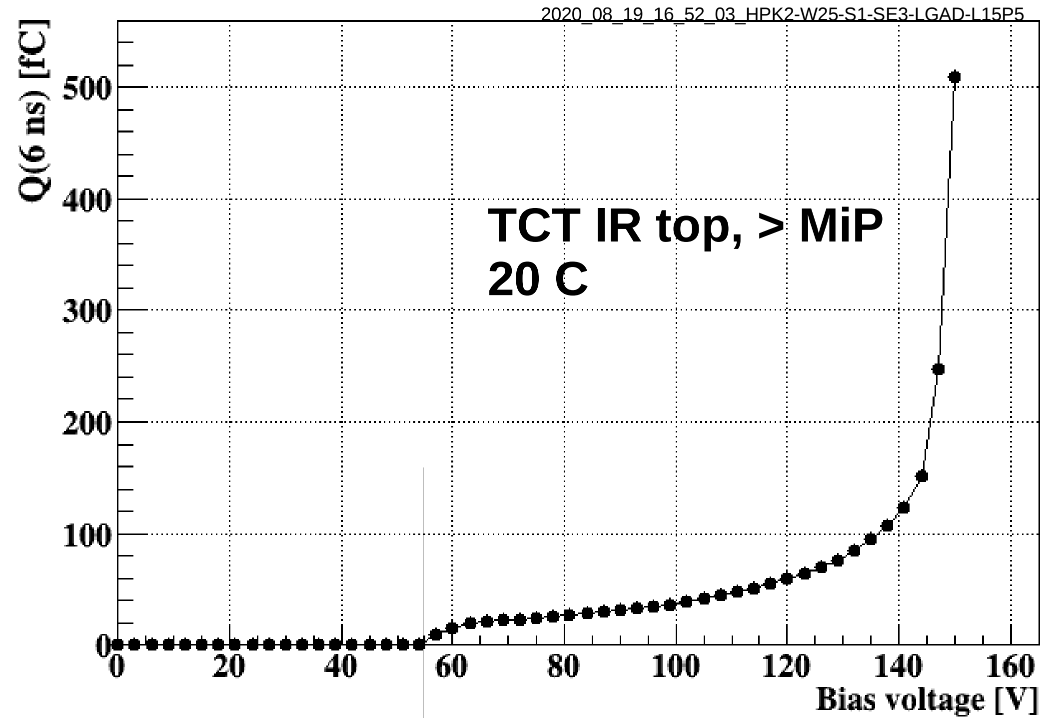

- All measurements at +20 C
  Freq: 1 kHz



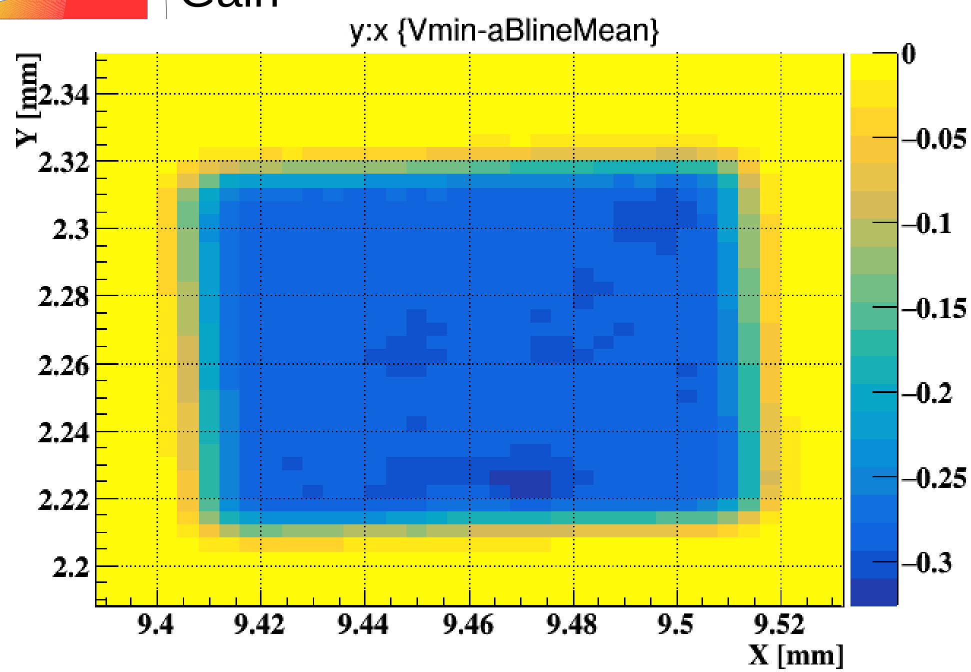

**CV included:**
**W42:** 16, **W36:** 19, **W31:** 26, **W25:** 17

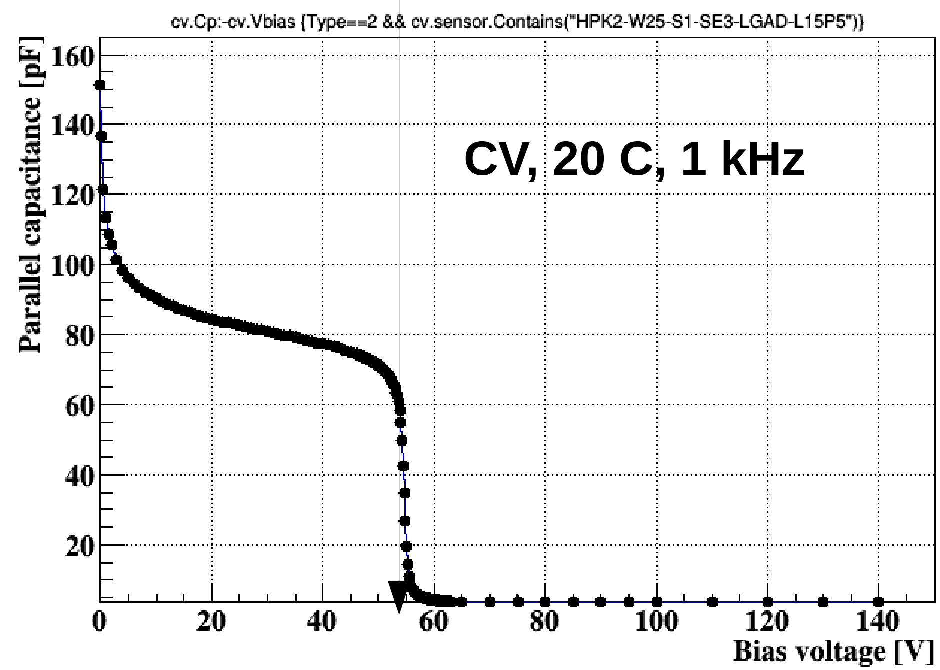
# TCT characterization



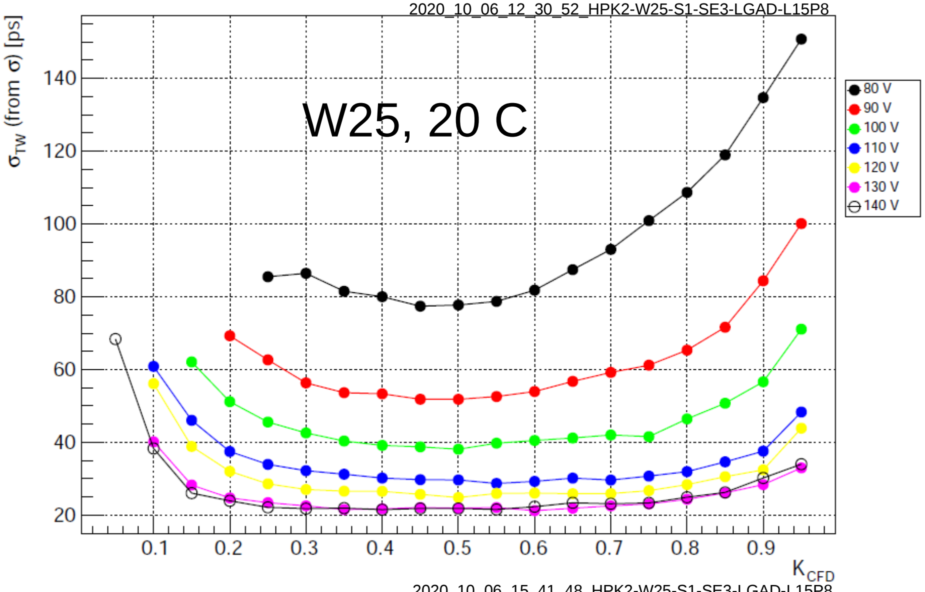


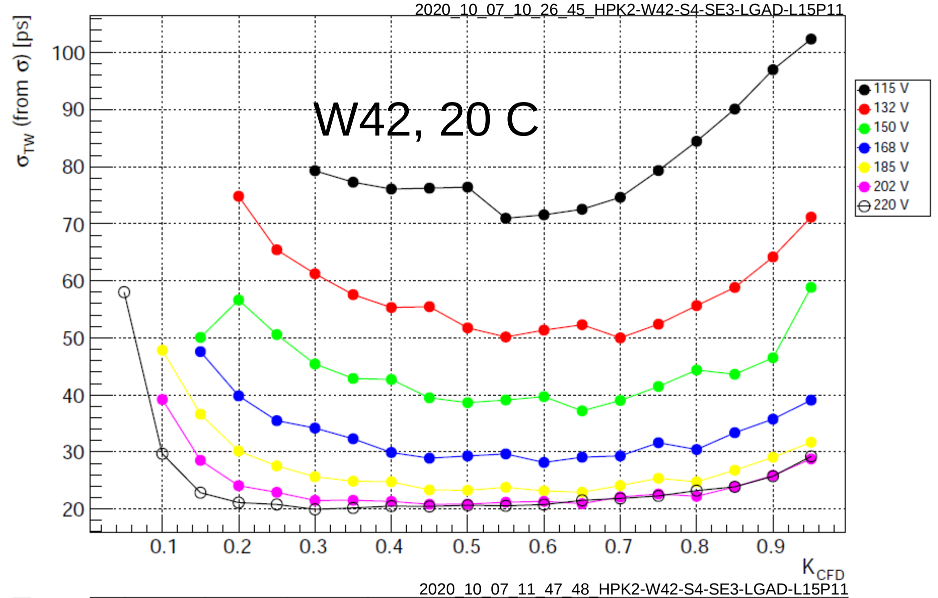


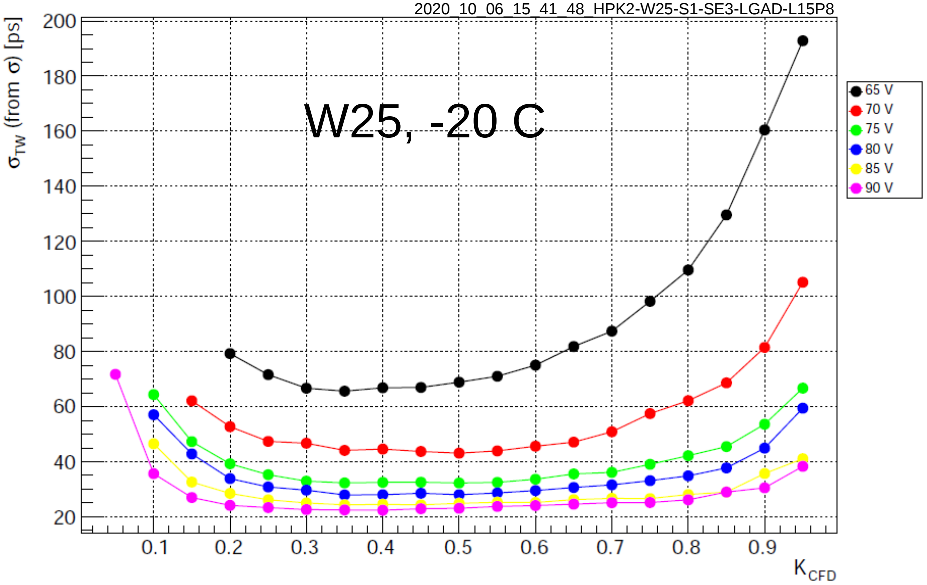



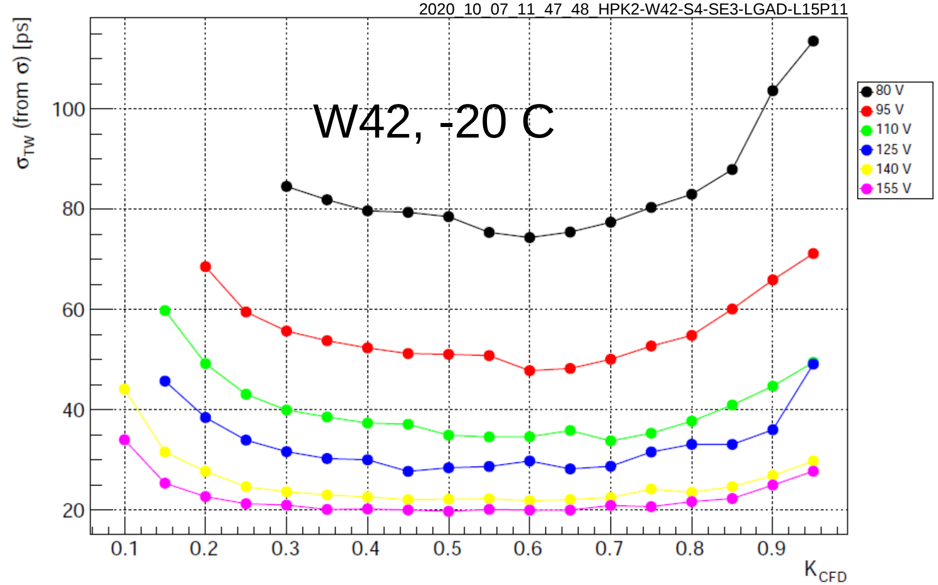
W42 W36 W31 W25
S4 S3 S2 S1
Gain

# TCT timing (1 MiP)



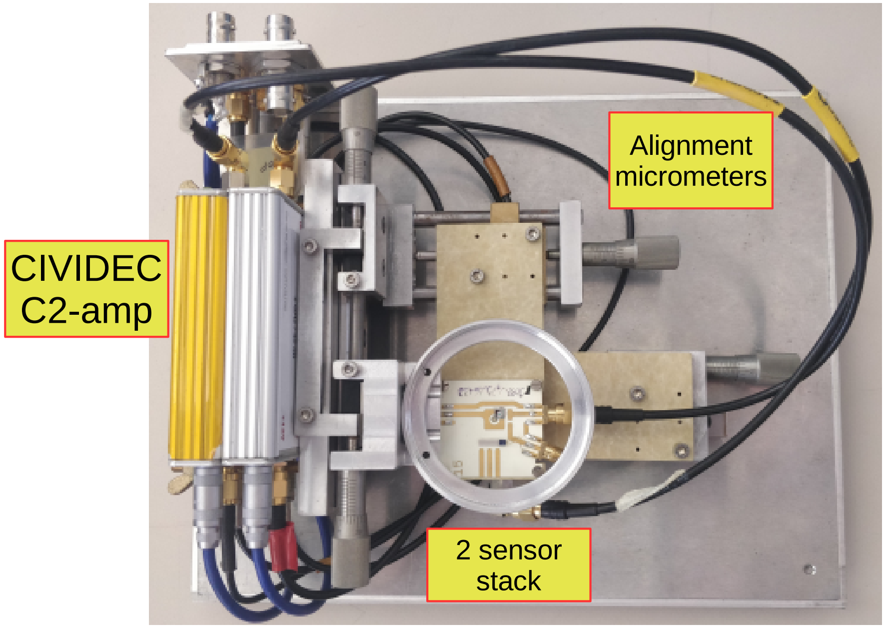



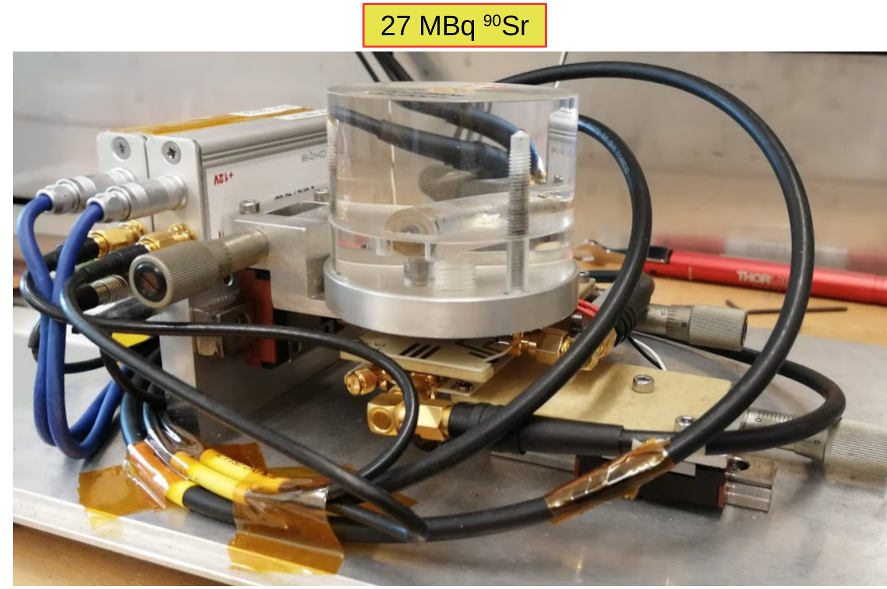



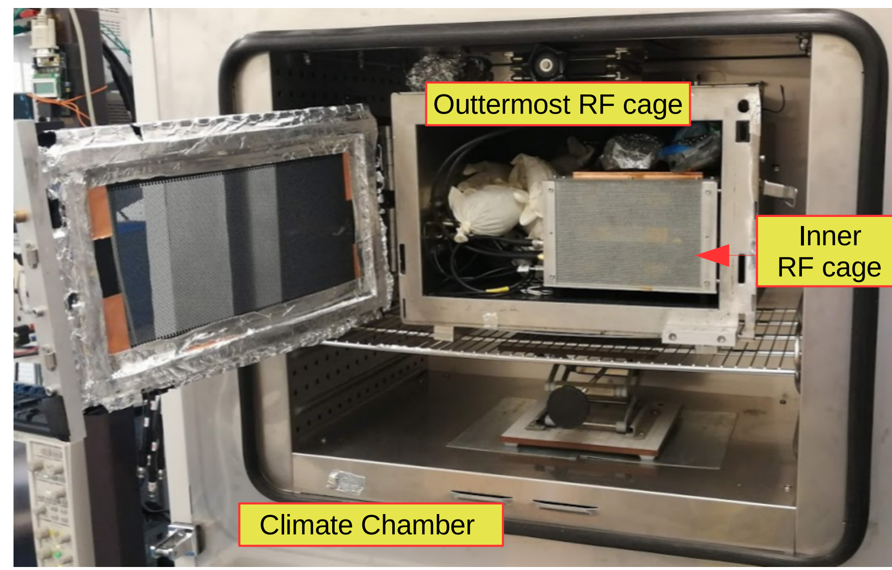




- Timing with laser measured using a direct and +50 ns delayed copy of the original pulse (see backup). Beam **focused** ($\sigma \sim 10$ $\mu$m) on the center of laser window
