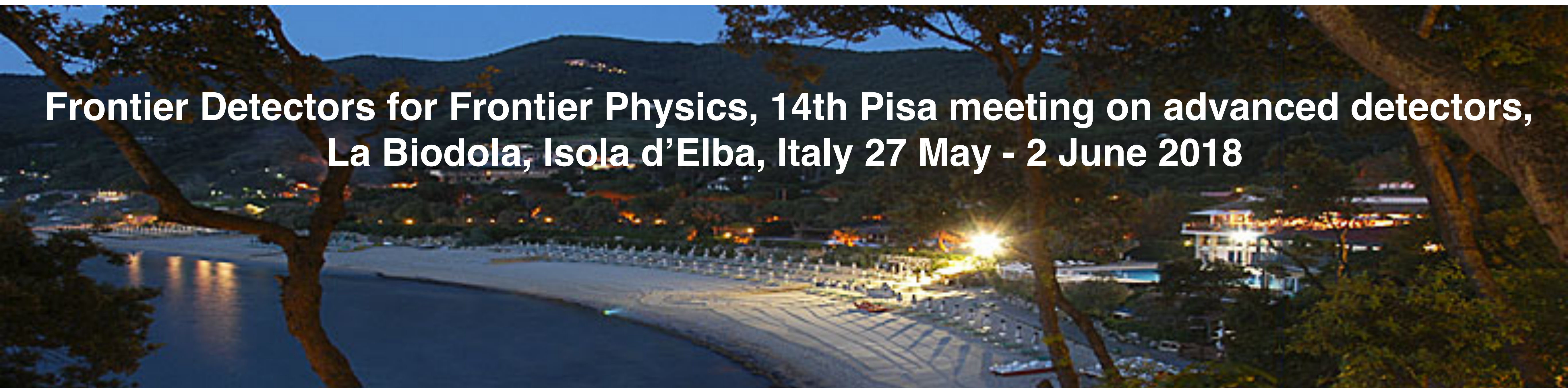
Development of Ultra Fast Silicon Detector for 4D tracking

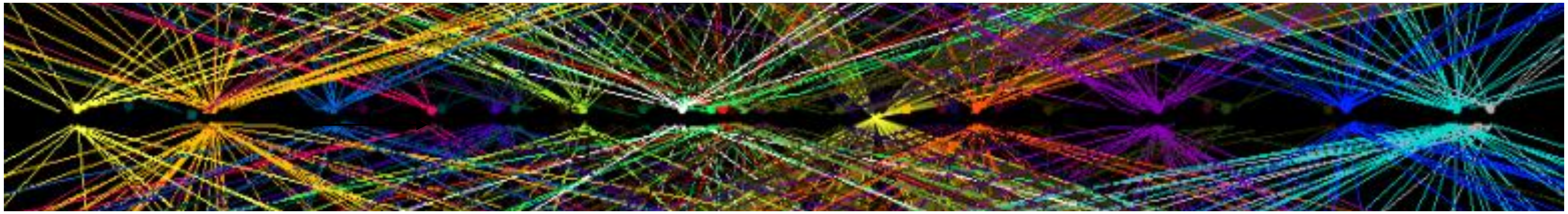


Frontier Detectors for Frontier Physics, 14th Pisa meeting on advanced detectors,
La Biodola, Isola d'Elba, Italy 27 May - 2 June 2018

Francesca Carnesecchi
on behalf of the UFSD & RSD groups
(University and INFN of Bologna, Torino and Trento, Centro Fermi Roma)

Why 4D tracking

New challenge in HEP: with the next generation of colliders (HL-LHC, FCC) probability of merged vertices >10%



HL-LHC: beamspot time spread (150-180) ps, pileup 150 - 200

CMS Simulation

<μ>	3D Merged Vertex Fraction
50	3.3%
200	13.4%

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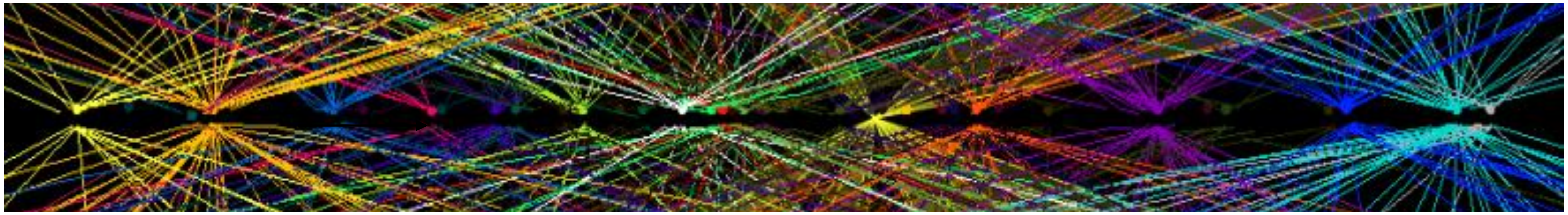

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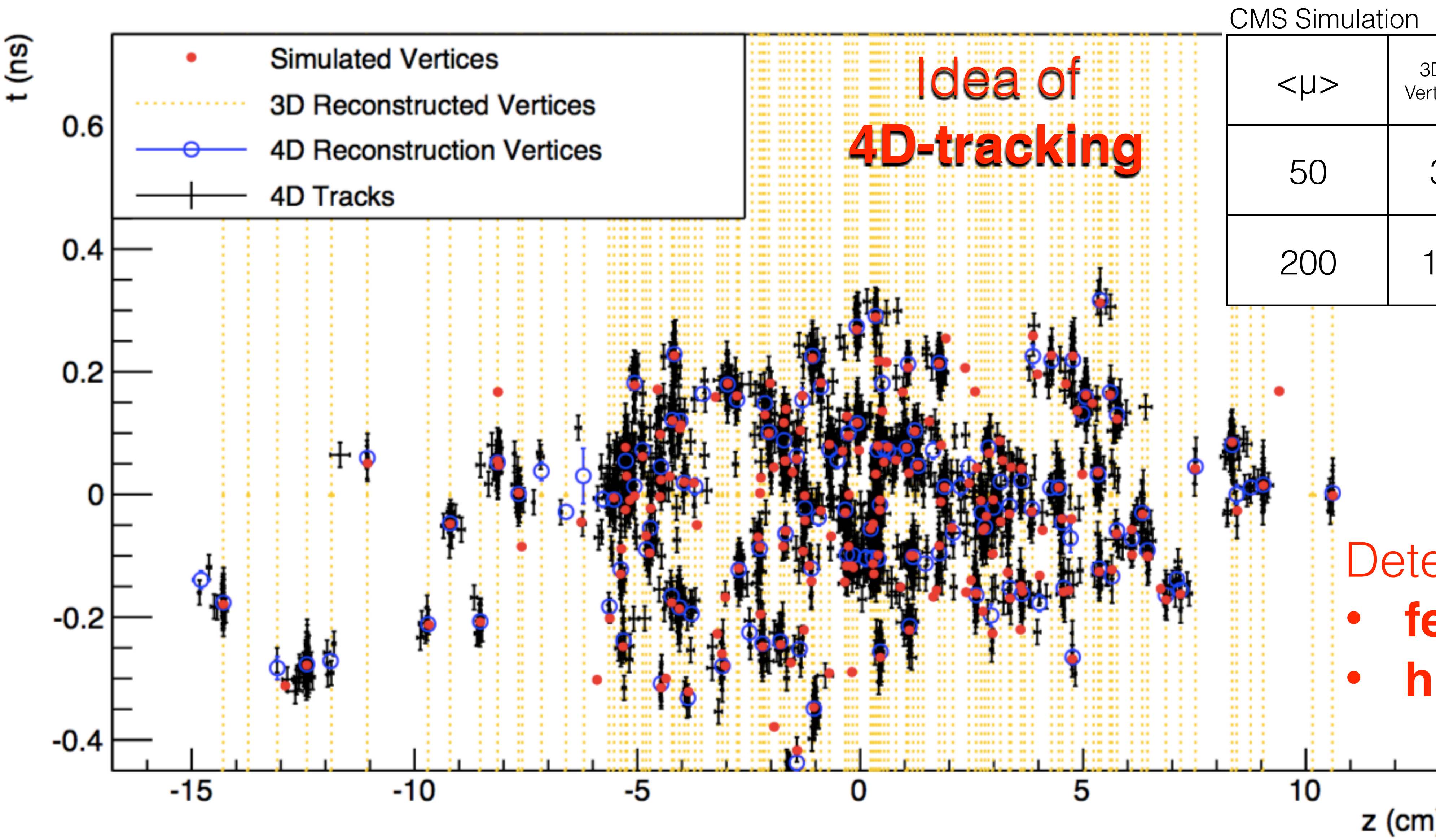


CMS Simulation

<μ>	3D Merged Vertex Fraction	4D Merged Vertex Fraction	Ratio of 3D/4D
50	3.3%	0.5%	6.6
200	13.4%	1.5%	8.9

Detector requirements:

- **few 10's ps**
- **high radiation levels**

UFSD

UFSD: a perfect candidate for 4D tracking

Silicon detectors **before** UFSD…

Spatial resolution —> 10’s ***μm***

Time resolution —> few **ns**

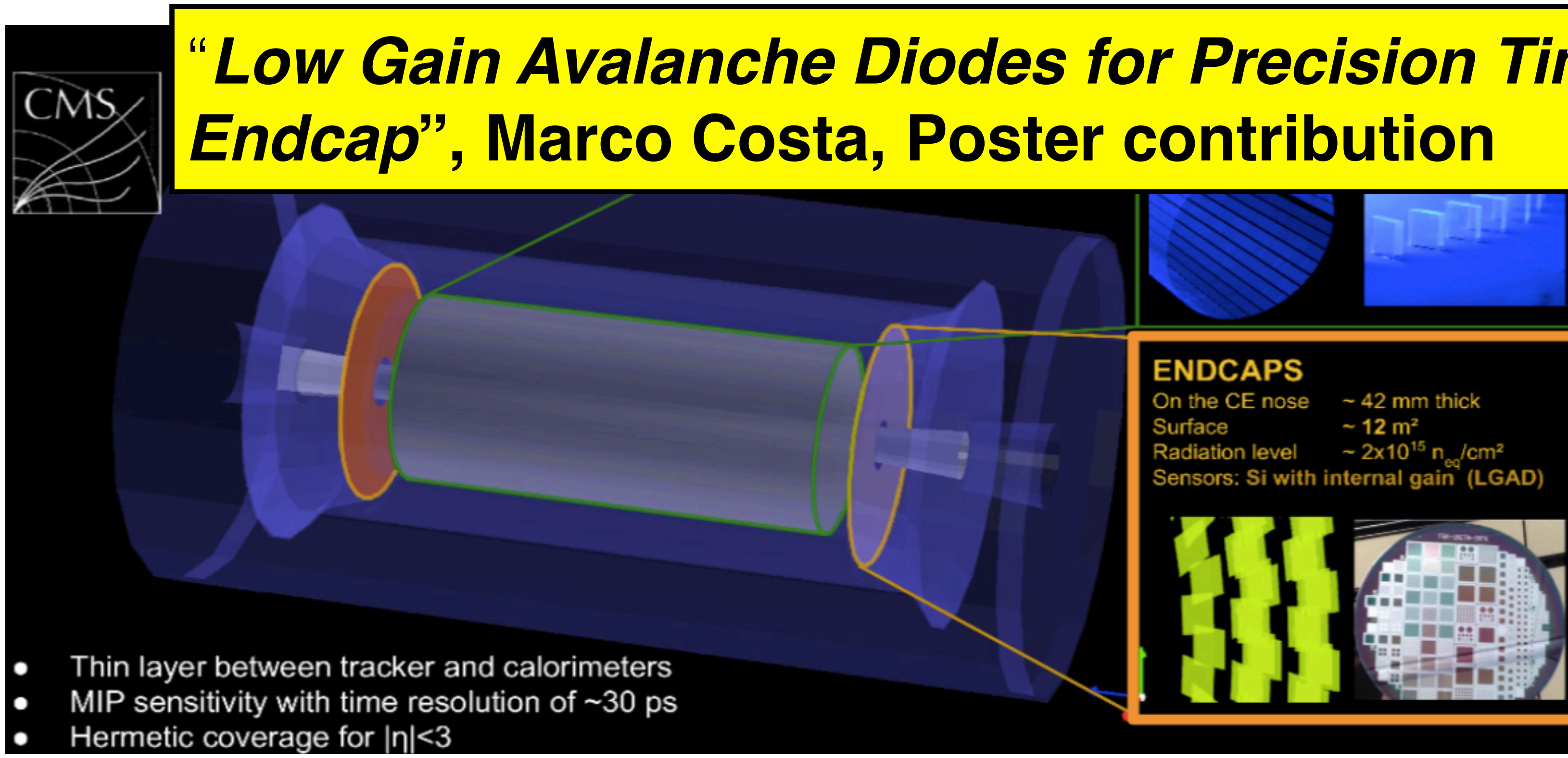
…**after**, with UFSD

Spatial resolution —> 10’s ***μm***

Time resolution —> few 10’s **ps**

HL-LHC: ATLAS and CMS are considering upgraded detectors with UFSDs

“*Low Gain Avalanche Diodes for Precision Timing in the CMS Endcap*”, Marco Costa, Poster contribution



