Ultra-Fast Silicon Detectors for High Luminosity LHC

Marta Tornago

Second-year seminar

Outlook

- ➤ The **High Luminosity LHC** challenge
- ➤ A timing layer for CMS: **the Minimum Ionizing Particles Timing Detector**

- ★ **Ultra-Fast Silicon Detectors for the CMS Endcap Timing Layer**
  - ★ **Laboratory measurements results**

- ✦ The **simulation** of the Endcap Timing Layer geometry

- ➡ An evolution of UFSD design: **Resistive AC-Coupled Silicon Detectors**

The High Luminosity LHC challenge

HL-LHC: instantaneous luminosity will increase by a factor 5

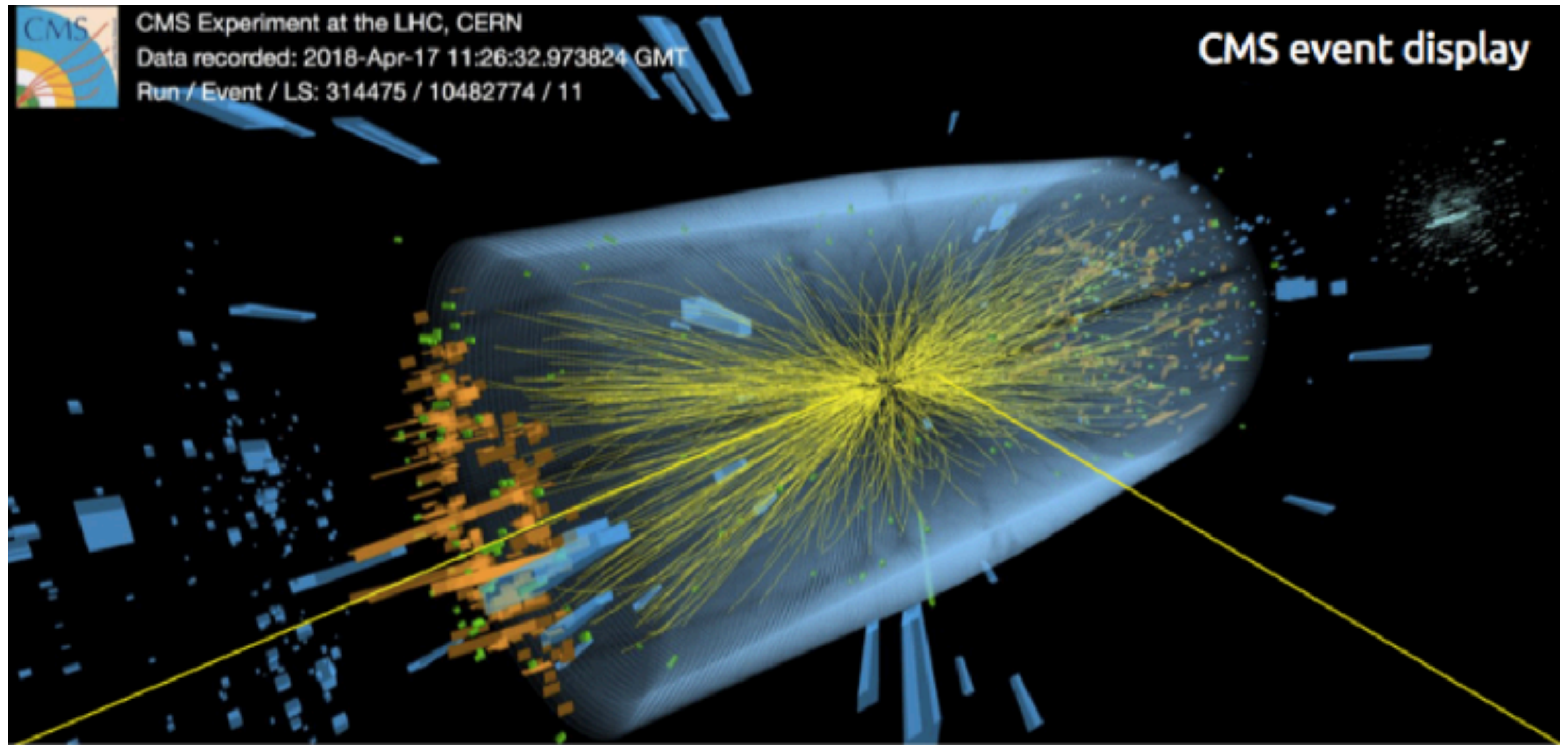
→ *At LHC 30-50 proton-proton collisions per bunch crossing (every 25 ns)*