- Time resolution after **CFD** TW correction (see backup) flattens at 20 ps, which should be very close to the intrinsic sensor jitter (due to noise and no infinitely fast rise time of the pulse)

# Sr-90 source setup@CERN-SSD



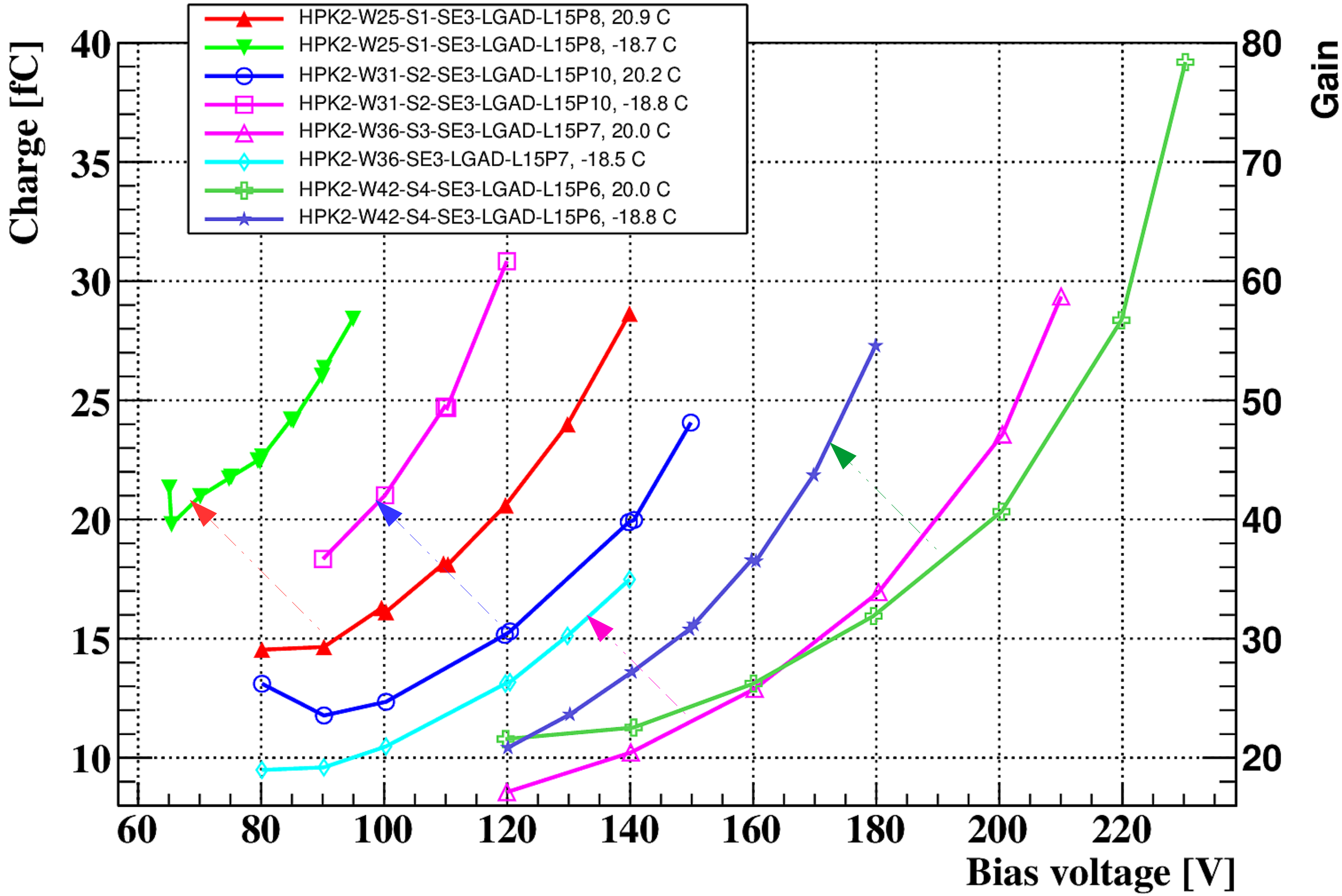




**RS setup:**

- Original setup built by former CERN fellow **M. Centis**
- Climate Chamber Binder MKT 115 (-70 to +180 C)
- 2 nested Faraday cages inside CC
- Source is a ~27 MBq $^{90}$Sr
- 2 sensors stack for timing (coincidence trigger)
- For this campaign:
  - → we tried to improve noise figures
  - → HW&SW re-commissioning
- Timing analysis uses a software CFD emulation