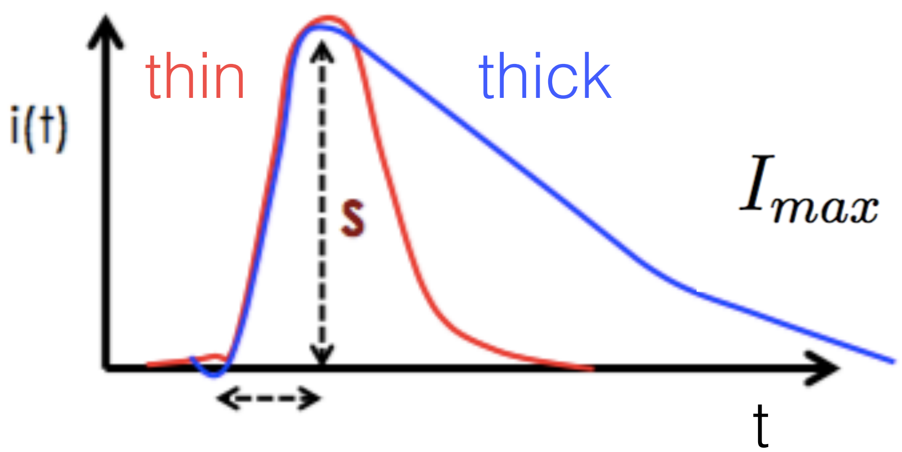
Other applications thanks to the good time resolution, e.g. in particle with **PID** and in medical Physics with **PET**

UFSD

Key ingredients for a good time resolution:

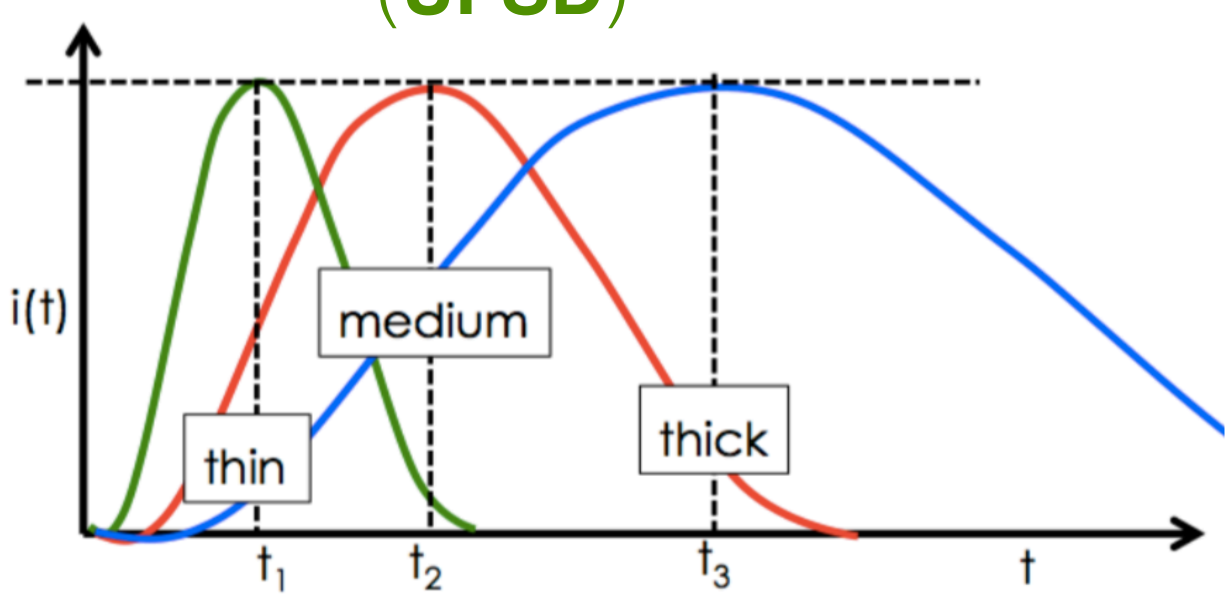
- High S/N
- Fast signal, t_{rise} (high slew rate, dV/dt)

Standard Silicon detector: **I_{max}** and **dV/dt** independent on thickness



$$I_{max} \propto nqv_{sat}\frac{1}{d} = Nd\ qv_{sat}\frac{1}{d} = Nqv_{sat}$$ ~1-2 μA

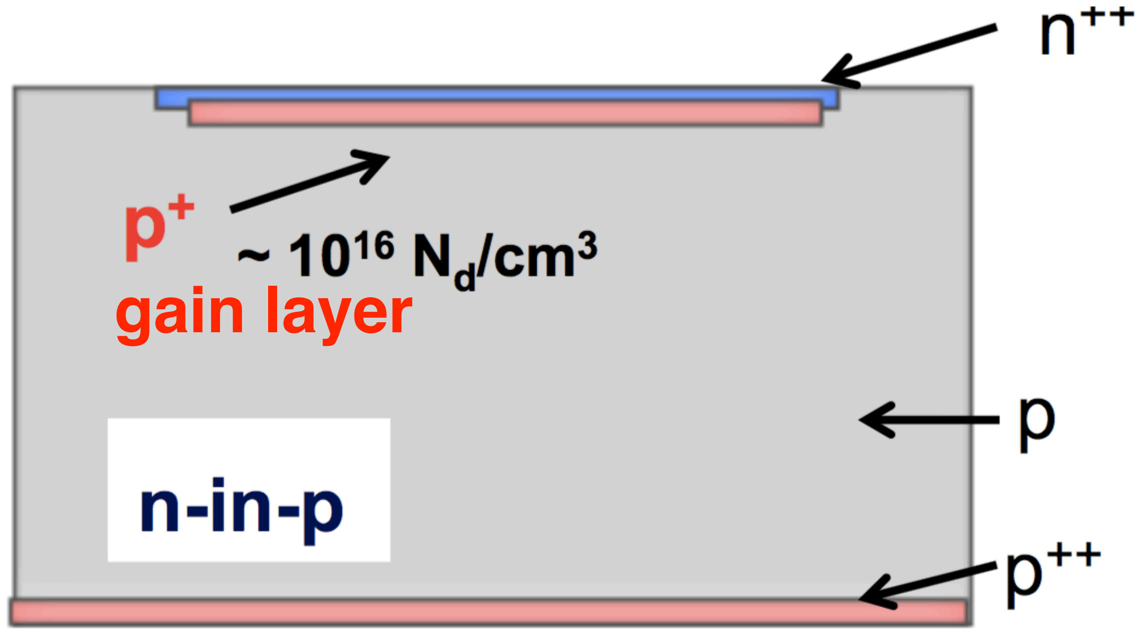
Gain silicon detector: **(UFSD)** — **I_{max}** ∝ G , independent on thickness