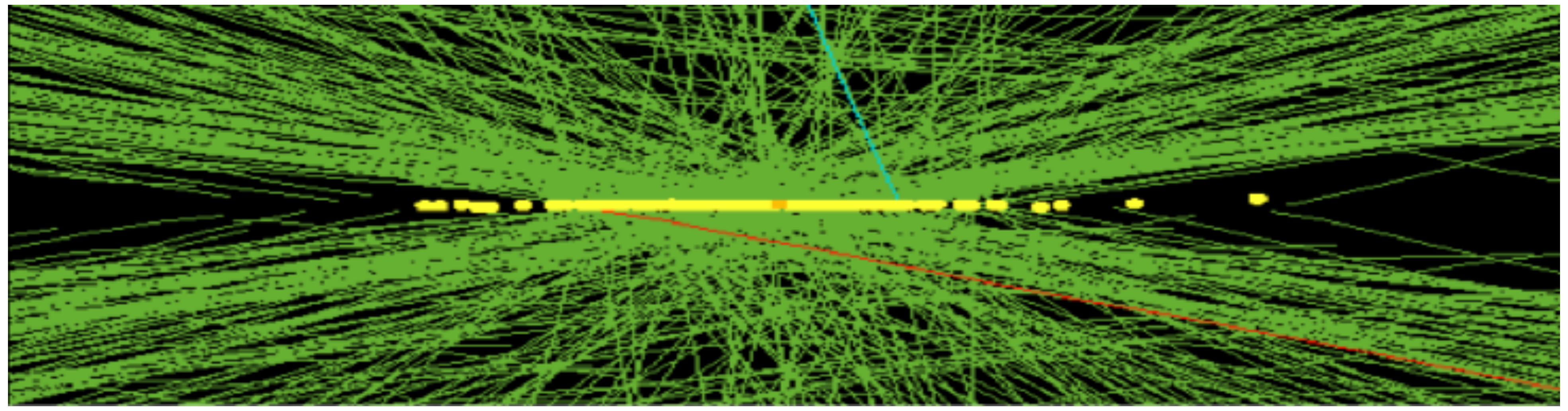
→ *140-200 proton-proton collisions per bunch crossing*

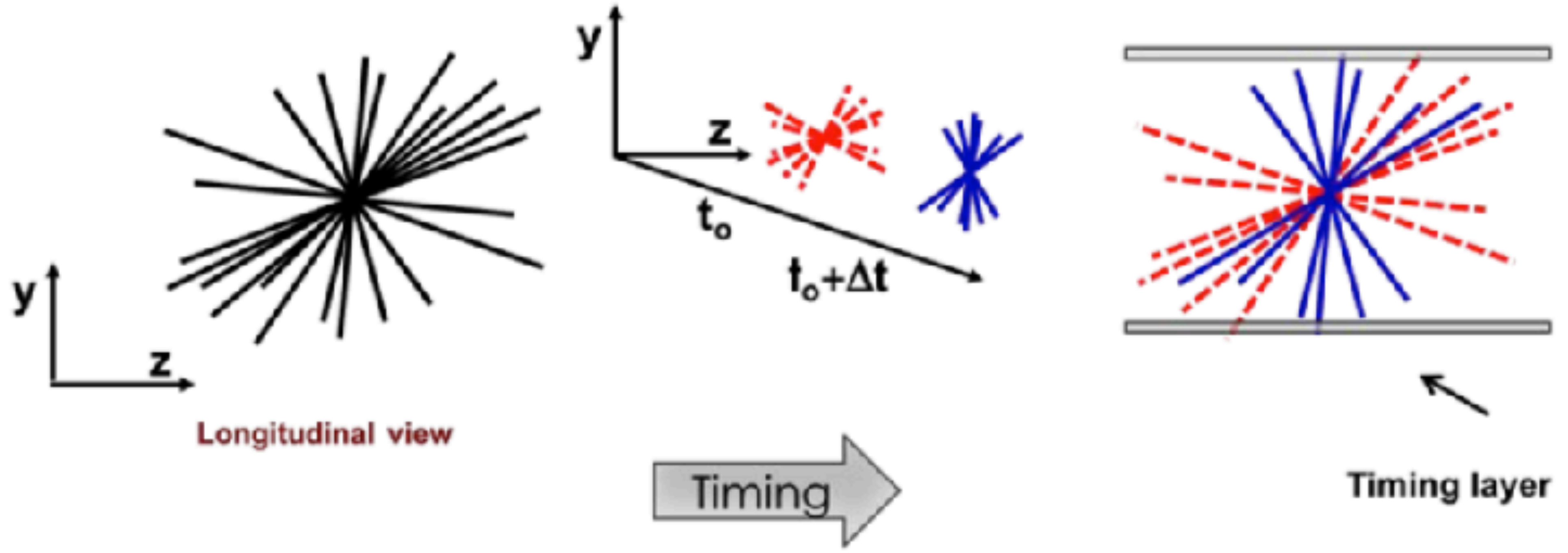
→ *Duration of a proton-proton collision: 150 ps*