More details about this setup in **Julian Böll**'s talk tomorrow

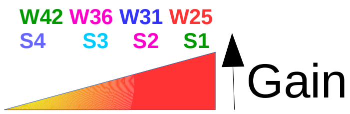
# RS: Voltage scans at 20 C and -20 C



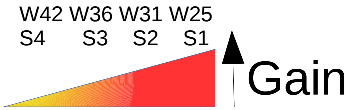

Arrows point from +20 C to -20 C. Measurements in β setup

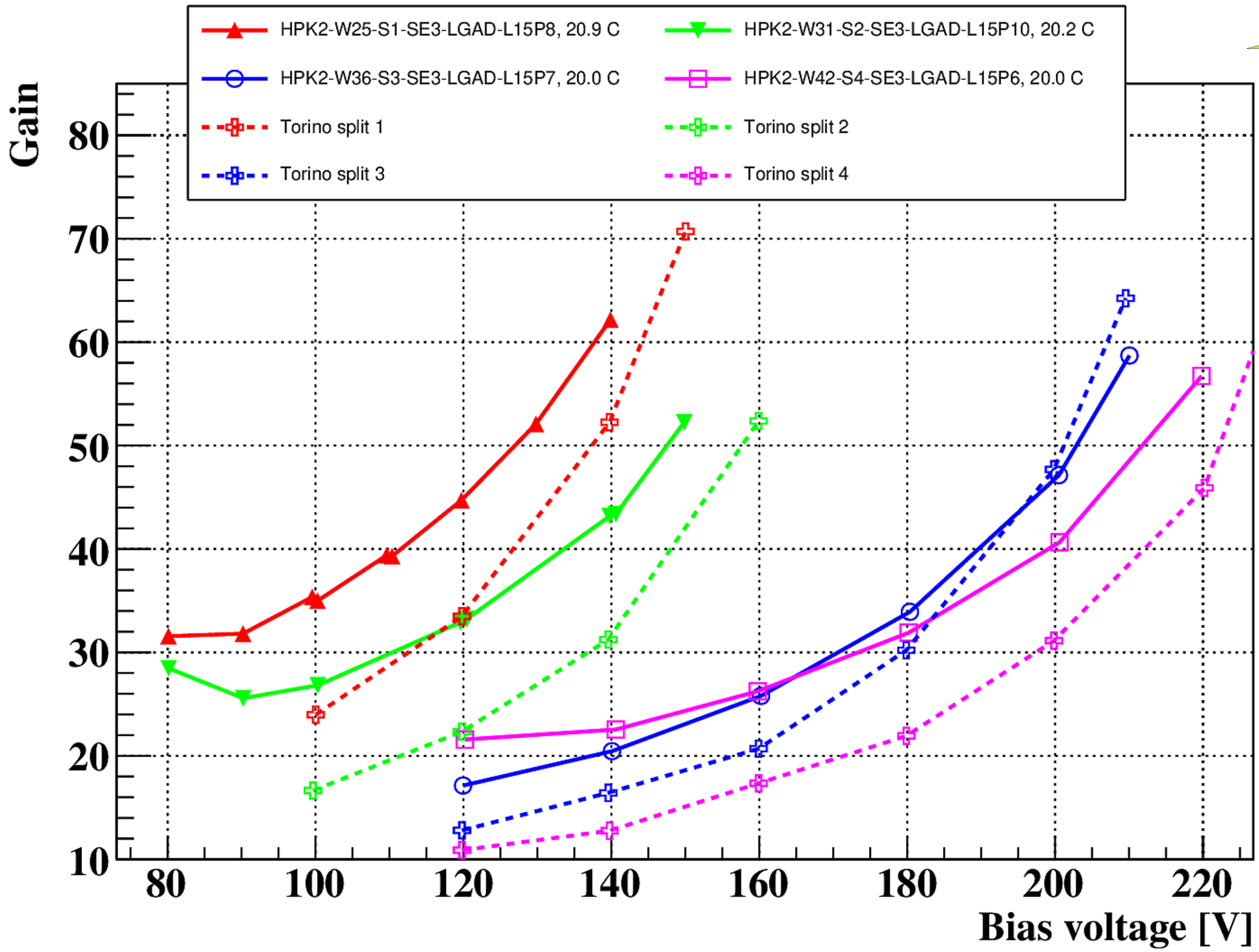
For reference, $Q_{PiN}$=0.5 fC

Note: charge values are mean values of charge distributions



# RS: Gain comparison at +20C



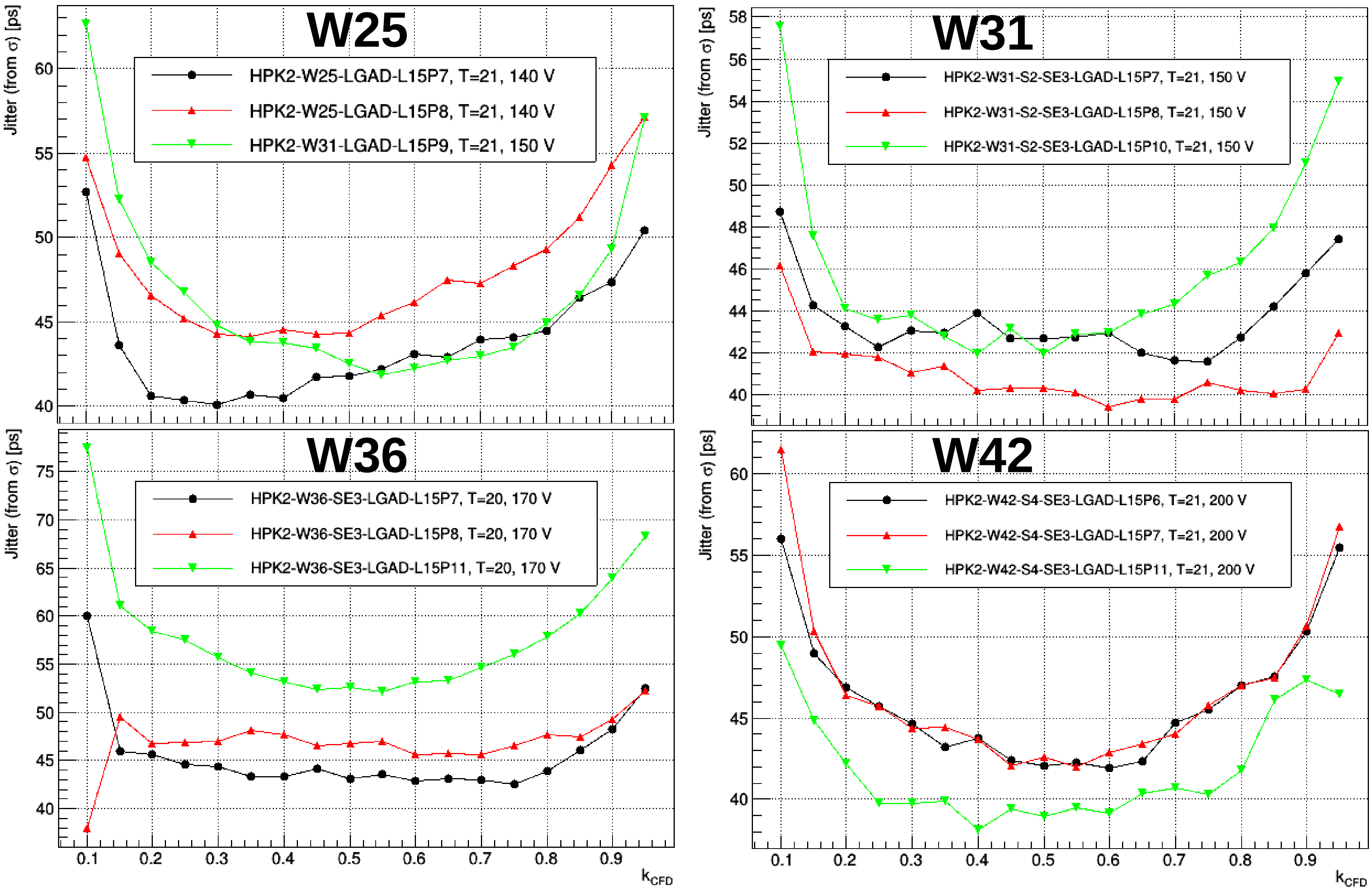




~25% gain differences wrt Torino measurements (to be followed up)
We use mean value to calculate charge.

# Timing calibration at 20 C

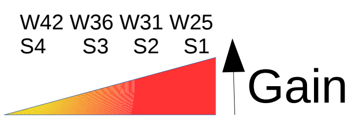
- Absolute time resolution: 3 detectors measured, in couples, in 3 different measurements.

$$\begin{cases} \sigma_{21}^2 = \sigma_2^2 + \sigma_1^2, \quad \sigma_{13}^2 = \sigma_1^2 + \sigma_3^2, \quad \sigma_{32}^2 = \sigma_3^2 + \sigma_2^2 \\ \sigma_1 = \left(\frac{1}{2}\left(\sigma_{21}^2 + \sigma_{13}^2 - \sigma_{32}^2\right)\right)^{\frac{1}{2}} \qquad \sigma_2 = \left(\frac{1}{2}\left(\sigma_{21}^2 - \sigma_{13}^2 + \sigma_{32}^2\right)\right)^{\frac{1}{2}} \\ \sigma_3 = \left(\frac{1}{2}\left(-\sigma_{21}^2 + \sigma_{13}^2 + \sigma_{32}^2\right)\right)^{\frac{1}{2}} \end{cases}$$