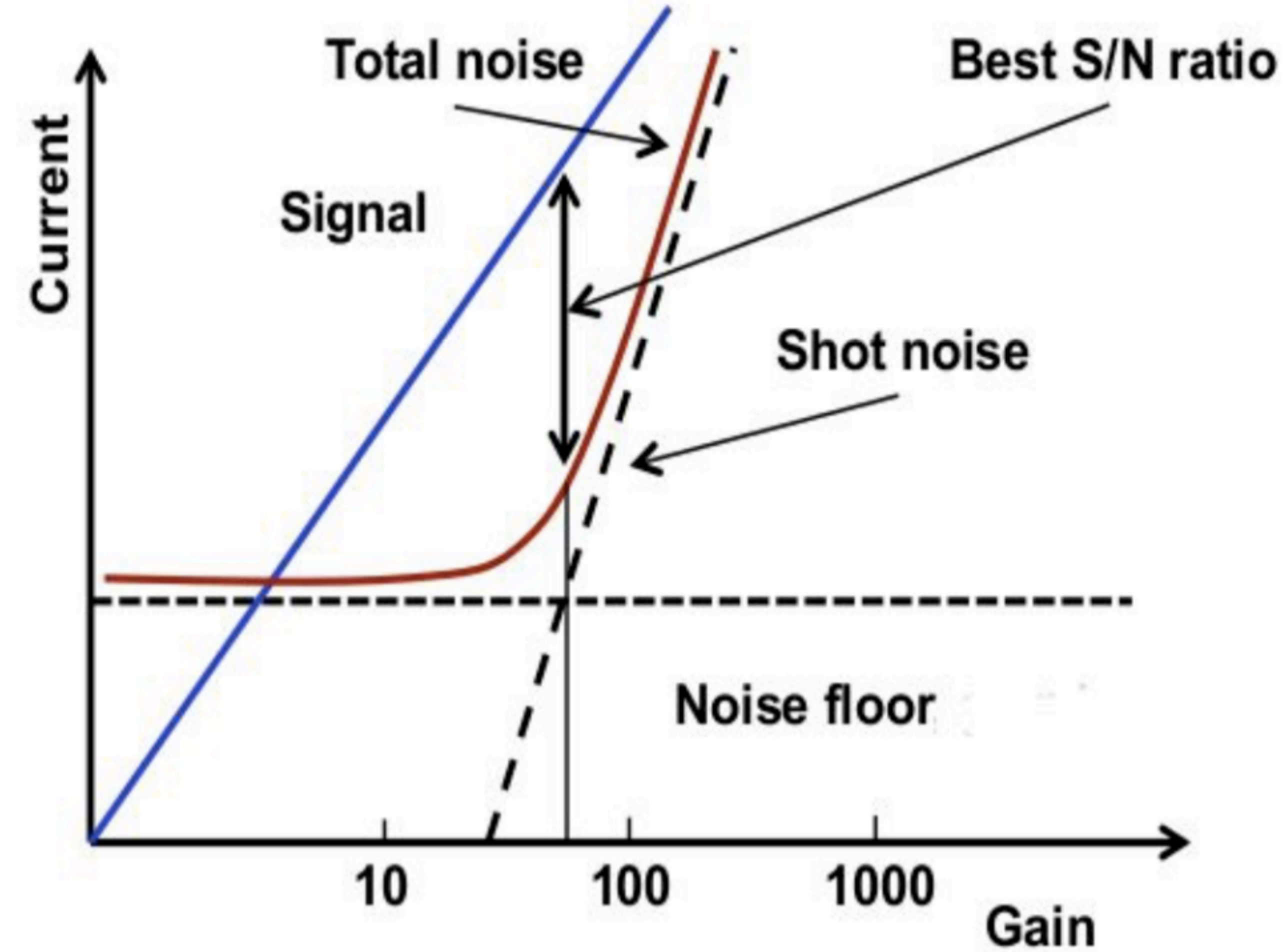


dV/dt ~ $\frac{di_{gain}}{dt} \propto \boxed{\frac{G}{d}}$

UFSD

Based on **Low Gain Avalanche Detector**

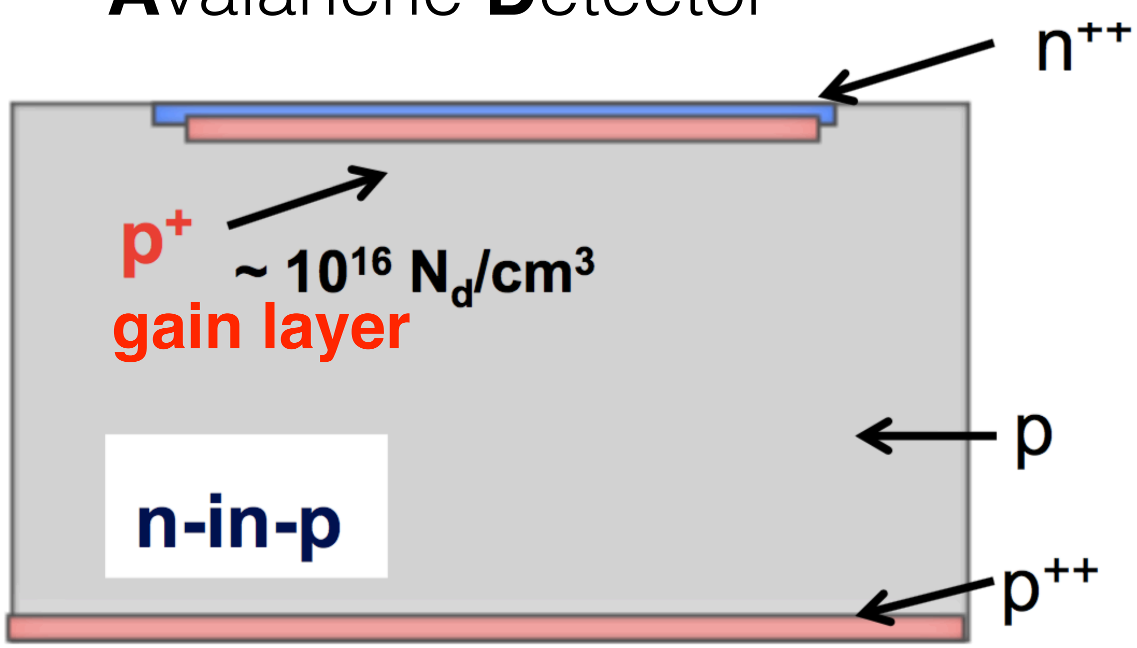


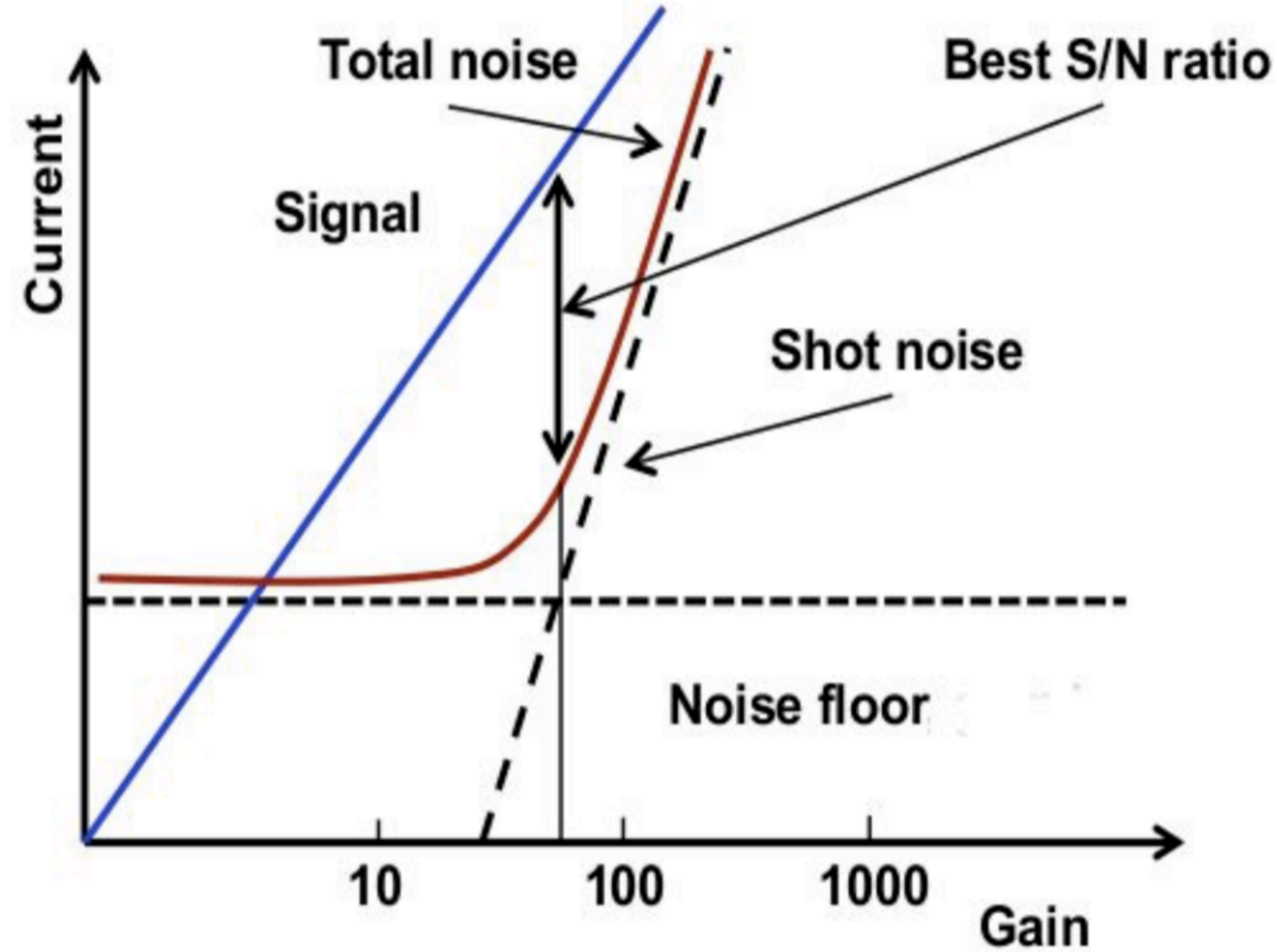


G ~ 20-30: best S/N, G > 50: S/N start to decrease

UFSD

Based on **L**ow **G**ain **A**valanche **D**etector





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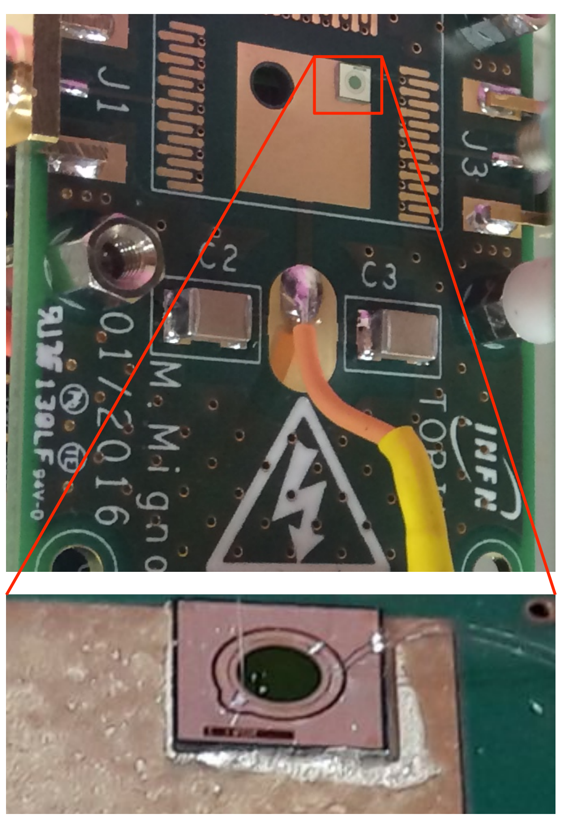
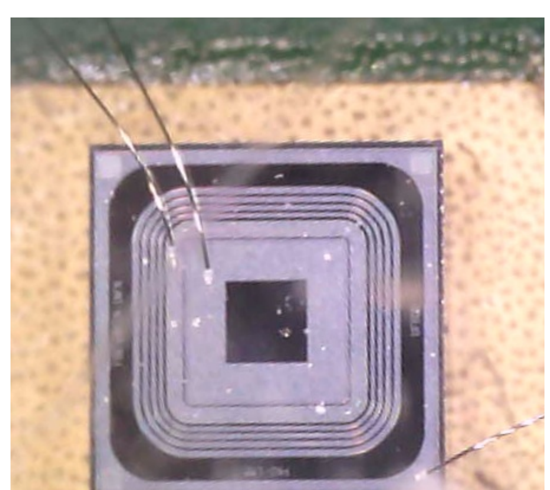
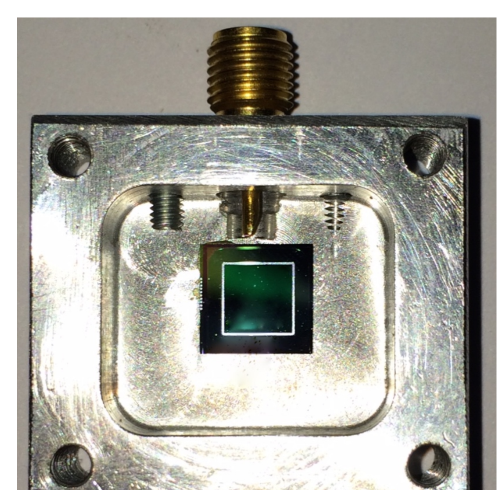