The CMS detector needs to maintain its excellent performance:

- *Additional timing information to distinguish events seen by the tracker as overlapped in space but occurring at different moments in time ($\sigma_t \sim 150ps/5 = 30ps$)*
- *Creation of a new Timing Layer for CMS*

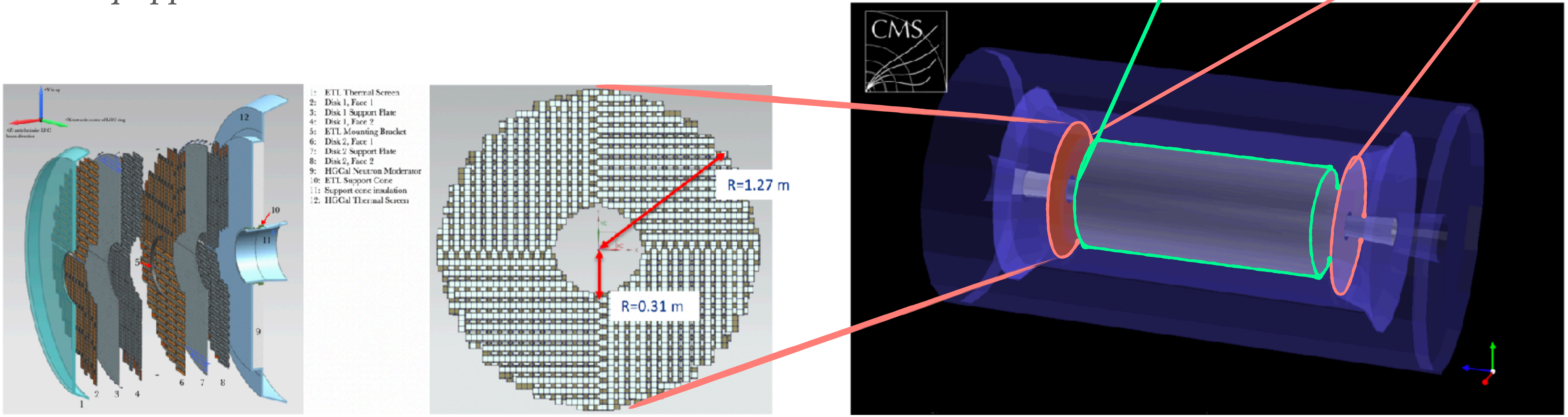




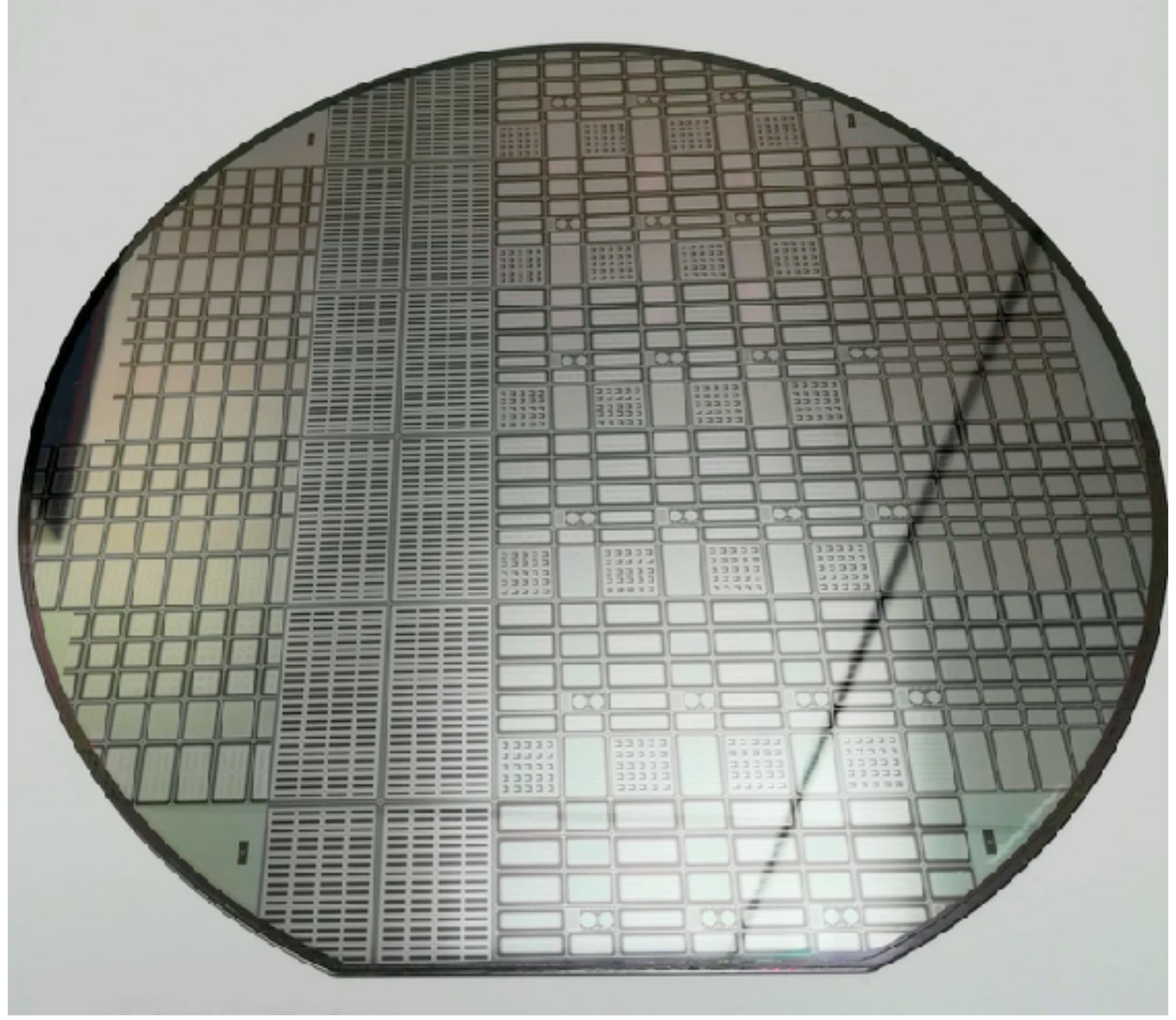


A Timing Layer for CMS

- *Timing layer: timing information associated to reconstructed tracks*
- *Minimum Ionizing Particles (MIP) Timing Detector: 38 m^2 barrel region (BTL) +14 m^2 endcap (ETL)*
- *BTL instrumented with LYSO crystals+SiPM*
- *ETL equipped with Ultra-Fast Silicon Detectors*



Ultra-Fast Silicon Detectors



Timing resolution of traditional silicon detectors is too large for experiments at HL-LHC $(\sigma_t \sim 150/200\ ps)$

→ *Need to develop* ***new sensors for timing measurements***

Ultra-Fast Silicon Detectors *is a project born in Torino in collaboration with the Fondazione Bruno Kessler and the University of Trento*