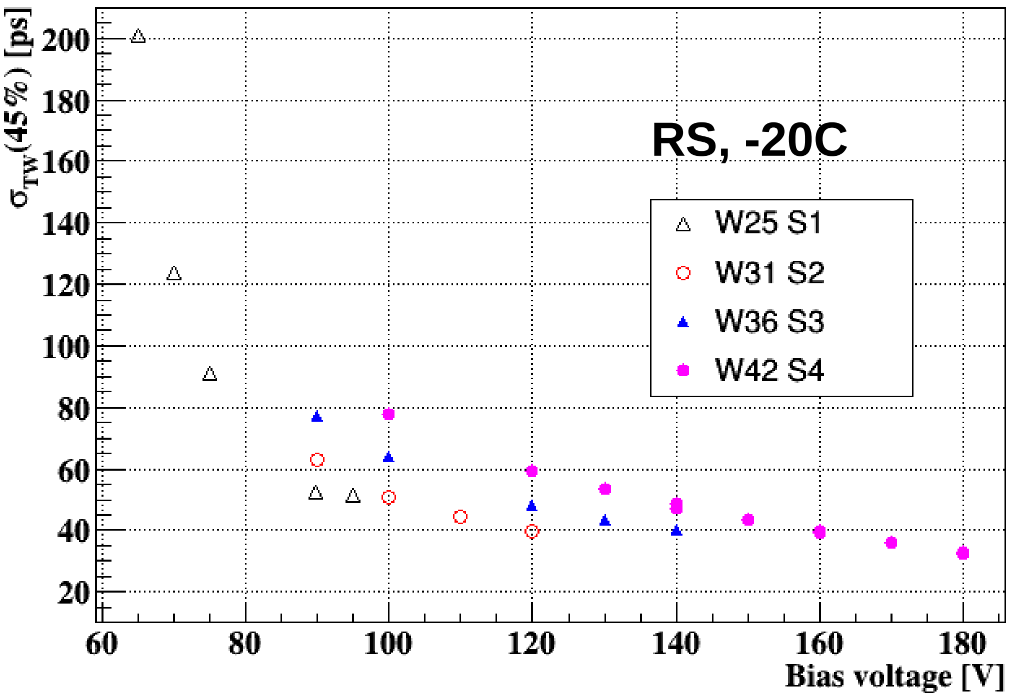


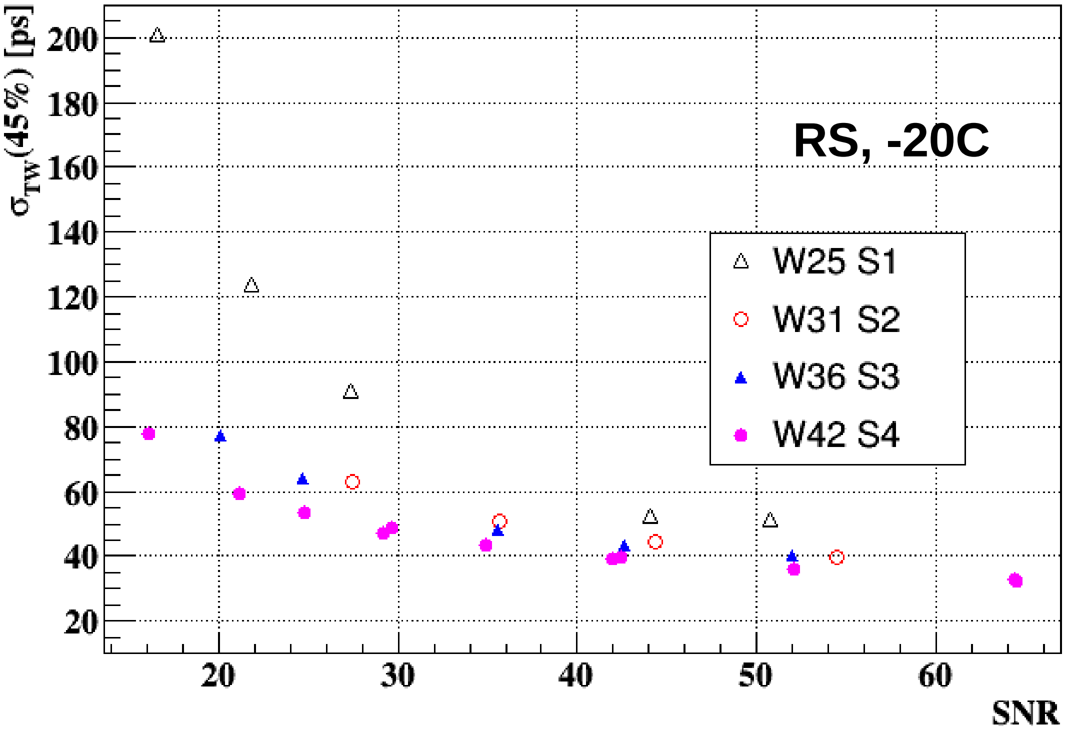

- Assumption all sensors from same wafer have same time resolution seems reasonable

*[1] See: Commissioning of a Beta Setup for Time Resolution Measurements, Paul McKarris, M. Centis, M. Wiehe, CERN-STUDENTS-Note-2019-159*

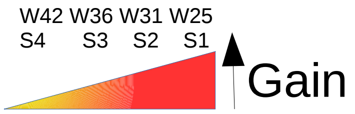


# Source: time resolution at -20 C

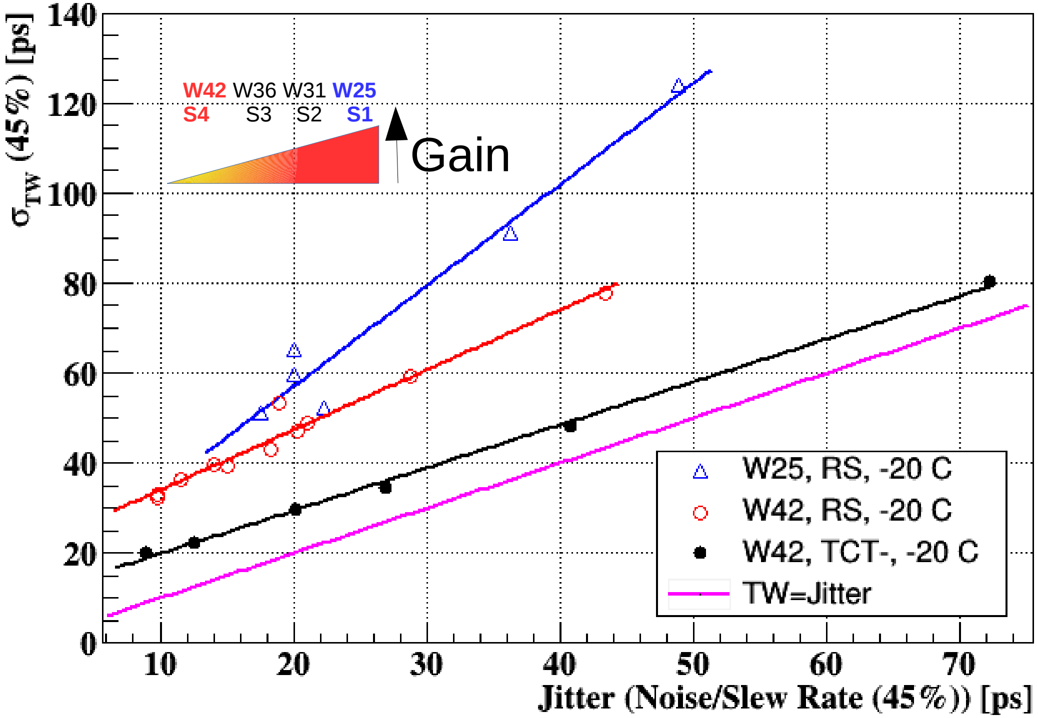



- Best timing resolution (30 ps) with RS achieved with W42 (lower gain split) at -20 C, 180 V.

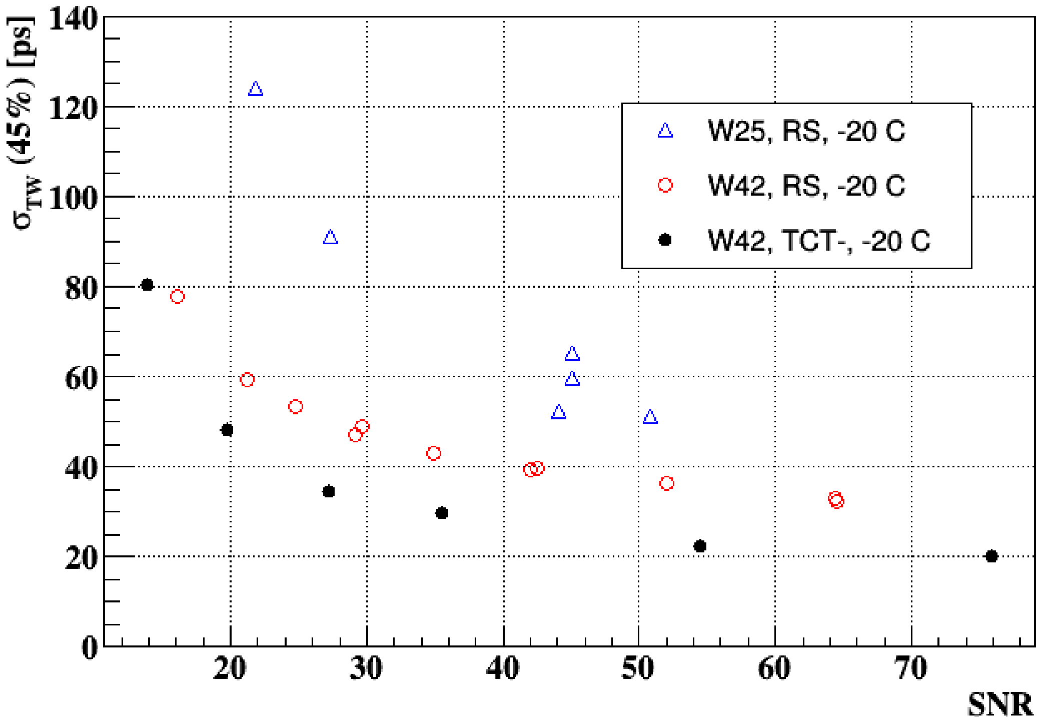


# TCT % RS: effect of Landau noise




► Time resolution after TW correction always better in TCT than in **RS** because of absence of Landau noise in the rising edge of the pulse.

For the same jitter (N/SR), higher gain split (W25) is worse than lower gain split (W42). Landau fluctuations have more impact for higher gain devices.

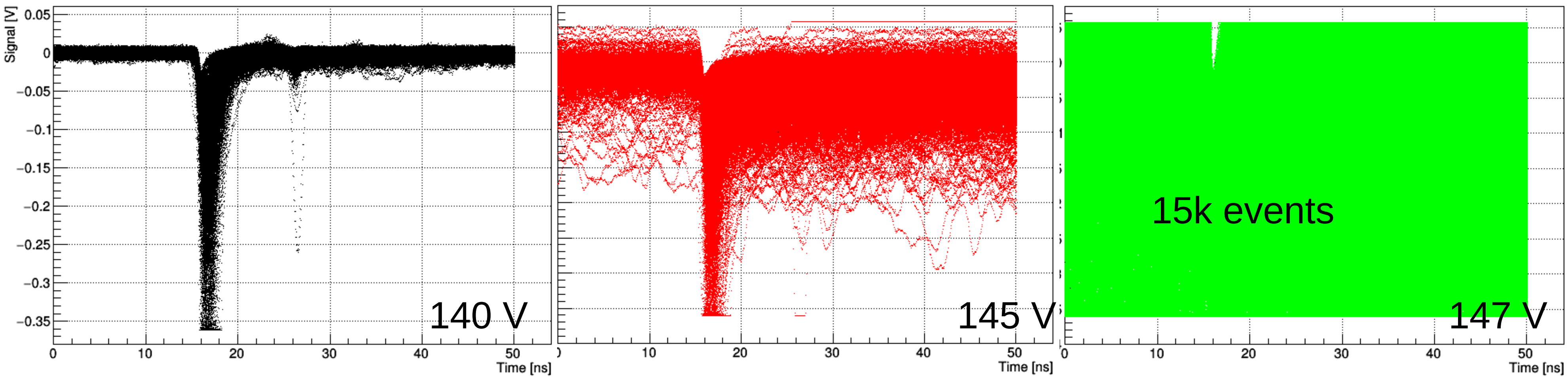


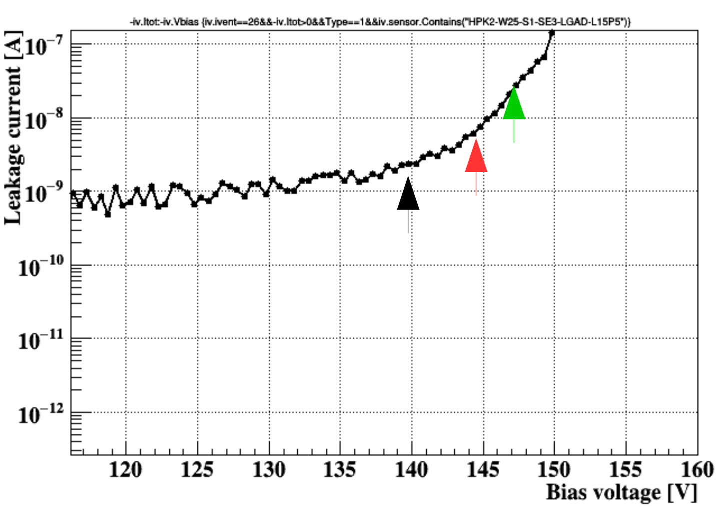

► For the same SNR:

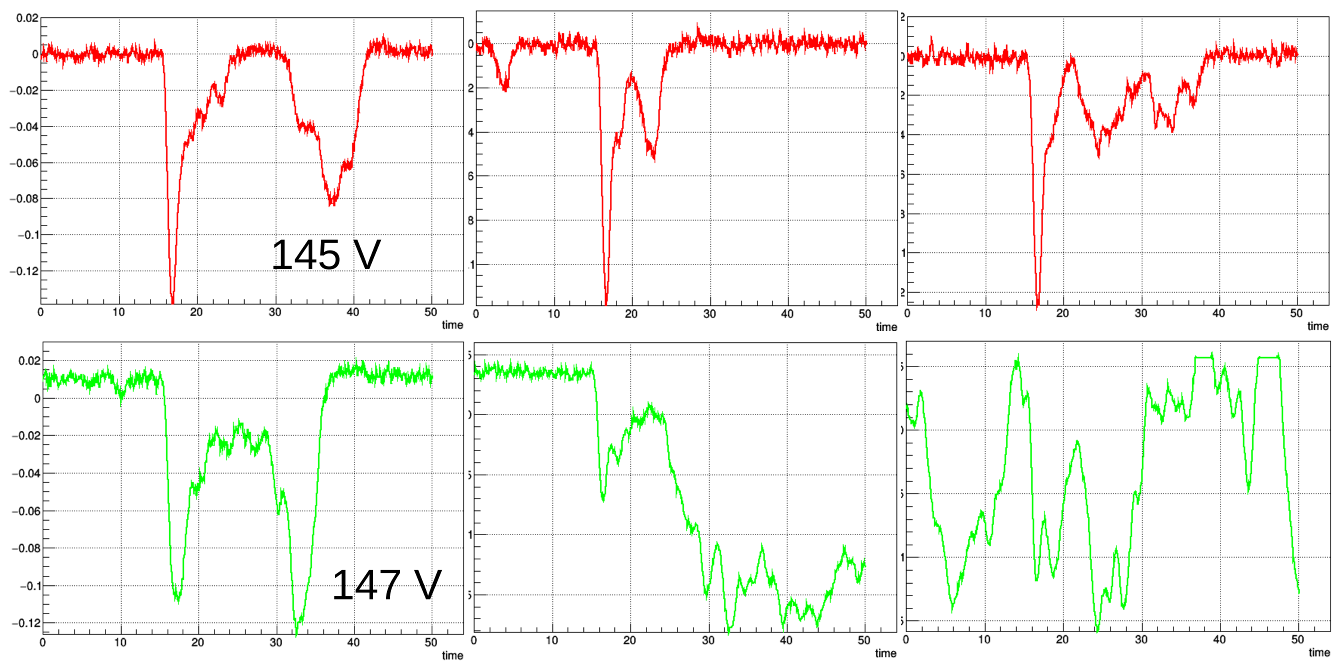
- Time resolution with TCT is better than RS
- Time resolution for low gain split better than higher gain split

# Stability of samples at breakdown

- Samples measured in β setup. Trigger is coincidental top bottom samples.
Soft breakdown, samples still working fine afterwards


2020-11-08_19-31-03_run
2020-11-08_19-44-05_run
2020-11-08_20-00-16_run

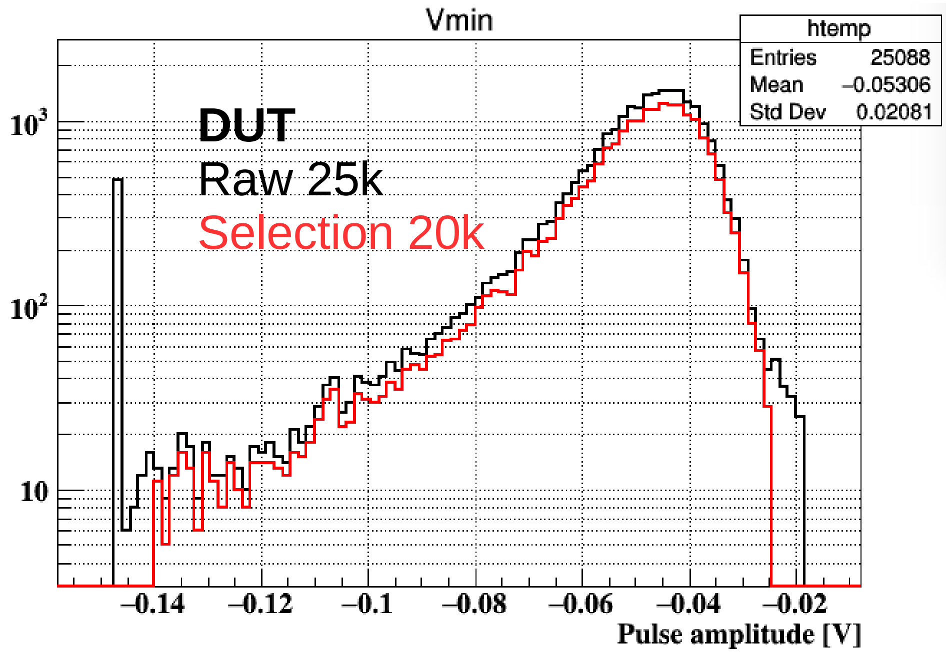
# Summary and conclusions

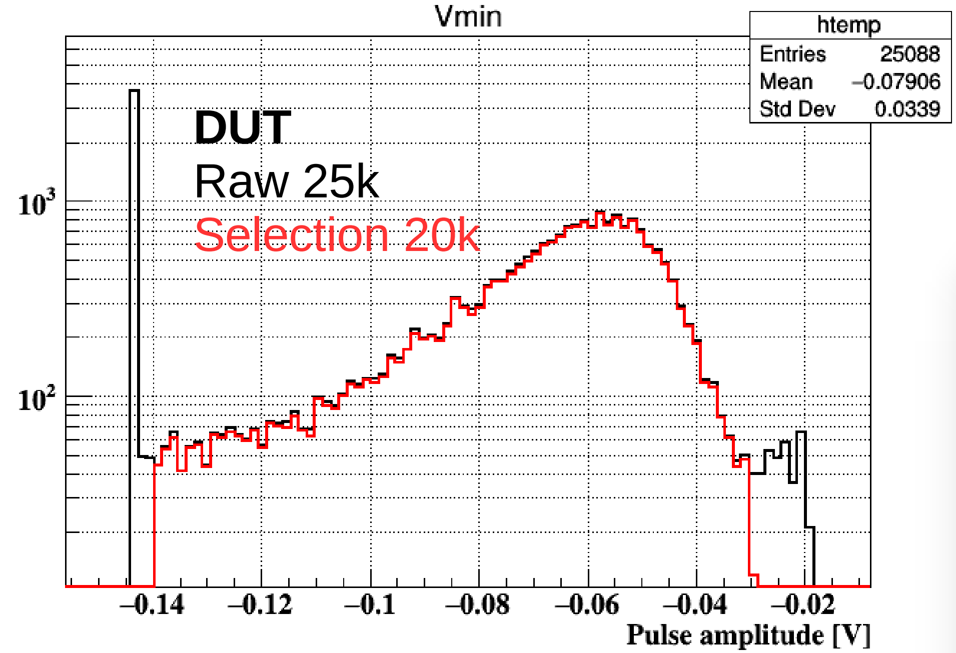
- **Recommissioning** of β-source setup and update of analysis software at **CERN-SSD**
- HPK2 samples received **this summer**. Despite short time between reception and shipping for irradiation, all samples (77 LGADs+48 PiNs) were characterized electrically.
- 4 LGADs and PiNs from each gain split kept for testing. Besides CV/IV, they were also measured in TCT and RS at 20 and -20 C. Some measurements still pending.
- CVIV measurements show **very good reproducibility** of electrical characteristics
- TCT measurements (tuned to 1 MiP) show time resolution, after TW correction, reaches **20 ps** for all samples
- RS measurements inside Climate Chamber allow measurements at low temperatures. For the moment, only +20 and -20 C visited.
- Comparisons of gain (at 20 C) with Torino data (Room Temp) show higher gain in our setup. **Analysis** fine **tuning** still needed (MPV charge value).
- **Robust** 3-sensor **calibration** method useful to characterize **timing** with RS. **RS** time resolution, after TW correction, reaches **40 ps at 20 C** for all sensors. At **-20 C**, sensors with lower implantation dose (higher split number) can reach higher bias and achieve **30 ps**.
- We pushed a detector ~5 V into breakdown and measured “afterpulses” (?). Detectors are safe after this operation.