HPK, 0.785 mm²

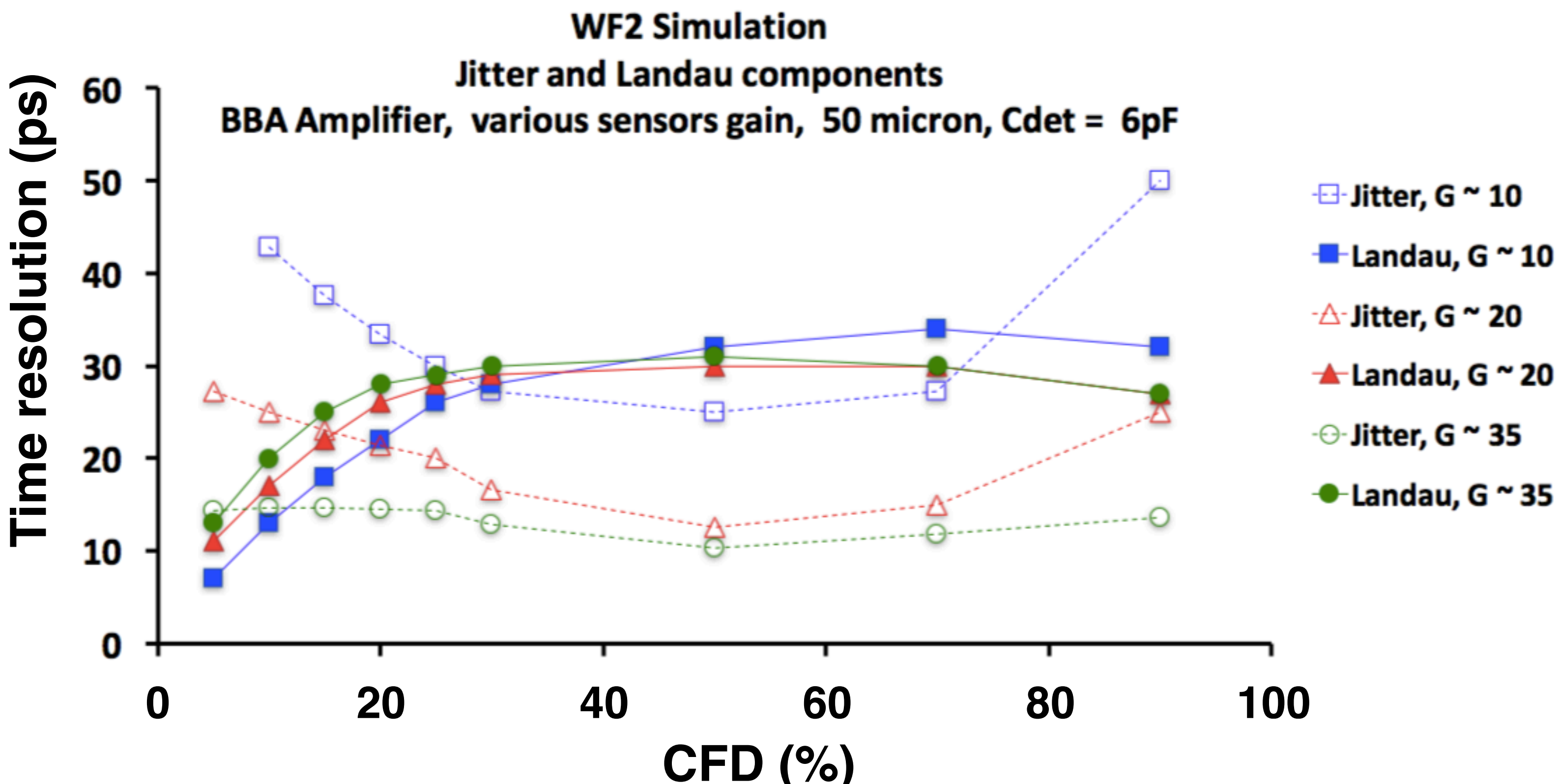
FBK, 1x1 mm²

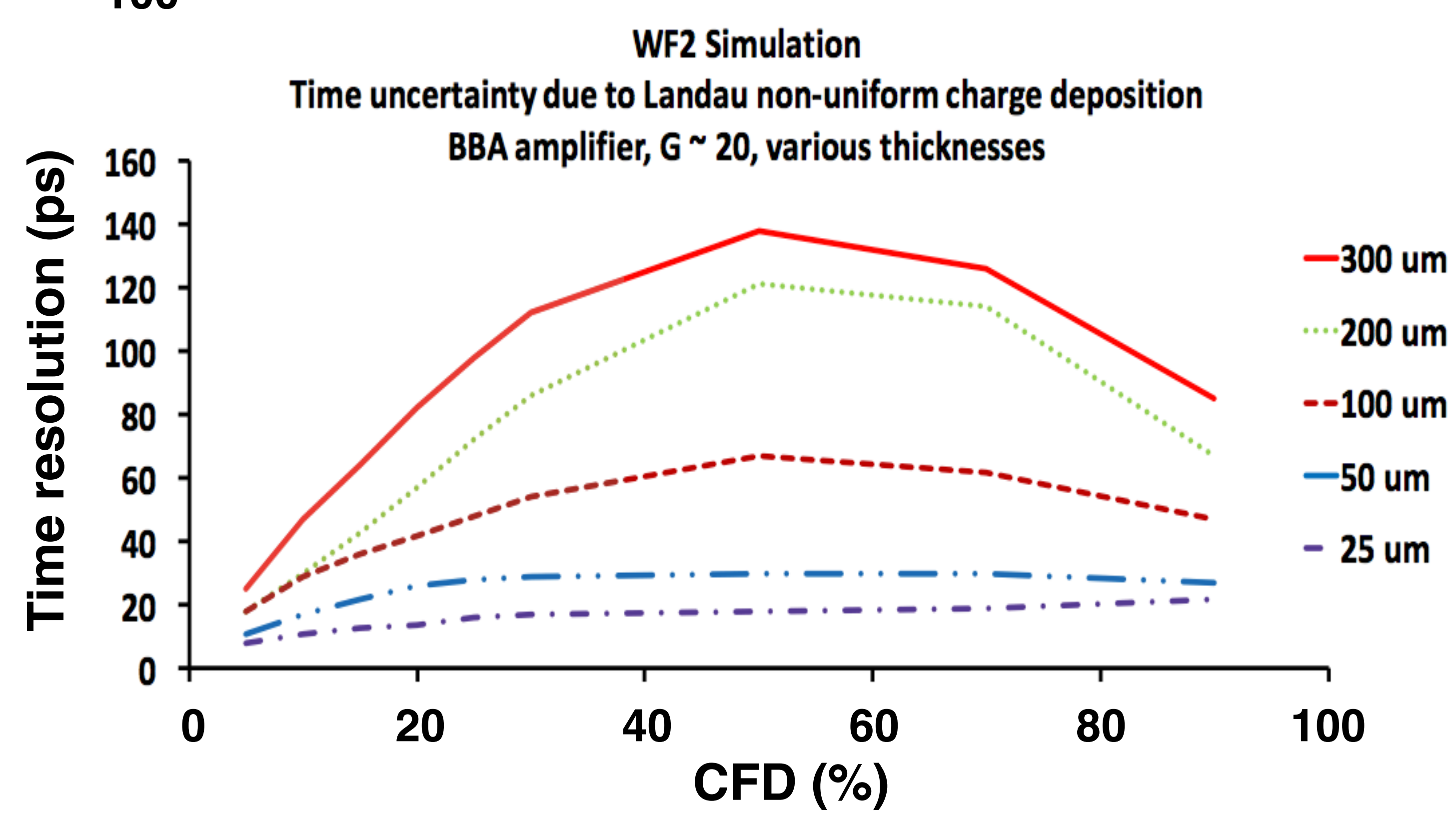
CNM, 5x5 mm²

Time resolution

For a planar detector geometry $\sigma_t^2 = \sigma_{TDC}^2 + \boxed{\sigma_{current}^2} + \sigma_{time\ slewing}^2 + \boxed{\sigma_{jitter}^2}$

with a saturated velocity, the σ_t main factor are: **Landau** fluctuations and **Jitter**





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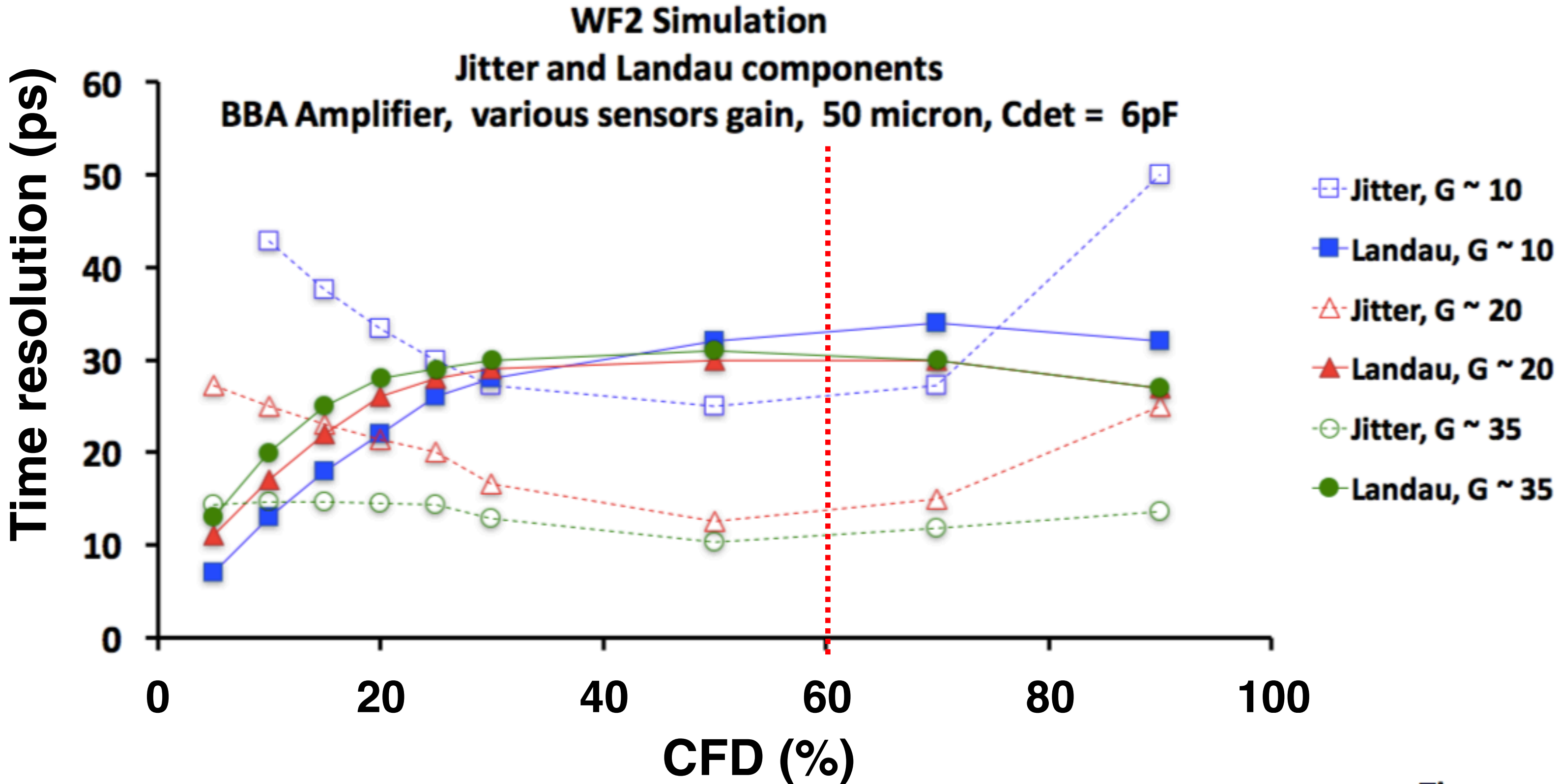


$$\sigma_{jitter} = \frac{N}{(dV/dt)_{V_{th}}} = \frac{t_{rise}}{S/N}$$

Improves with:

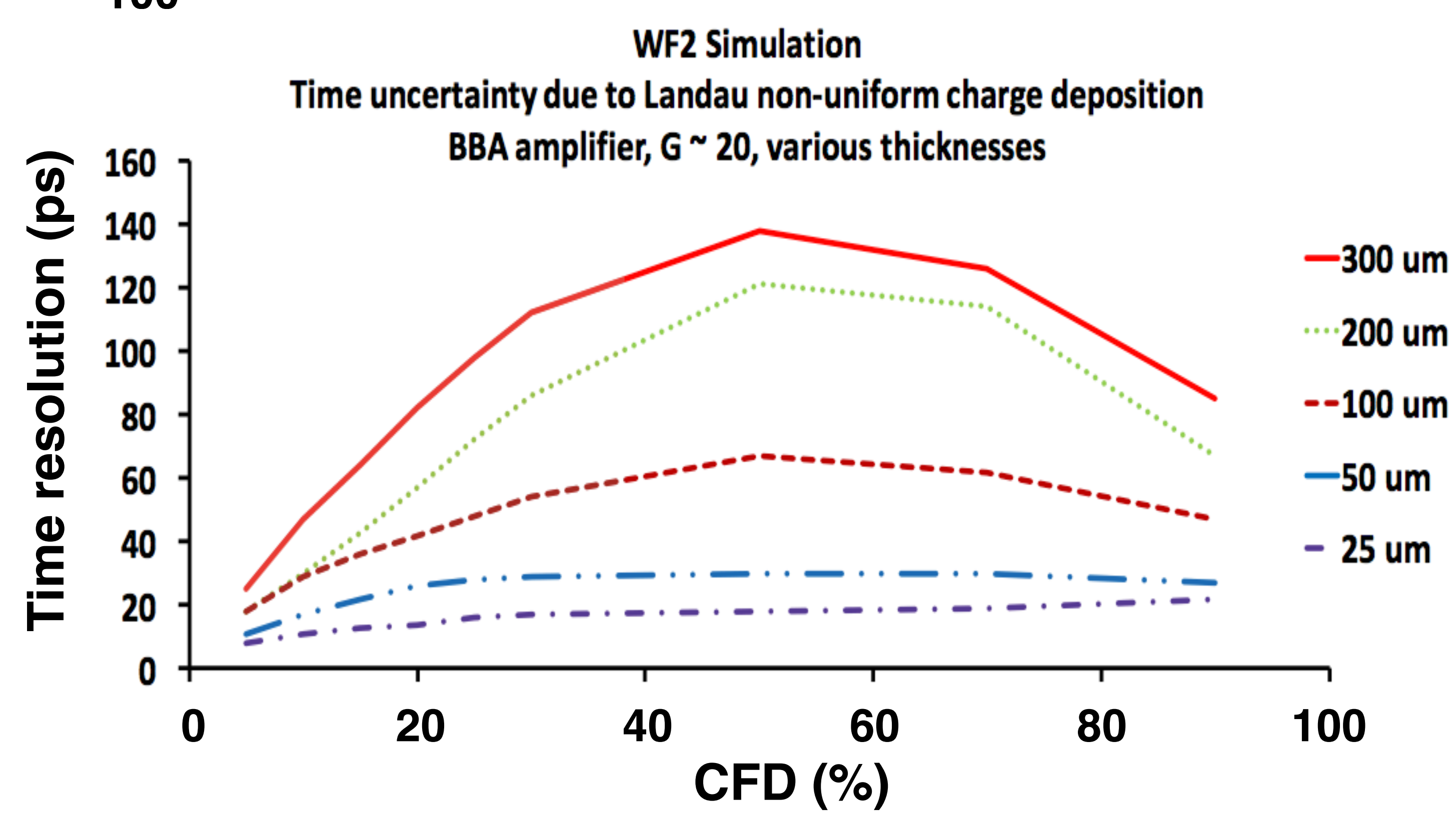
- > CFD (until ~ 60%)
- < d
- > G

Improves with

- < CFD (until ~ 60%)
- < d

~ Independent on G

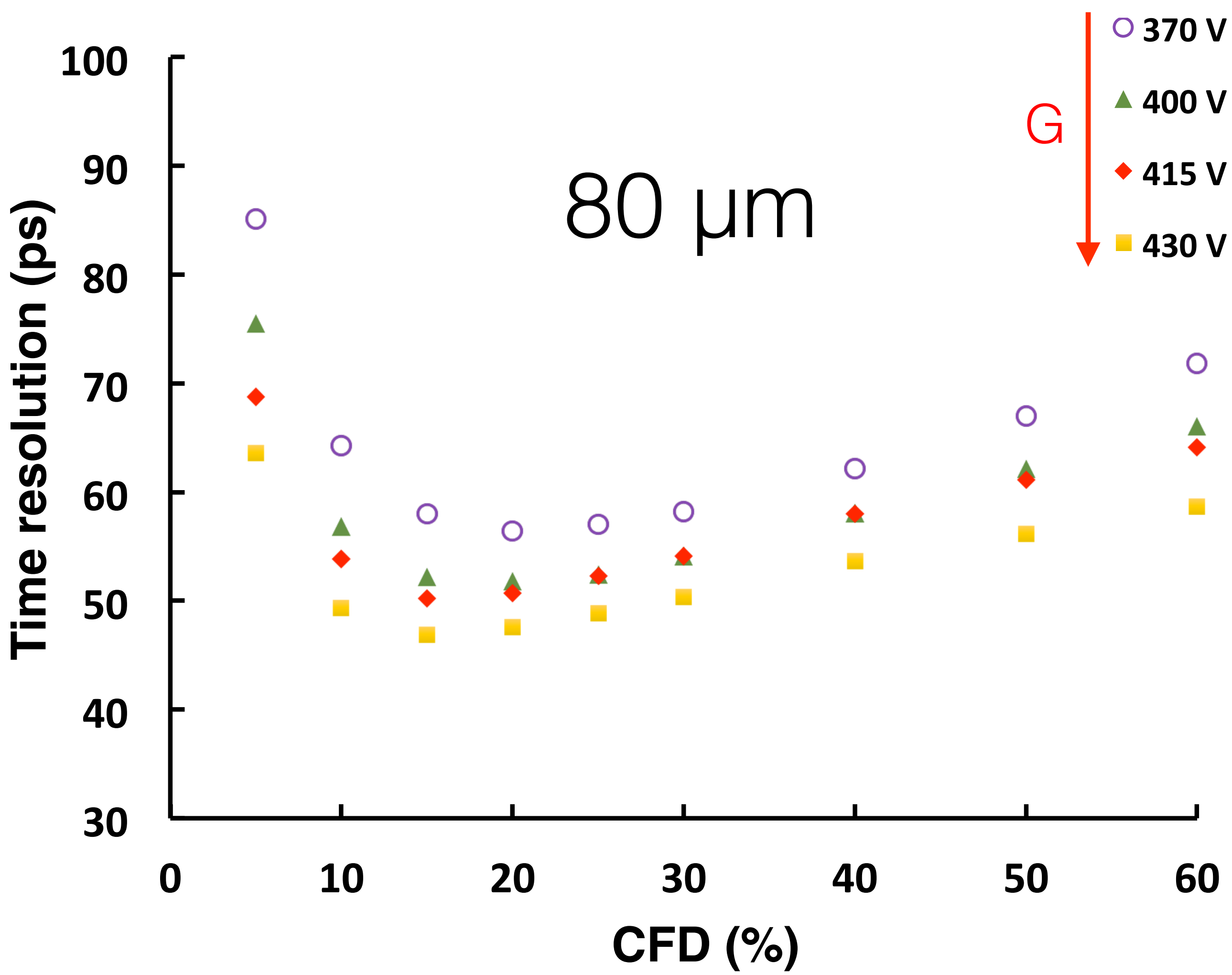
Landau fluctuations —> physical limit to time resolution