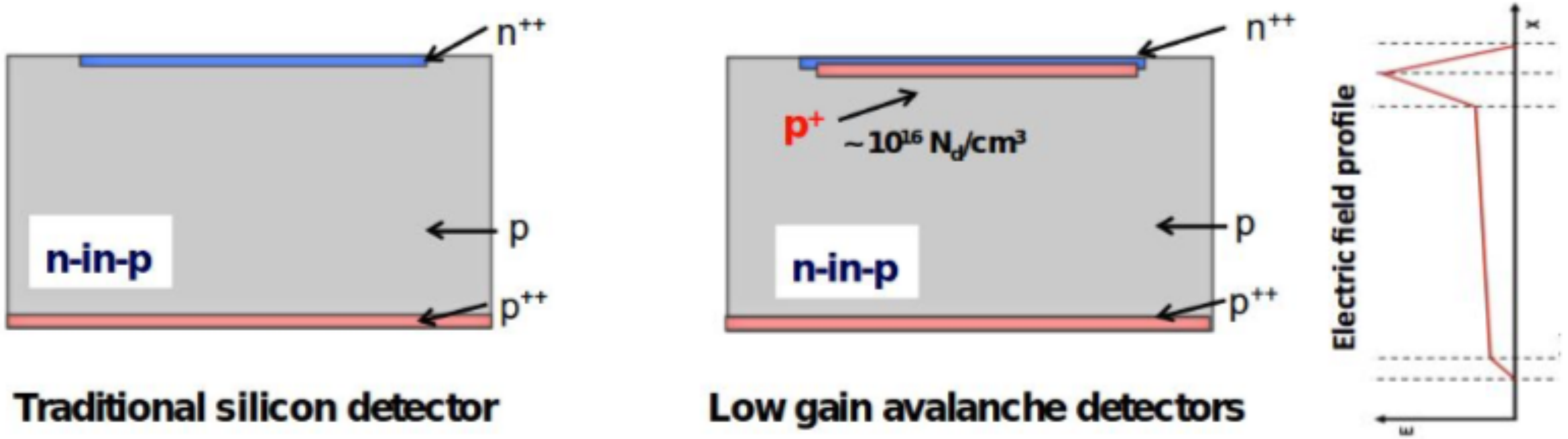
The goal is to develop innovative silicon detectors with an ***excellent timing resolution*** *by adding a* ***gain mechanism***

Batches: UFSD1 (2016), UFSD2 (2017), UFSD3 (2018), UFSD3.1 (2019), UFSD3.2(2020), UFSD4 (2021)

Low Gain Avalanche Diodes

UFSDs are based on the **Low Gain Avalanche Diode** (LGAD) technology

LGADs are silicon detector with a moderate internal gain



- *inversely polarized device*
- *Thin highly-doped layer placed near the p-n junction (**gain layer**)*
  - → *High local electric field, **primary charges multiplication***
- *Gain factor must be **moderate** in order to prevent multiplication noise from being dominant*
  - → ***Signal/noise ratio maximization***