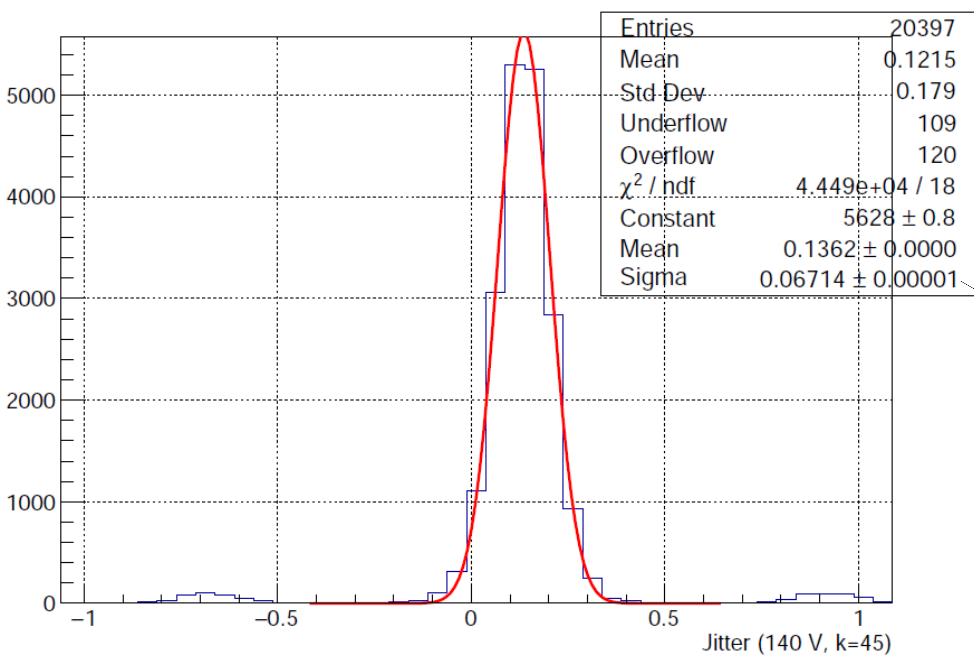
# Extra info

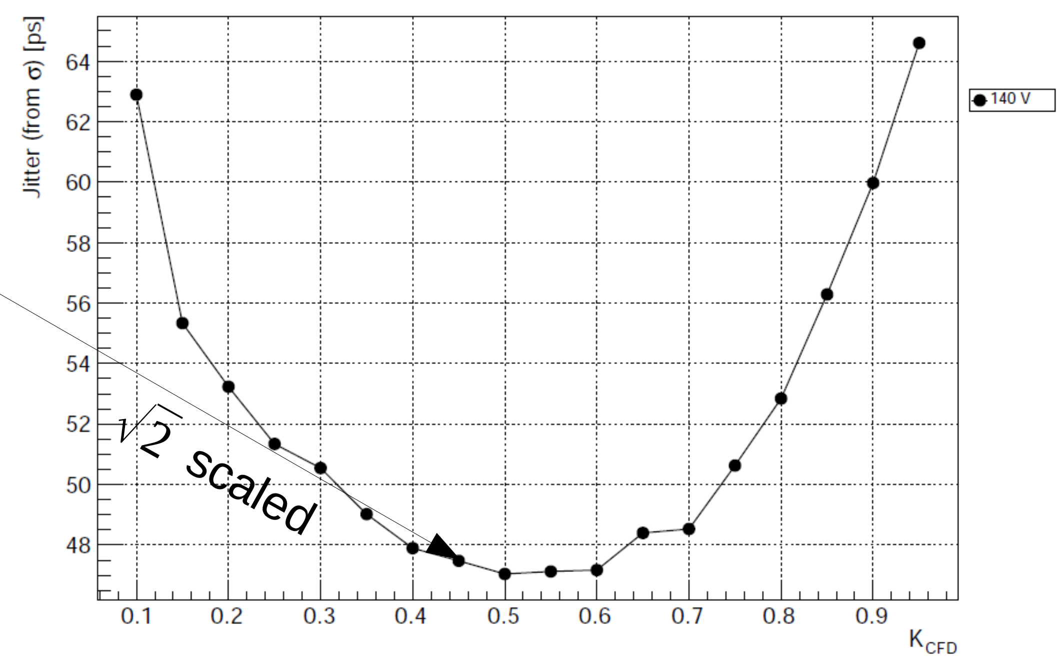
# Analysis intermediate steps

**Trigger**: Coincide between both detectors
**Selection**: Discard very low amplitude and saturation (in both samples)



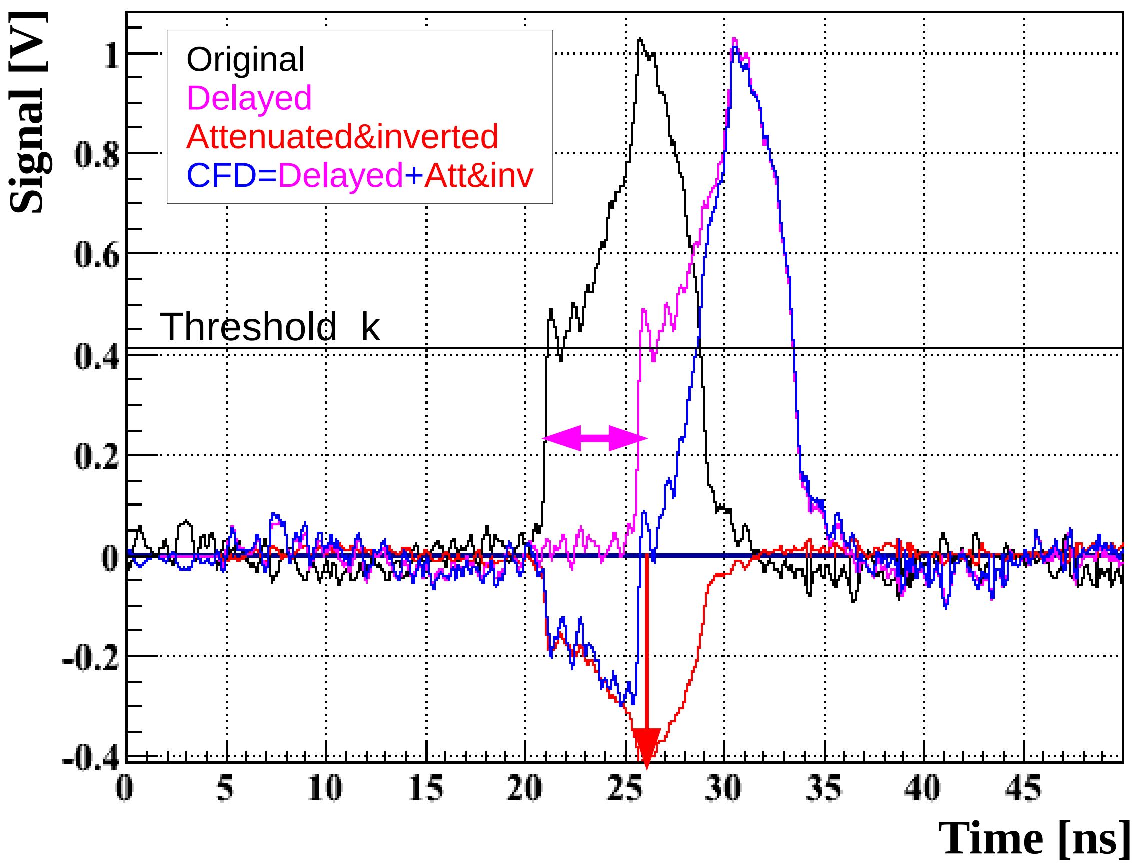

2020-11-04_07-06-30

# Timing analysis

**Time resolution contributions:**

**1) No Landau fluctuations with lasers**
**2)** Timing differences due to amplitude fluctuations **(Time Walk)** possible due to power fluctuations (no averaging) & splitting ratio≠50%. They can be corrected by **C**onstant **F**raction **D**iscrimination electronics.

Simulating **CFD** (software) over signal coming from **fast current amplifier**




**CFD algorithm**:
*Input*: pulse of **known** shape, threshold K
*Output*: **bipolar** pulse
Bipolar pulse ingredients:

1) **Delayed** copy of the pulse with respect to one of the 2 peaks (e or h).

2) **Attenuated and inverted** copy (**-K**)

CFD = Delayed + Attenuated & inverted

CFD yields threshold crossing of delayed pulse
Timing calculated when CFD pulse passes by 0

# Timing analysis

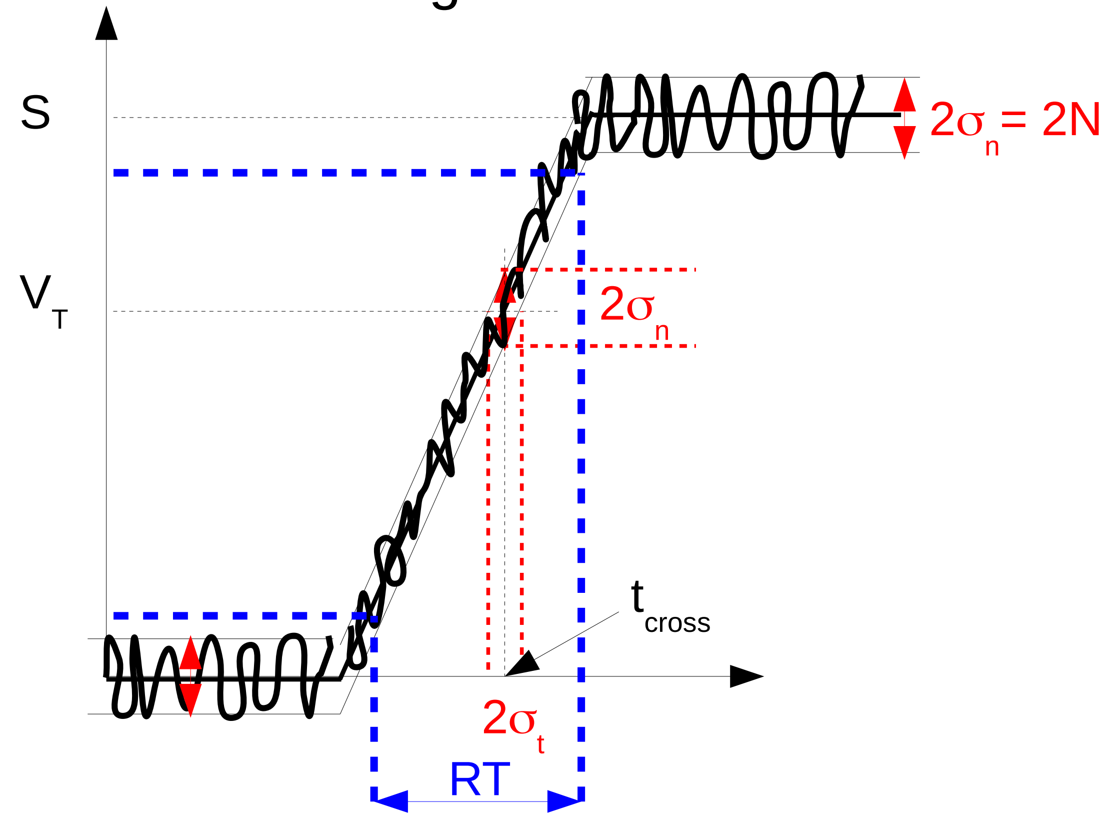
## Time resolution contributions:

3) **Sensor jitter**: because of noise fluctuations, the time of threshold crossing fluctuates. The variance of the crossing time is the sensor jitter.

**Jitter** is proportional to either:

1) Noise over Slew Rate
*(aka Slope-To-Noise Ratio)*
Slope=Slew Rate

2) Rise Time over SNR

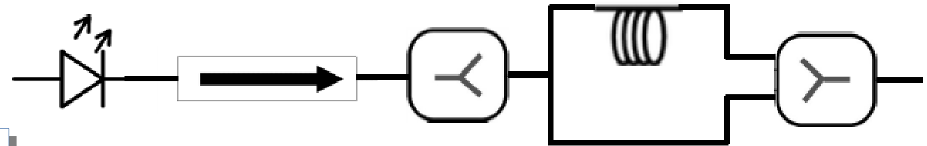



$$\sigma_t = \frac{\sigma_n}{\left.\frac{dV}{dt}\right|_{V_T}} = \frac{N}{SR(T)} \approx \frac{N}{\frac{S}{RT}} = \frac{RT}{SNR}$$

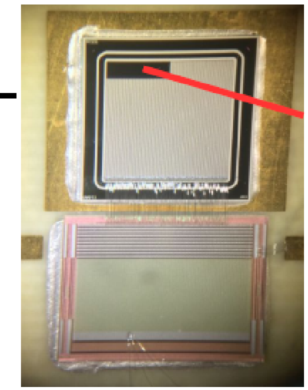
*SR=Slew Rate=dV/dt*
*RT=Rise Time*
*SNR=Signal To Noise*

# Timing Resolution

To avoid **laser jitter** we split the laser pulse in two copies and use one as a reference.




DUT

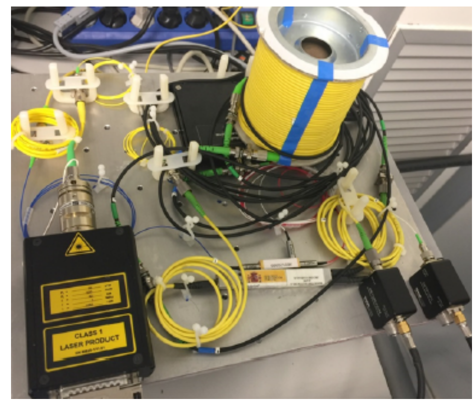


Metal removed in small rectangular window

CNM Pitch Adapter
AC coupling
Bias all strips

Timing-TCT setup at
**IFCA-Santander**

10 m long fiber
(=50 ns delay)
Avoids external time reference



Copy of the pulse (#2) used as time reference: $\Delta t = t_1 - t_2$

Time resolution of the detector: $\sigma_1 = \sigma_t$ $\quad \sigma_{\Delta_t}^2 = \sigma_1^2 + \sigma_2^2 = 2\sigma_t^2$

Resolution $\sigma_t$ is proportional to the variance of time of arrival differences ($\sigma$) of the 2 pulses: $\sigma_t = \frac{\sigma_{\Delta_t}}{\sqrt{2}}$

To minimize **scope jitter**, both pulses readout using same scope channel.