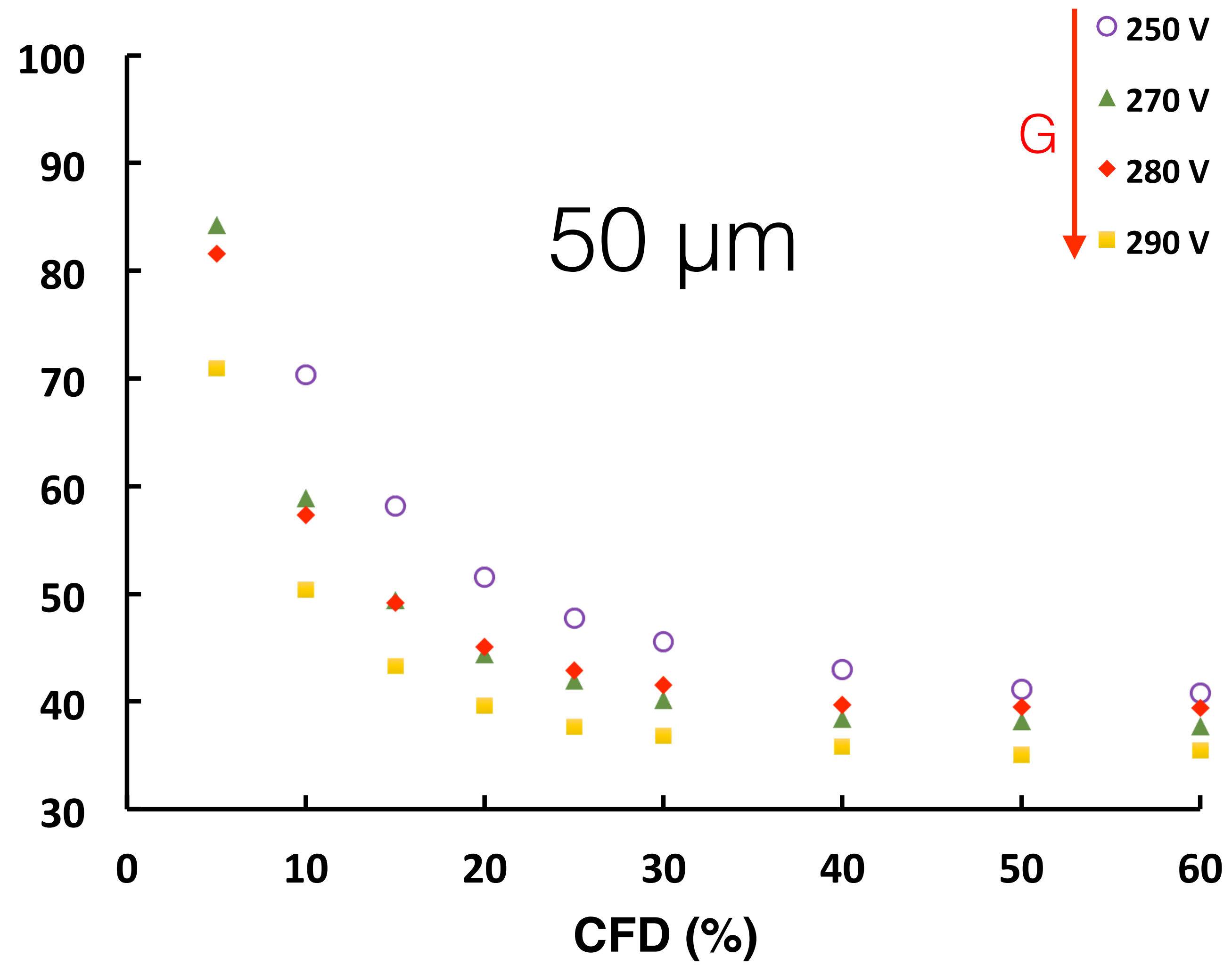


Time resolution

HPK data in a **beam test** setup (H8), at **CERN**

→ time VS CFD (%) for different thickness



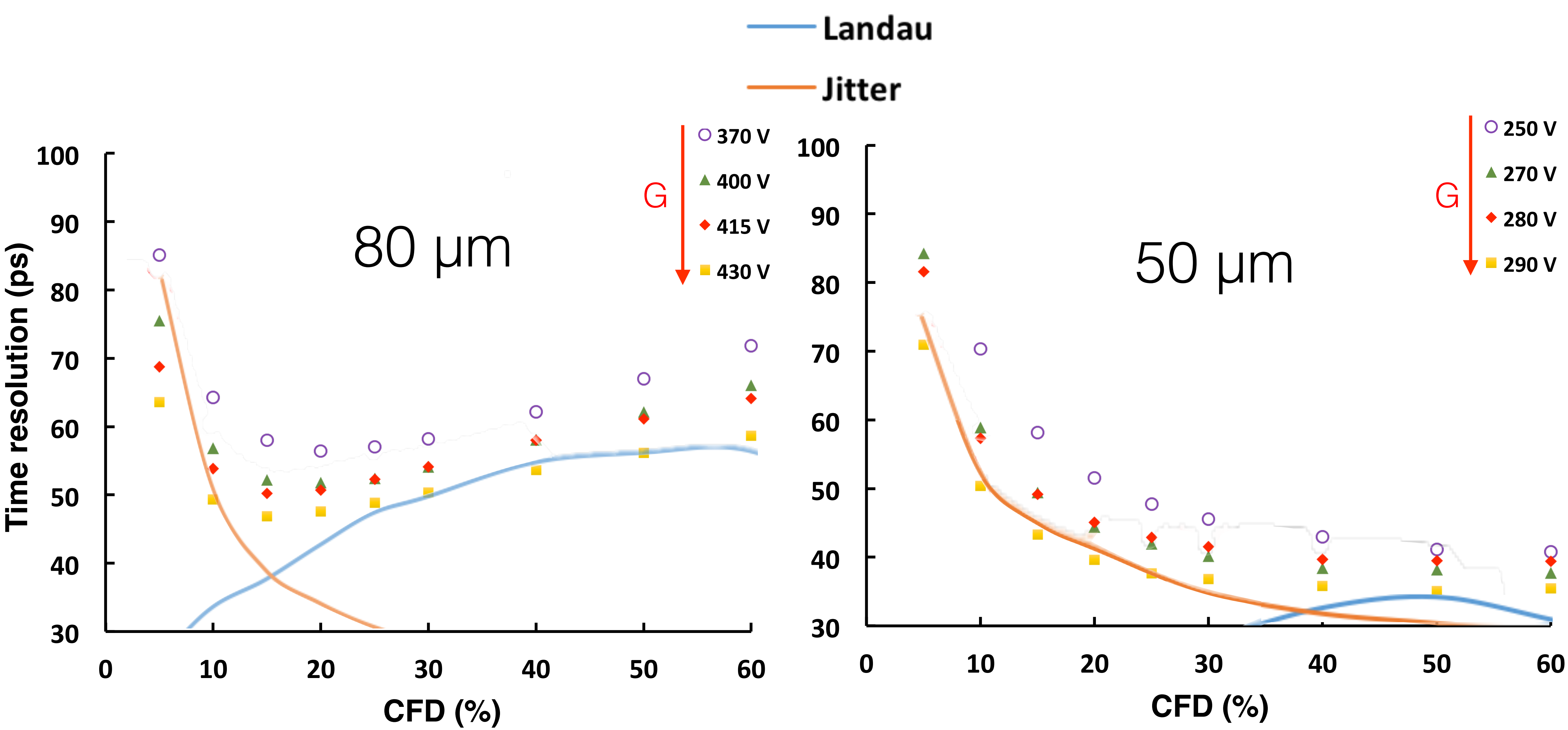


Time resolution

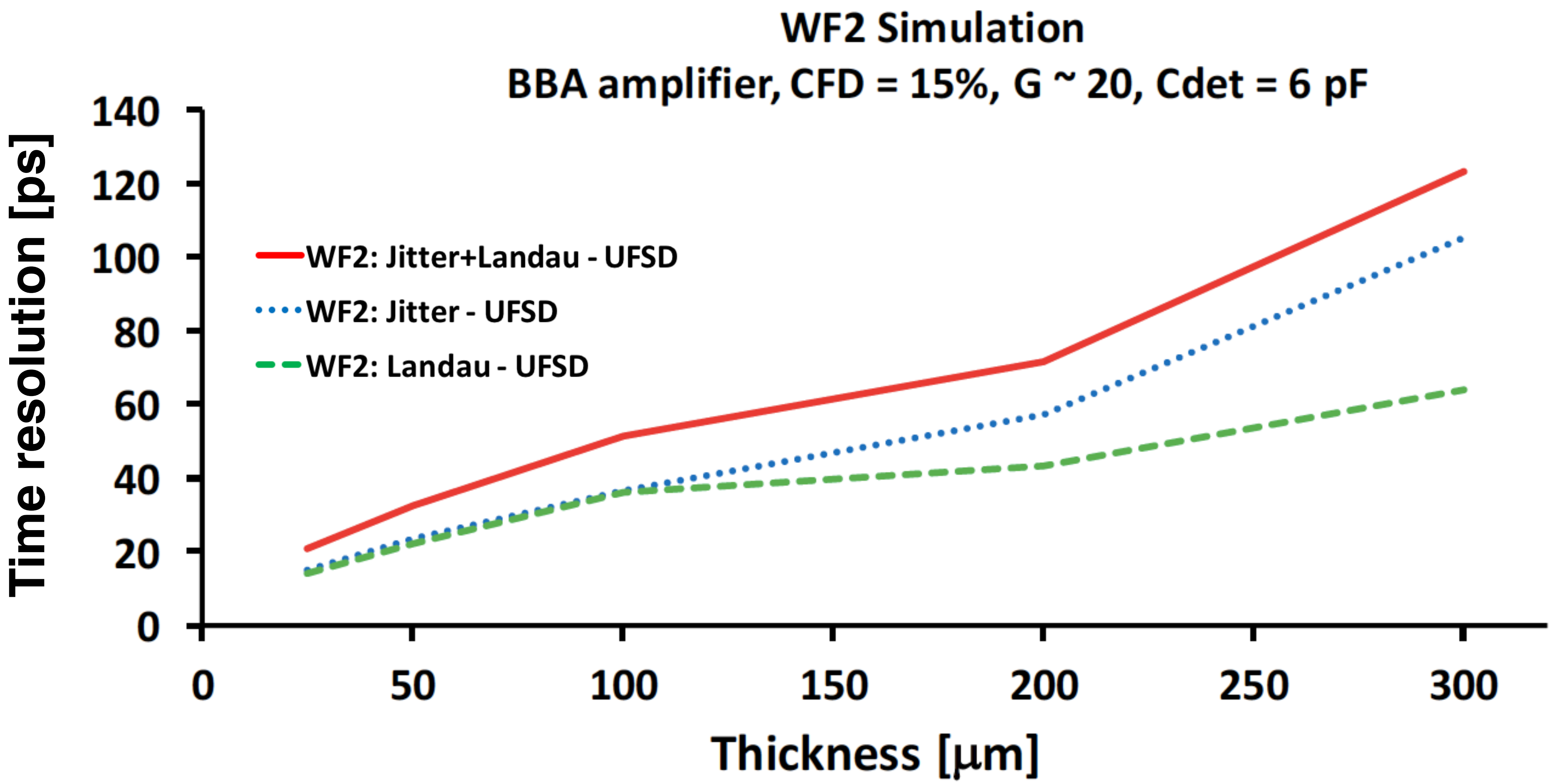
HPK data in a **beam test** setup (H8), at **CERN**