Timing resolution

UFSDs are LGADs optimised for timing measurements

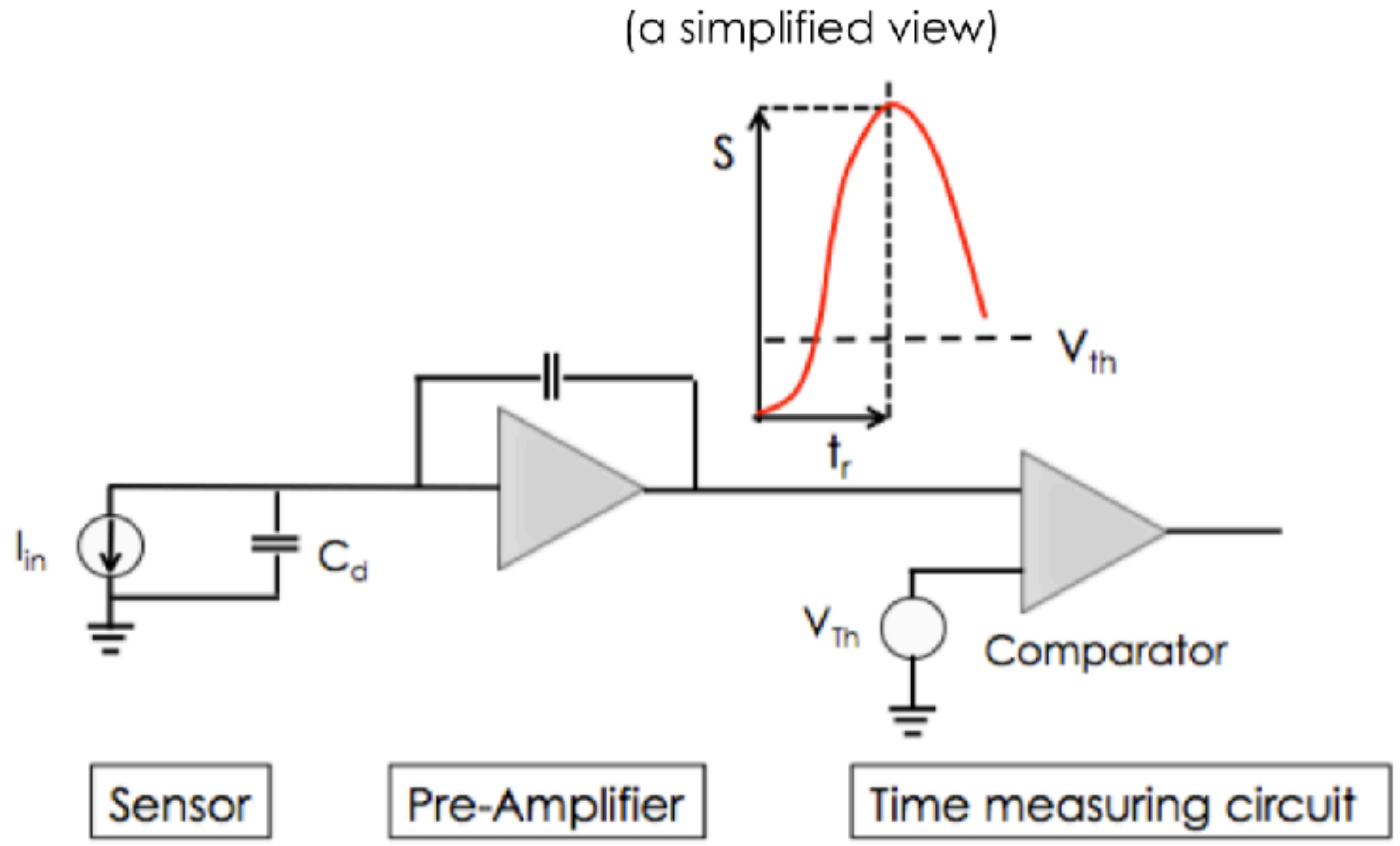
$$\sigma_t^2 = \sigma_{\mathrm{non-uniform\ ionization}}^2 + \sigma_{\mathrm{jitter}}^2$$

$$\sigma_{\mathrm{Jitter}} = \frac{N}{dV/dt}$$

Term minimized with:

- *Low noise* → *Low noise electronics + moderate gain*
- *High dV/dt* → *Gain + thin sensors*