**Two pulses** timing + **TW correction**⇒measured **time resolution** ≈ **jitter** of the detector

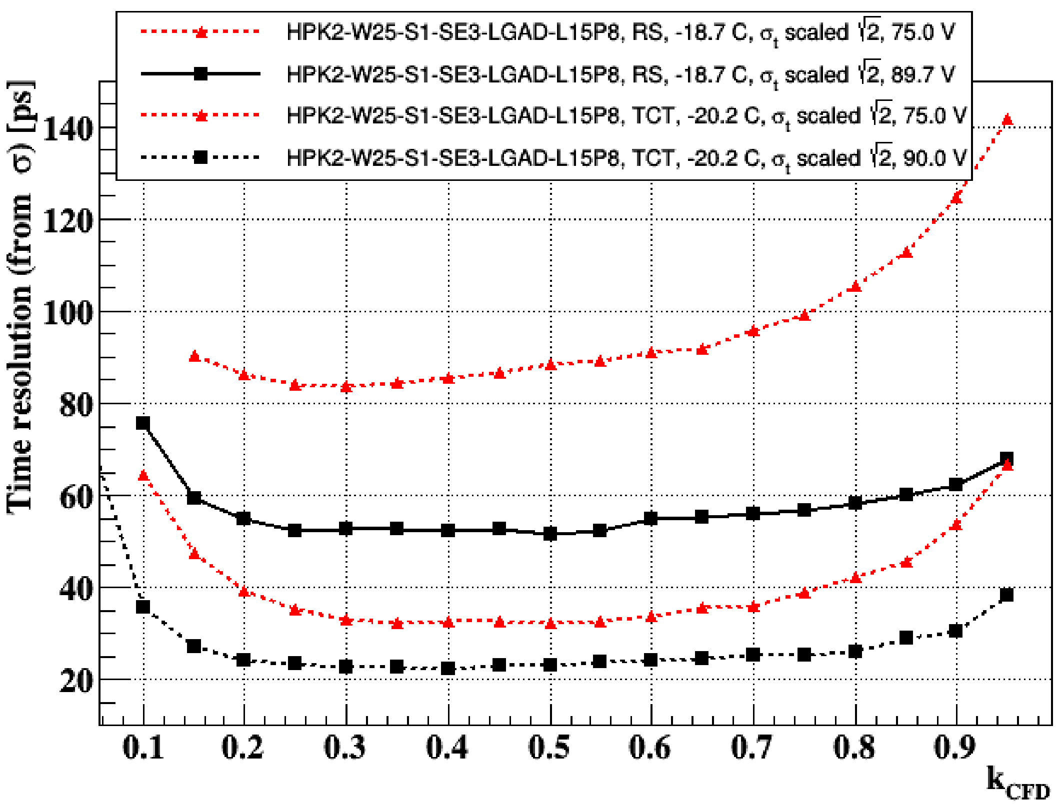
## W25: comparison RS with TCT

RS

TCT

30-60 ps contribution from Landau and inhomogeneity at +20C and -20C

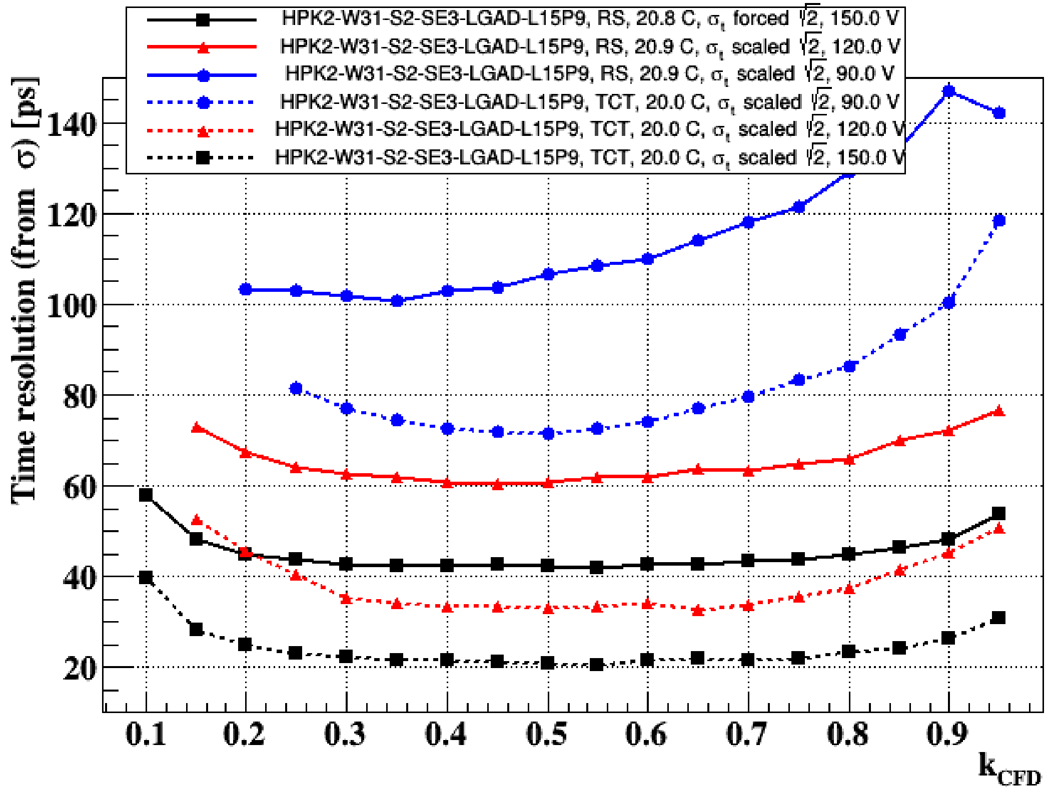
Check Q in TCT: MiP ?