→ time VS CFD (%) for different thickness

→ In **agreement** with expectation



Time resolution



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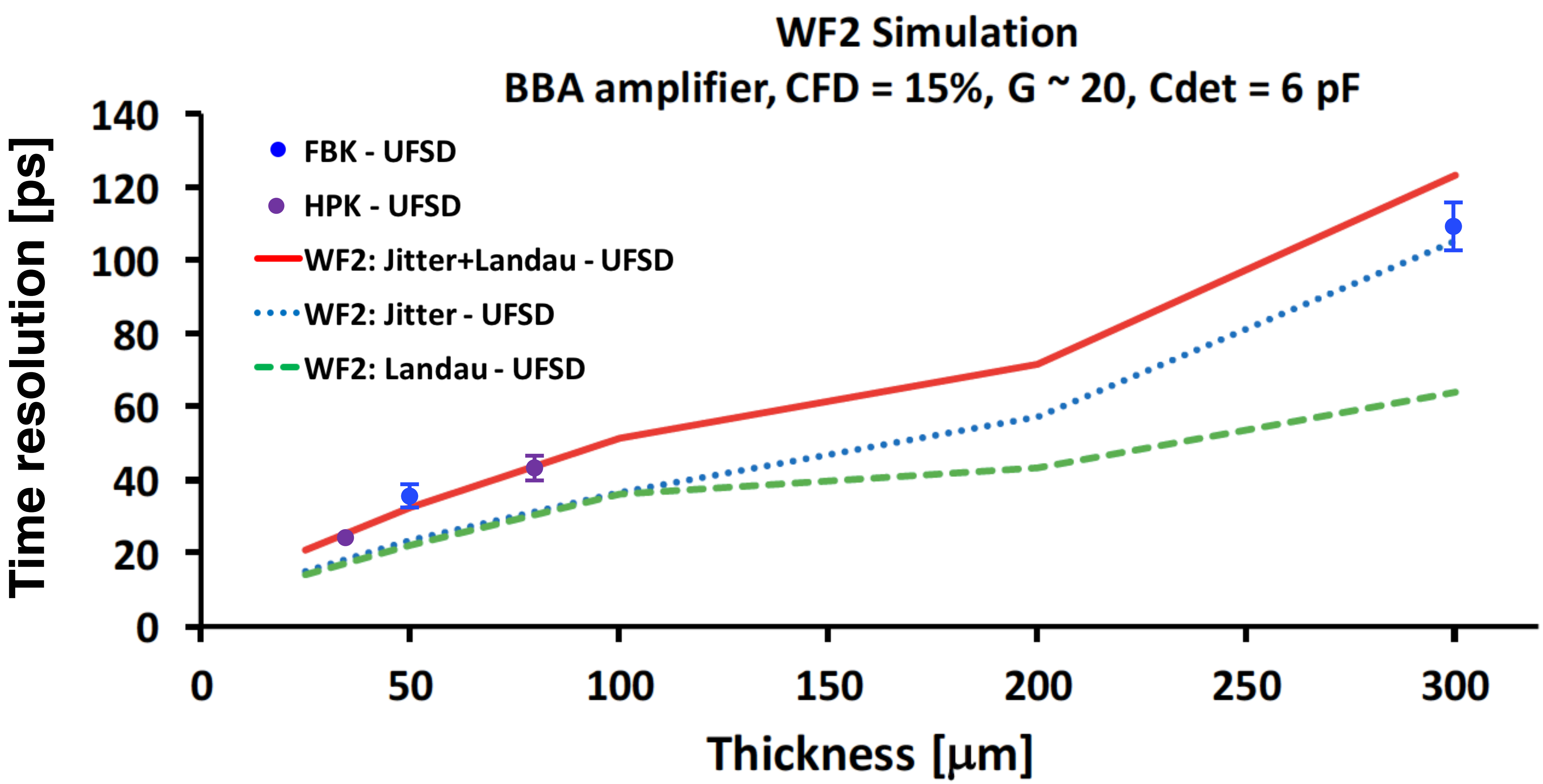

- **Goal reached**
- **Go thin**!
- **BUT** thinner detectors (e.g. **35 *µm***) means larger capacitance and hence smaller signal…**electronic issue**

Radiation hardness

The UFSD should withstand to **2-9 10^{15} n_{eq}/cm^2** ! Several prototypes studied:

- Different **doping concentration**
- Different **temperature diffusion** (LD, HD)
- **Gallium** (Ga) instead of Boron (B)
- **Carbon** (C) co-implanation

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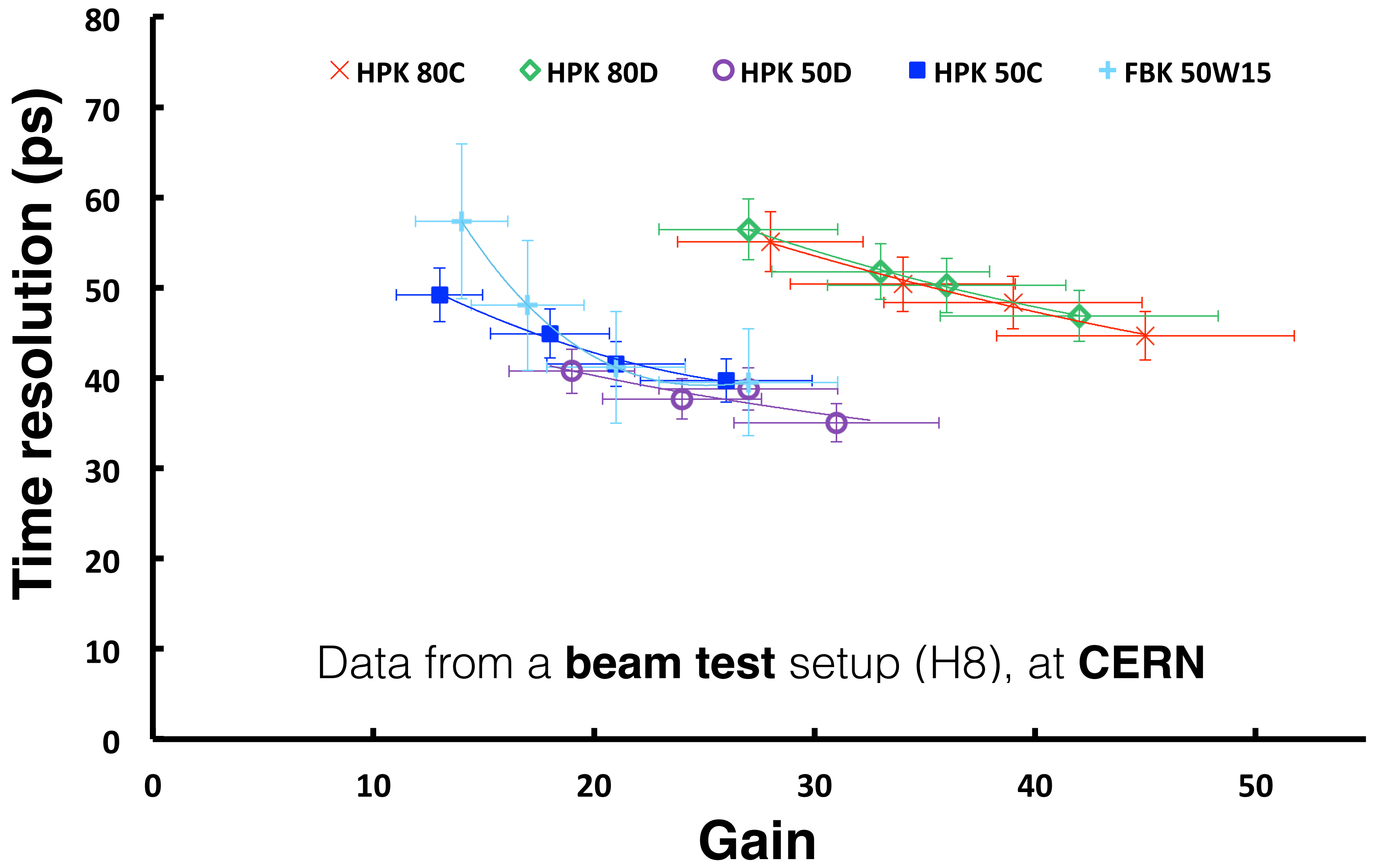


- HPK C, D low and high doping concentration
- FBK W15: Ga + C

Time resolution does not change depending on the several prototypes BUT just on the thickness

Radiation hardness

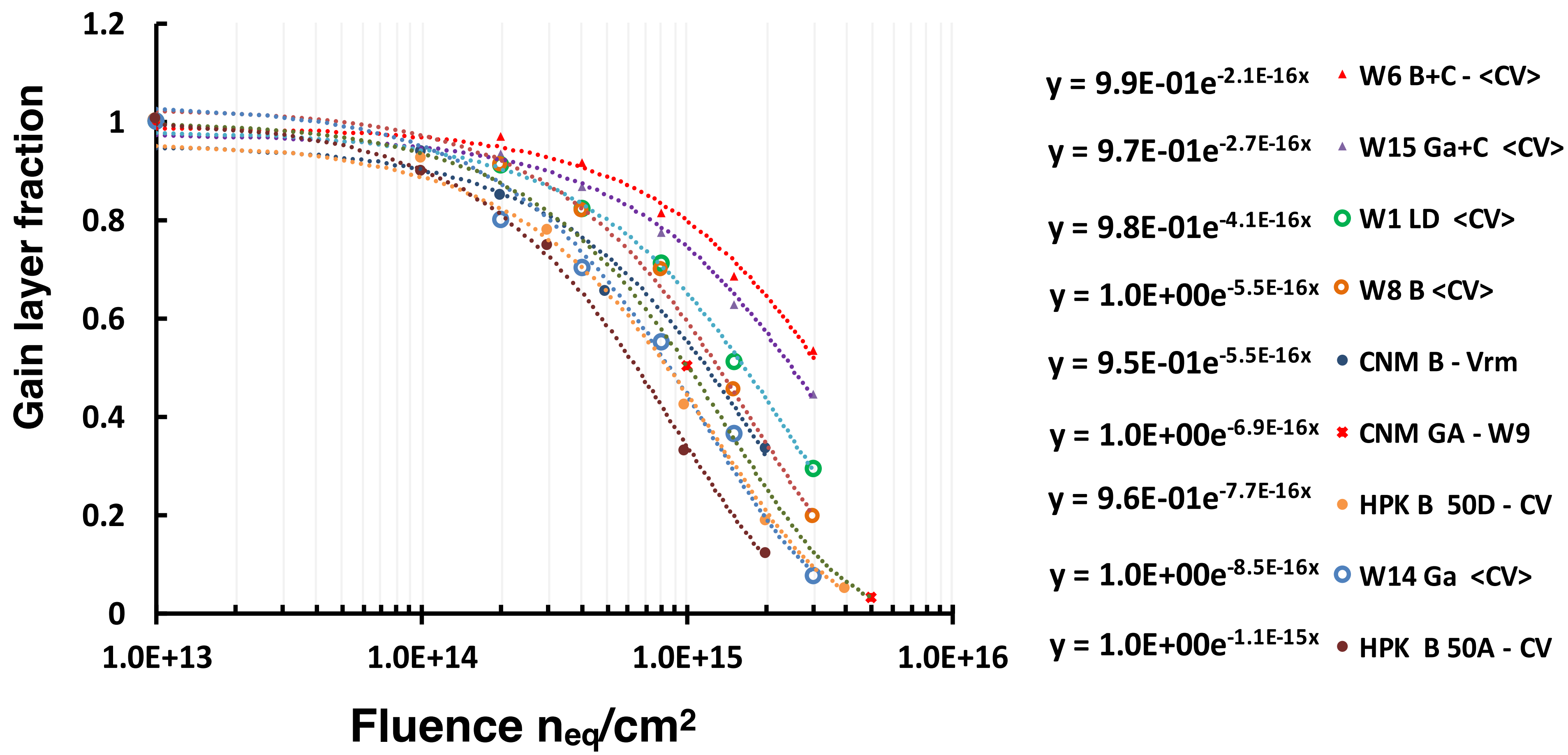
acceptor creation, g_{eff} =0.02 cm^{-1}=const

Acceptor density (N_A) with fluence (ϕ):

$$N_A(\phi) = \boxed{g_{eff} \cdot \phi} + \boxed{N_A(0)\ e^{-c \cdot (N_A(0)) \cdot \phi}}$$