Minimized with thin sensors



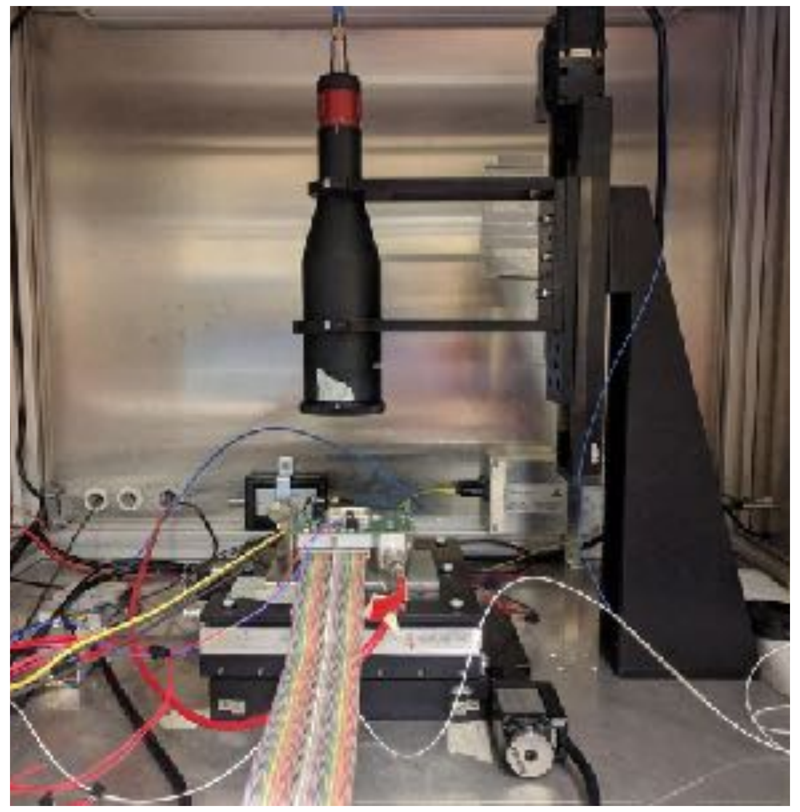
The perfect sensor for CMS

On the hardware side, my PhD project includes the journey from the studies for the ***development of a single sensor*** *to the production of the* ***final batch*** *of the detector for the CMS Endcap Timing Layer*

Requests from the ***Endcap Timing Layer*** *(ETL):*

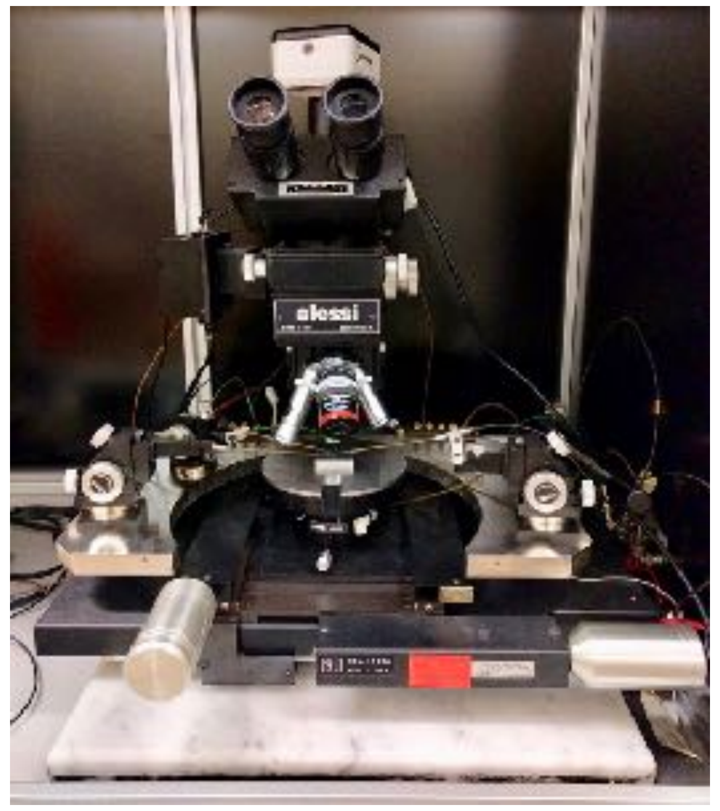
- *Total timing resolution of* $\sigma_t \sim \mathbf{30ps}$
- ***gain uniformity*** *of large sensors*
- *sensors providing* ***large and uniform signals****, with delivered charge >8 fC when new, >5 fC for irradiated*
- ***low leakage current*** *to limit power consumption and noise*
- *sensors* ***resistant to radiation fluences up to*** $\phi \sim \mathbf{10^{15} n_{eq}/cm^2}$
- *total detector coverage >95%* → *sensors with narrow inactive interpad area* $< 50\ \mu m$