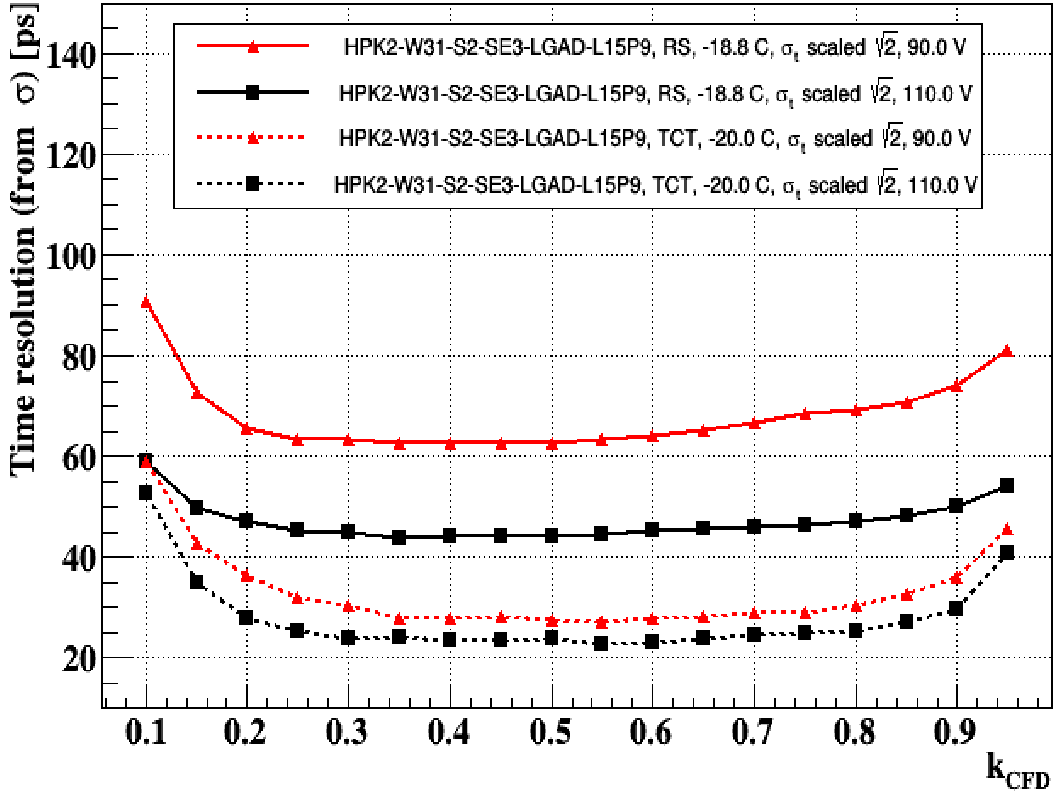



RS

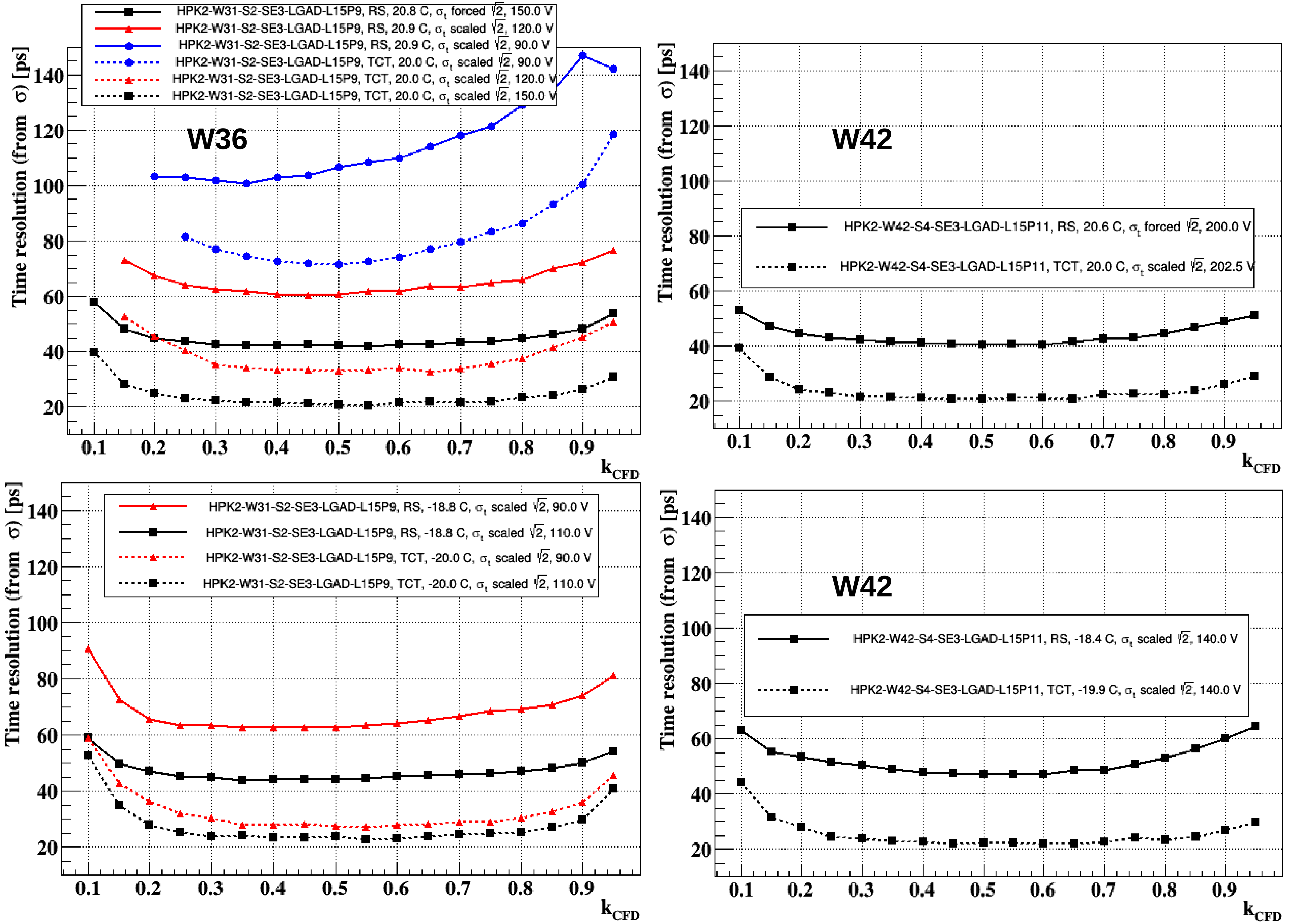
TCT

# W31: comparison RS with TCT

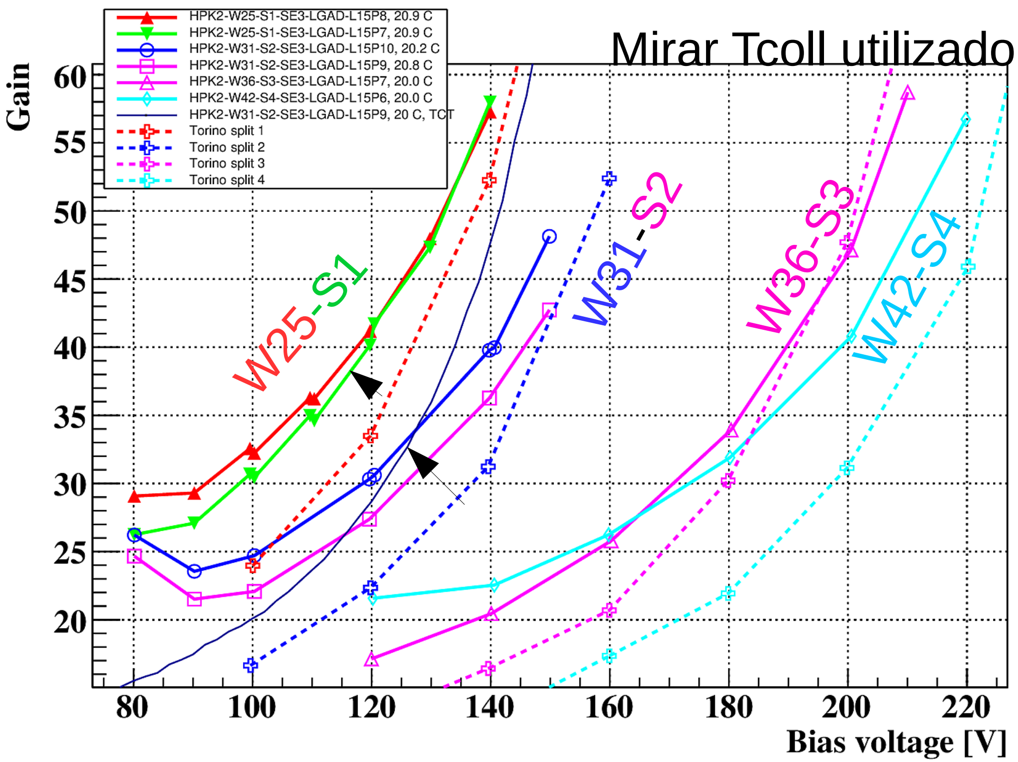


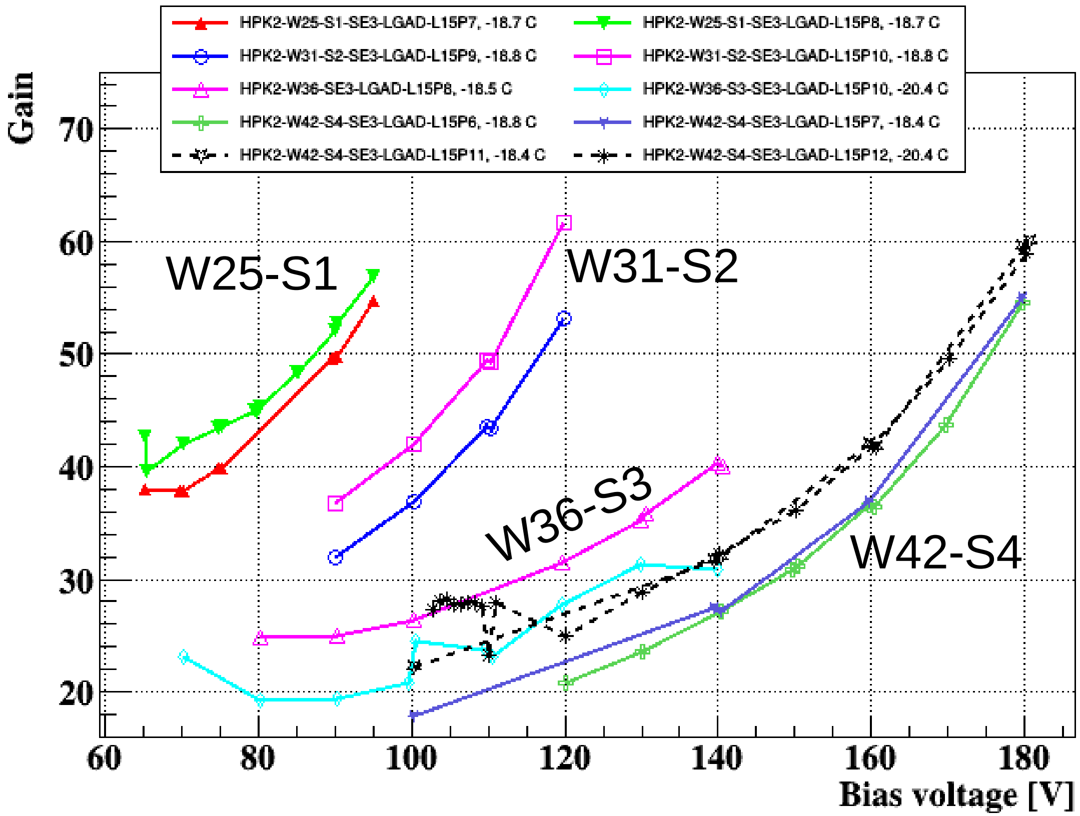




30-60 ps contribution from Landau and inhomogeneity at +20C and -20C


HPK2-W31-S2-SE3-LGAD-L15P9, RS, 20.8 C, σt forced √2, 150.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, RS, 20.9 C, σt scaled √2, 120.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, RS, 20.9 C, σt scaled √2, 90.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, TCT, 20.0 C, σt scaled √2, 90.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, TCT, 20.0 C, σt scaled √2, 120.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, TCT, 20.0 C, σt scaled √2, 150.0 V
W36
Time resolution (from σ) [ps]
kCFD
W42
HPK2-W42-S4-SE3-LGAD-L15P11, RS, 20.6 C, σt forced √2, 200.0 V
HPK2-W42-S4-SE3-LGAD-L15P11, TCT, 20.0 C, σt scaled √2, 202.5 V
HPK2-W31-S2-SE3-LGAD-L15P9, RS, -18.8 C, σt scaled √2, 90.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, RS, -18.8 C, σt scaled √2, 110.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, TCT, -20.0 C, σt scaled √2, 90.0 V
HPK2-W31-S2-SE3-LGAD-L15P9, TCT, -20.0 C, σt scaled √2, 110.0 V
HPK2-W42-S4-SE3-LGAD-L15P11, RS, -18.4 C, σt scaled √2, 140.0 V
HPK2-W42-S4-SE3-LGAD-L15P11, TCT, -19.9 C, σt scaled √2, 140.0 V

# Gain

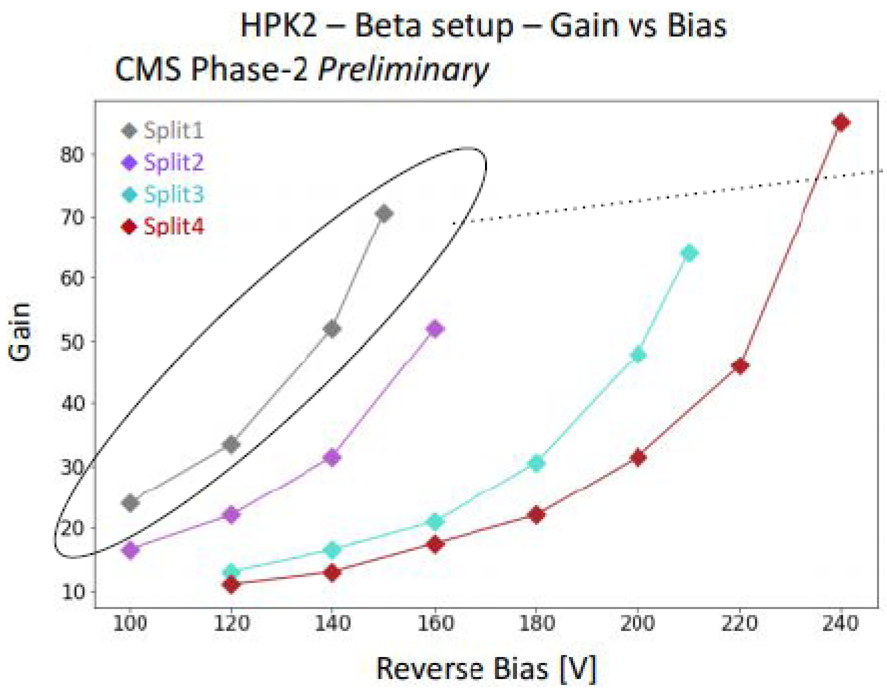


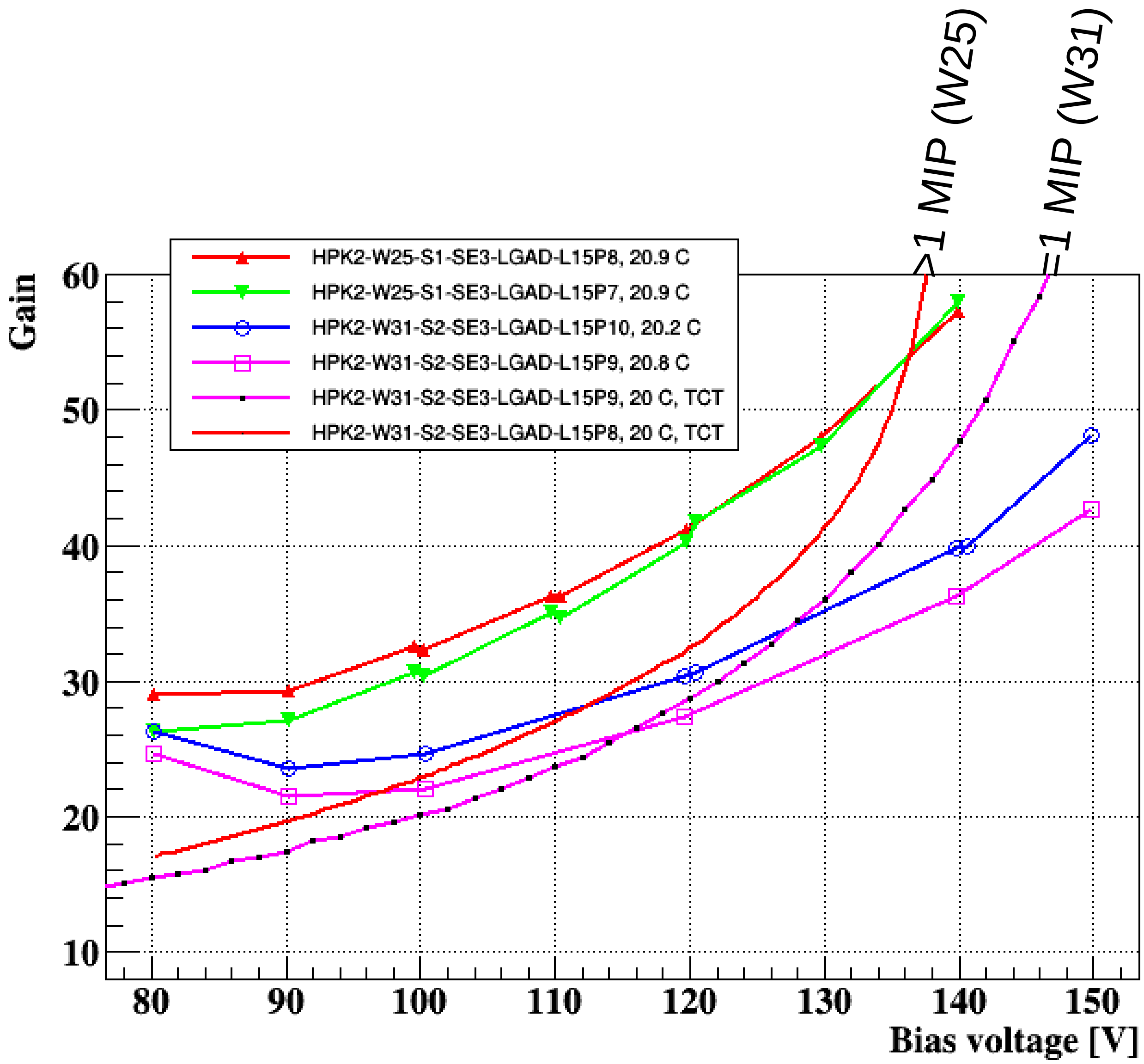




RS=continuous line with markers
RS Torino=dashed
TCT=continuous line, no marker

Plots in same scale

# Torino data


HPK2 – Beta setup – Gain vs Bias
CMS Phase-2 *Preliminary*
Split1
Split2
Split3
Split4
Gain
Reverse Bias [V]
10
20
30
40
50
60
70
80
100
120
140
160
180
200
220
240




TCT~1 MiP overestimates gain
TCT>1 MiP understimates