Initial acceptor removal, ***c*** depends on:

- Irradiation type
- **Acceptor types**
- Initial acceptor **density**



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Initial acceptor removal, ***c*** depends on:

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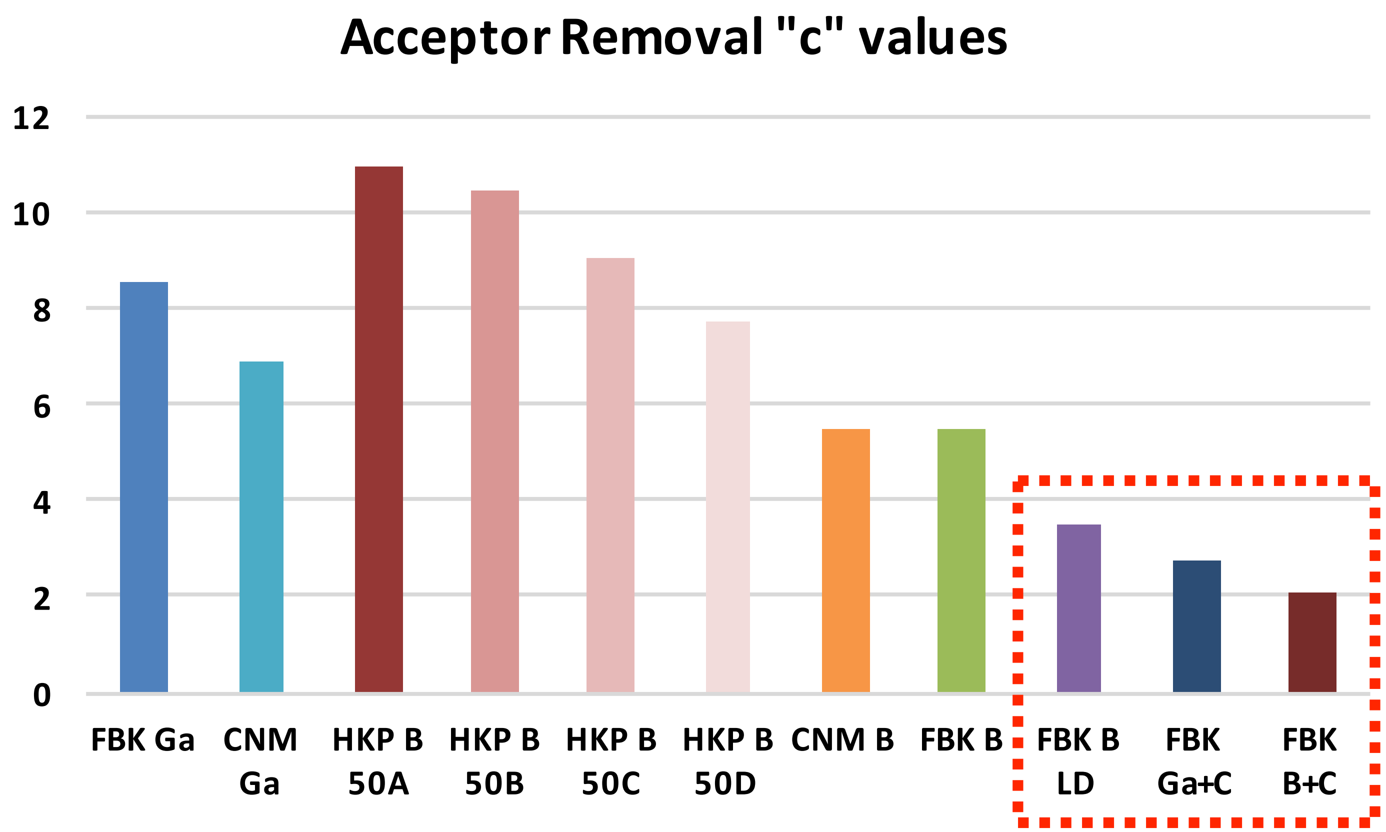
Low *c* ⟶ less gain layer disappearance

⟶ **higher radiation resistance** detector

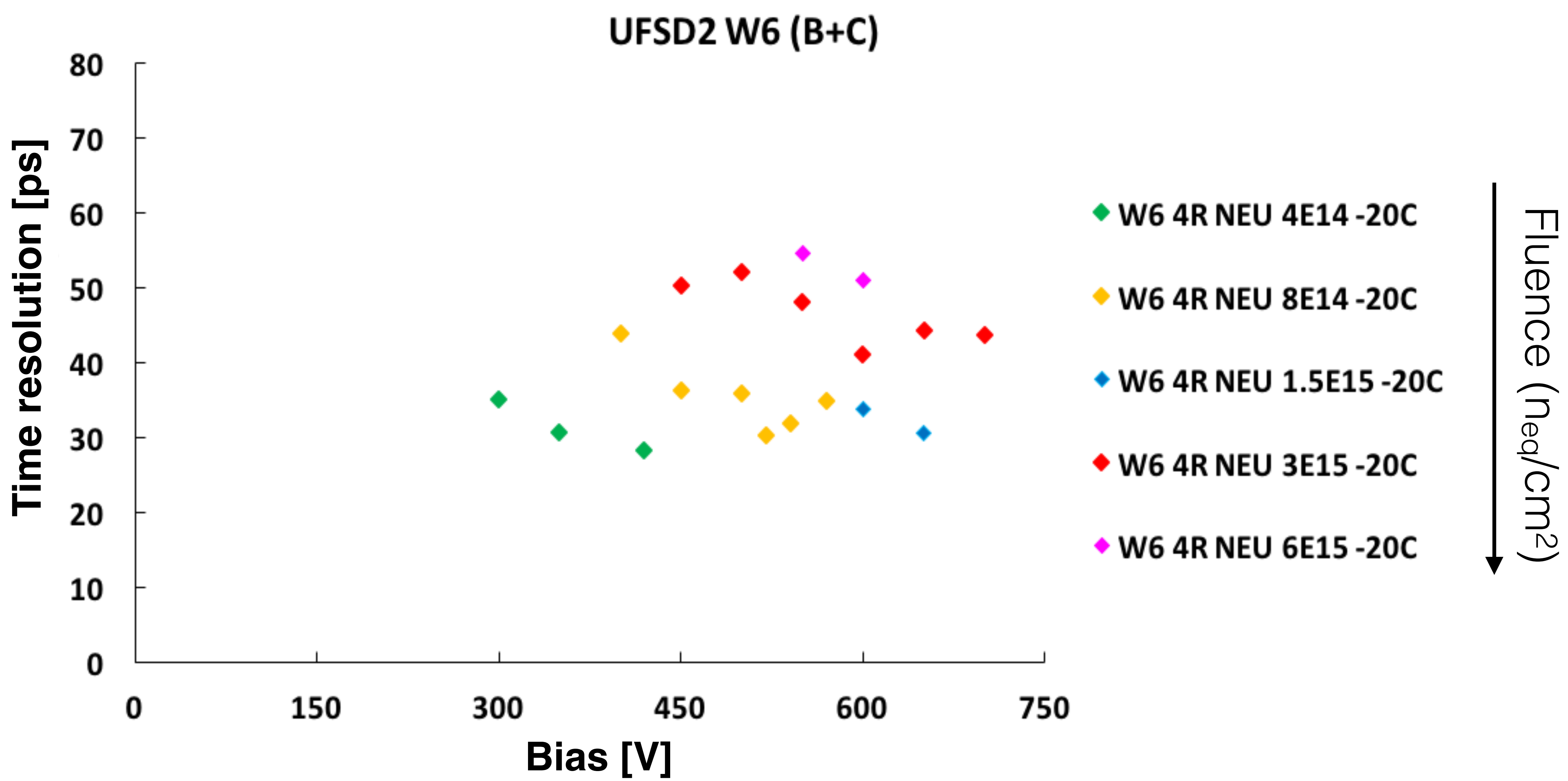


Receipt for a high radiation resistant detector:

- Continue using **Boron**
- Add **Carbon**
- Make the gain layer thin (**LD**)

Radiation hardness

Preliminary results measured with β source, at low temperature, for W6 (**B+C**) in Santa Cruz



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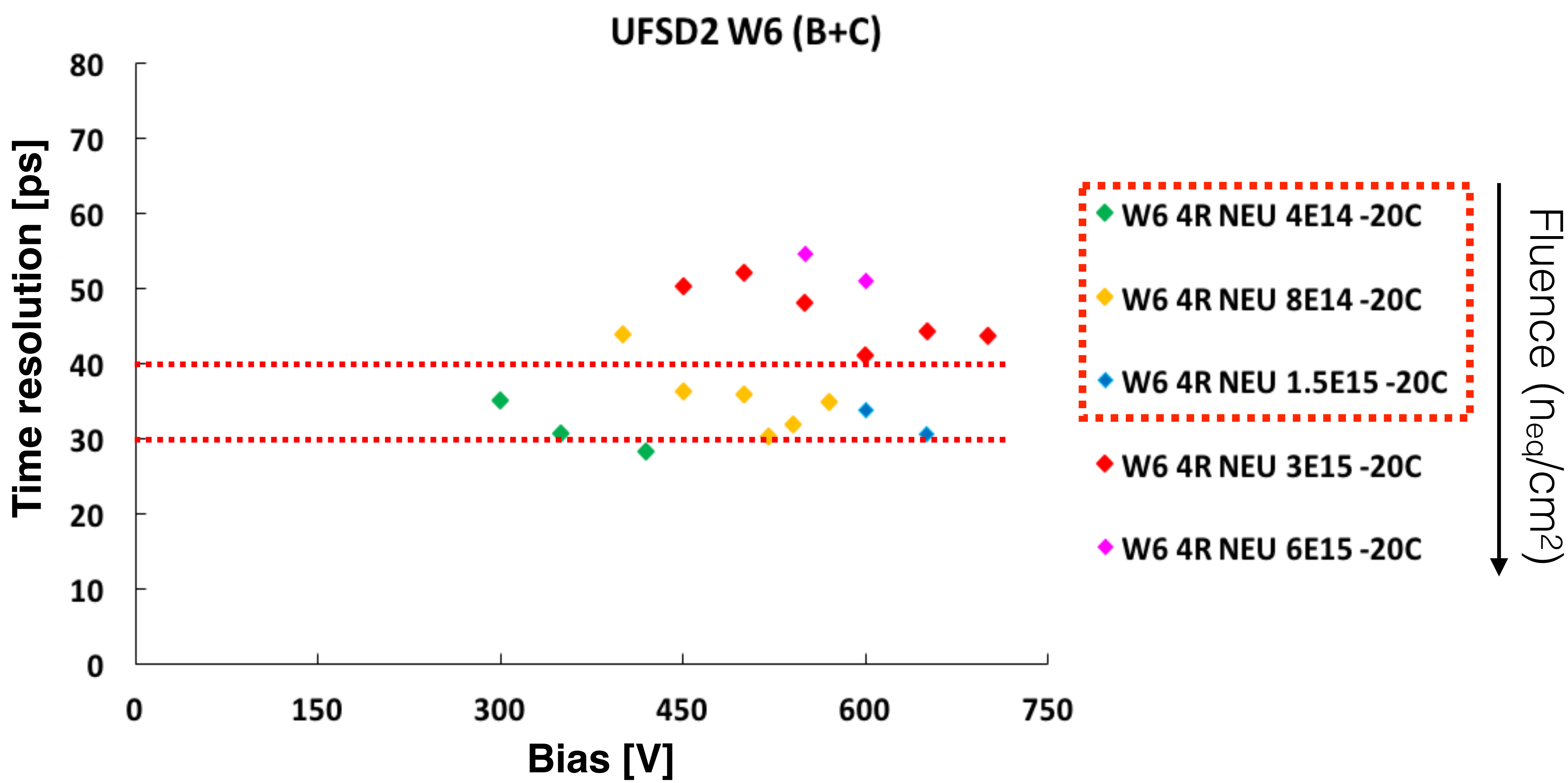
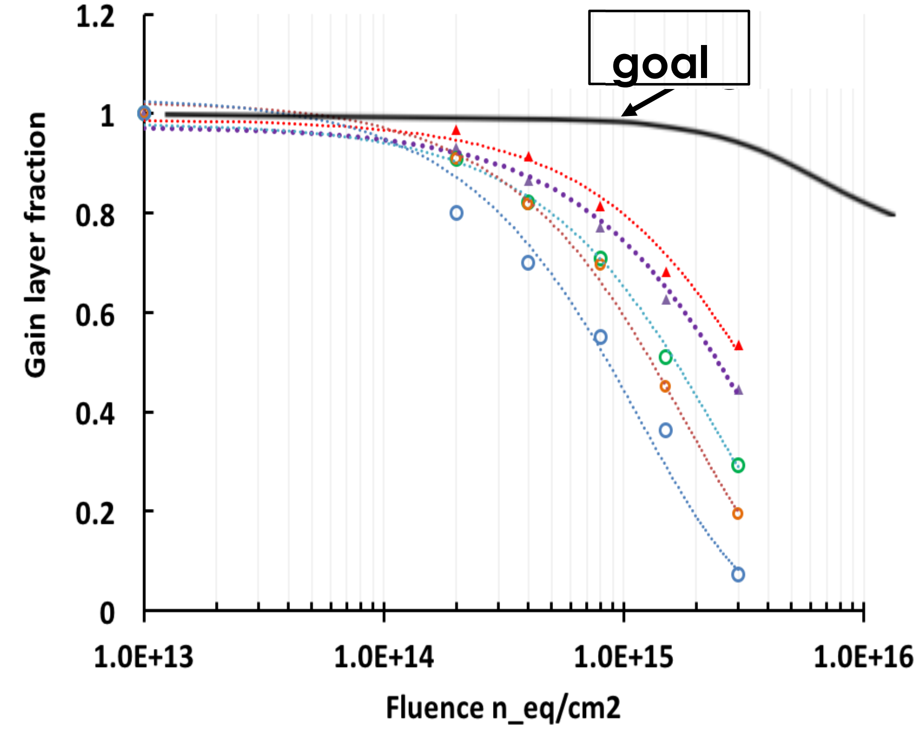


The time resolution, for a 50 µm thickness, is between **30-40 ps** up to a fluence of **1.5 10^{15} n_{eq}/cm^2** !

Future R&D

1. Even higher radiation resistance
2. Lower material budget
3. Monolithic detector

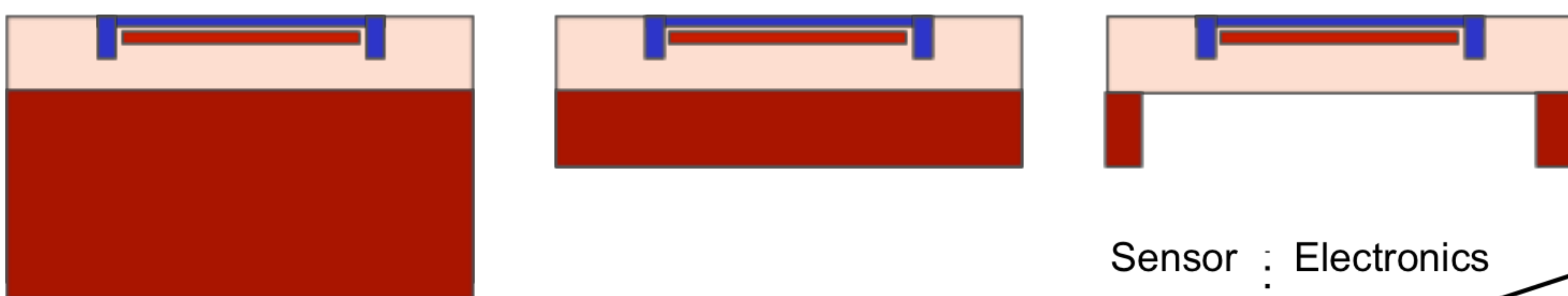
1.



a) Thin LGAD on a thick support wafer

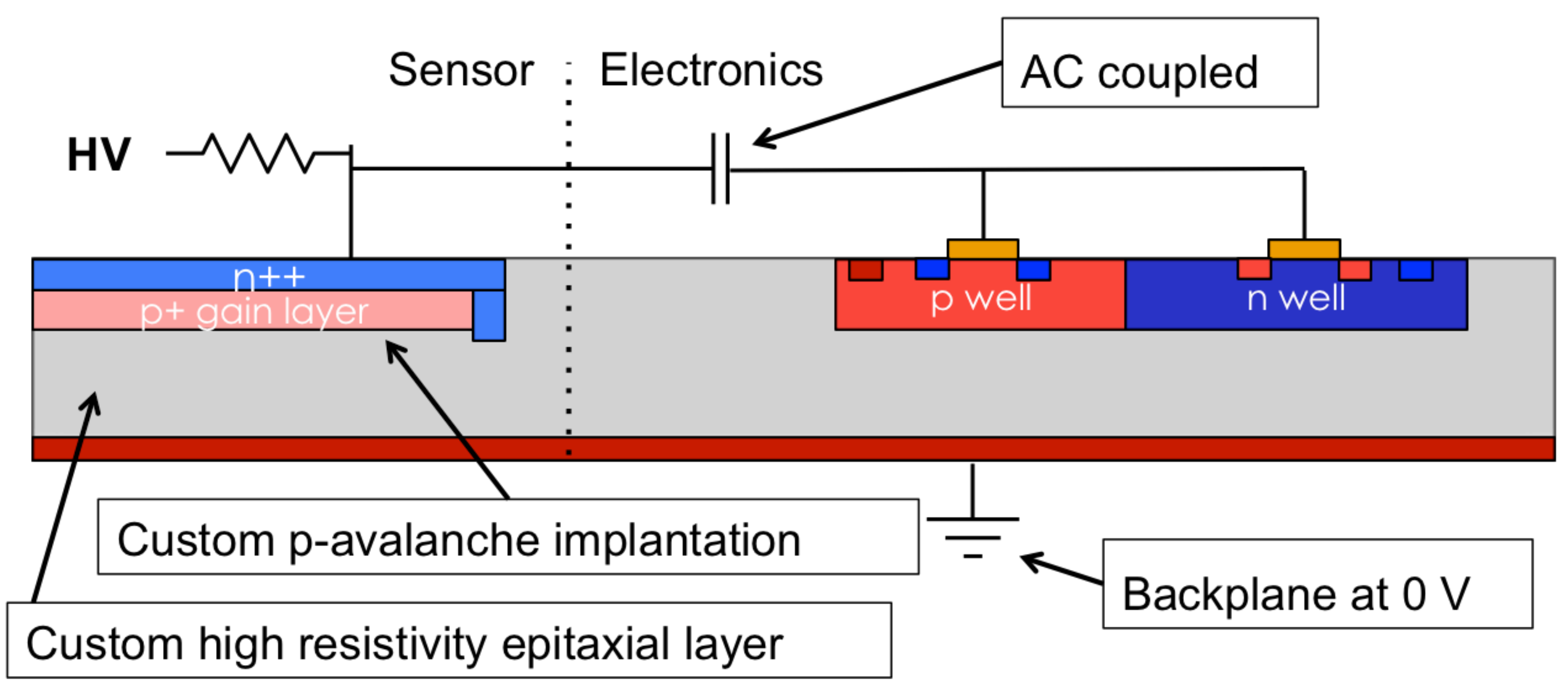
b) Thin LGAD on a thinned support wafer

c) Thin LGAD on ribs



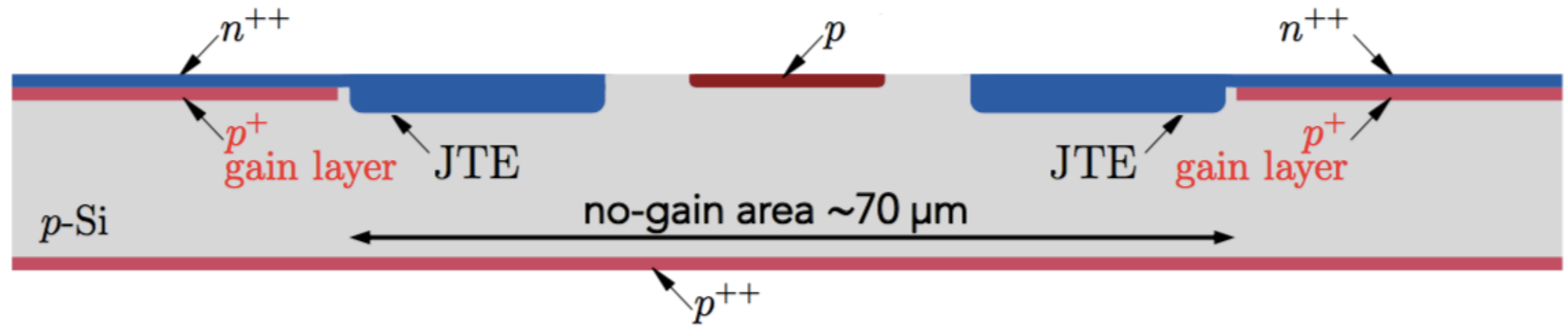
2.

3.



Future R&D

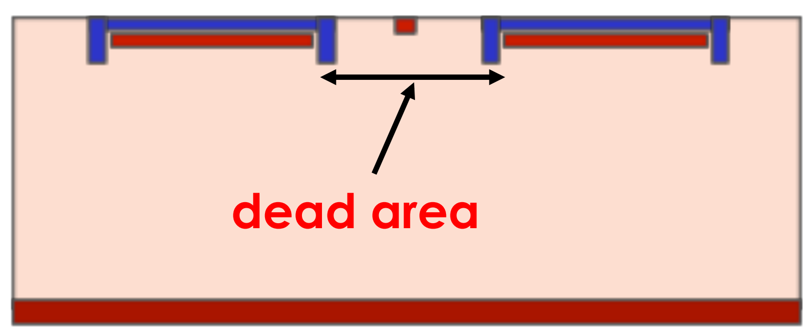
Fill Factor, **actual** situation:
91% (for 3 mm² pad)



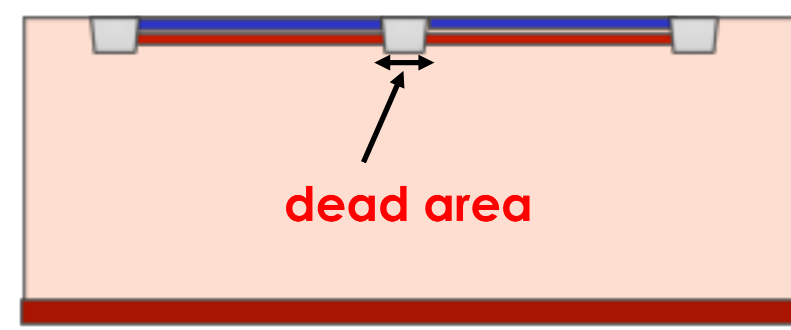
First Idea: optimise the geometry until the physical limit of 30 μm gap. **96%** fill factor.

"*Low Gain Avalanche Diodes for Precision Timing in the CMS Endcap*", Marco Costa, Poster contribution

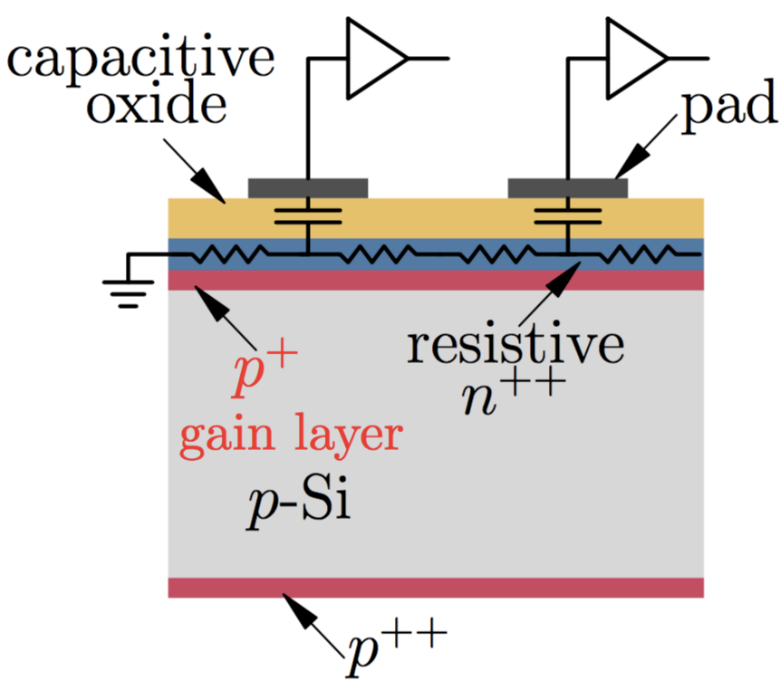
Second Idea: taking example from SiPM, using a trench design. **About 100%** fill factor.



a) JTE + p-stop design



b) Trench design



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

Conclusion

- A **4D tracking** will become **necessary** for the **HL-LHC** to fight against the higher pileup foreseen
  - It can be achieved using the **UFSD**, **based on** the **LGAD** technology, builded nowadays from **three different manufacturer**

- The **time resolution simulations** have found to be totally in **agreement** with experimental data
  - It has **reached the goal of 35 ps** for a **50 μm** (can go to ~23 ps for a 35 μm but readout electronic issue)

- The **UFSD radiation hardness** has been **improved**, thanks to **FBK** UFSD new prototypes: based on a **LD** or **B+C** gain layer
  - The **time resolution**, for a 50 μm thickness, is between **30-40 ps** up to a fluence of **1.5 10^{15} n_{eq}/cm^2**

- The **R&D** on UFSD is still **ongoing** both to **improve** the **radiation hardness** and **other** important **feature** of the detector