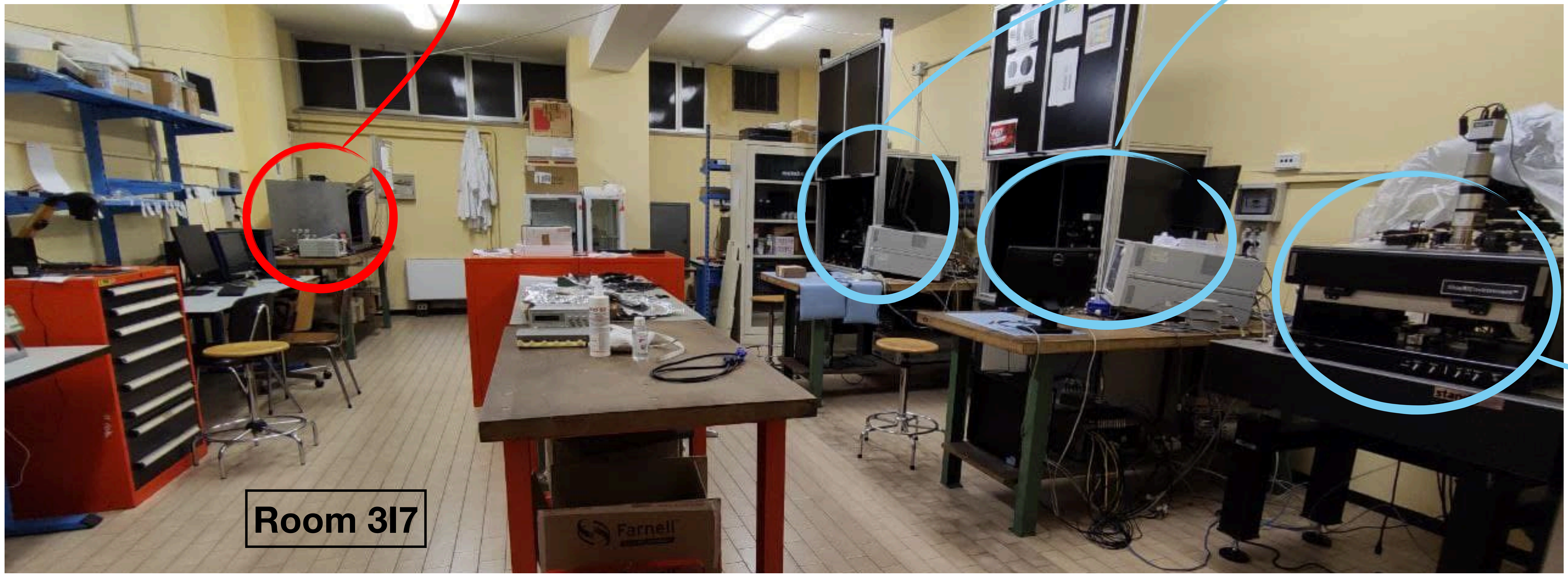
Laboratory for Innovative Silicon Sensors (LISS)



Transient Current Techniques setup: laser measurements

Probe stations for electrostatic characterization

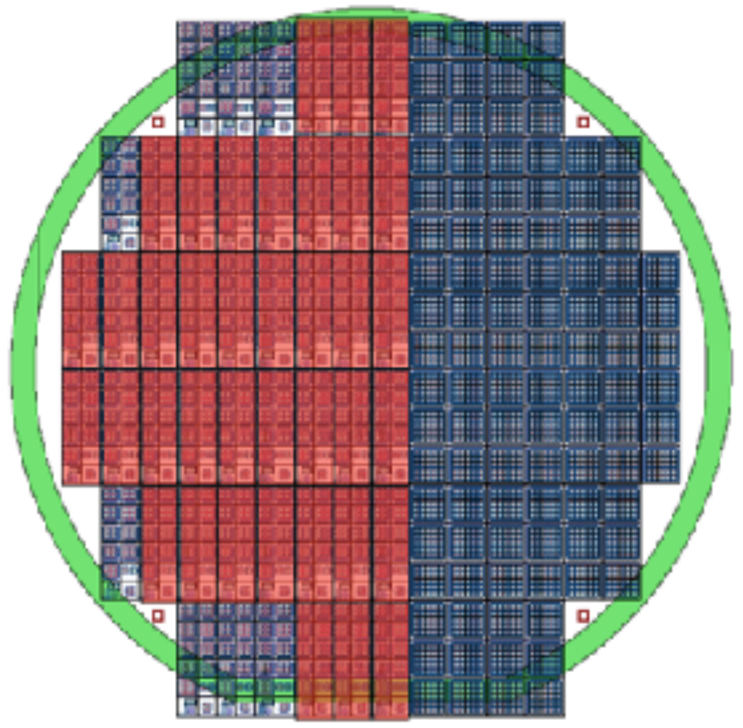




Cold probe station for studies on irradiated sensors

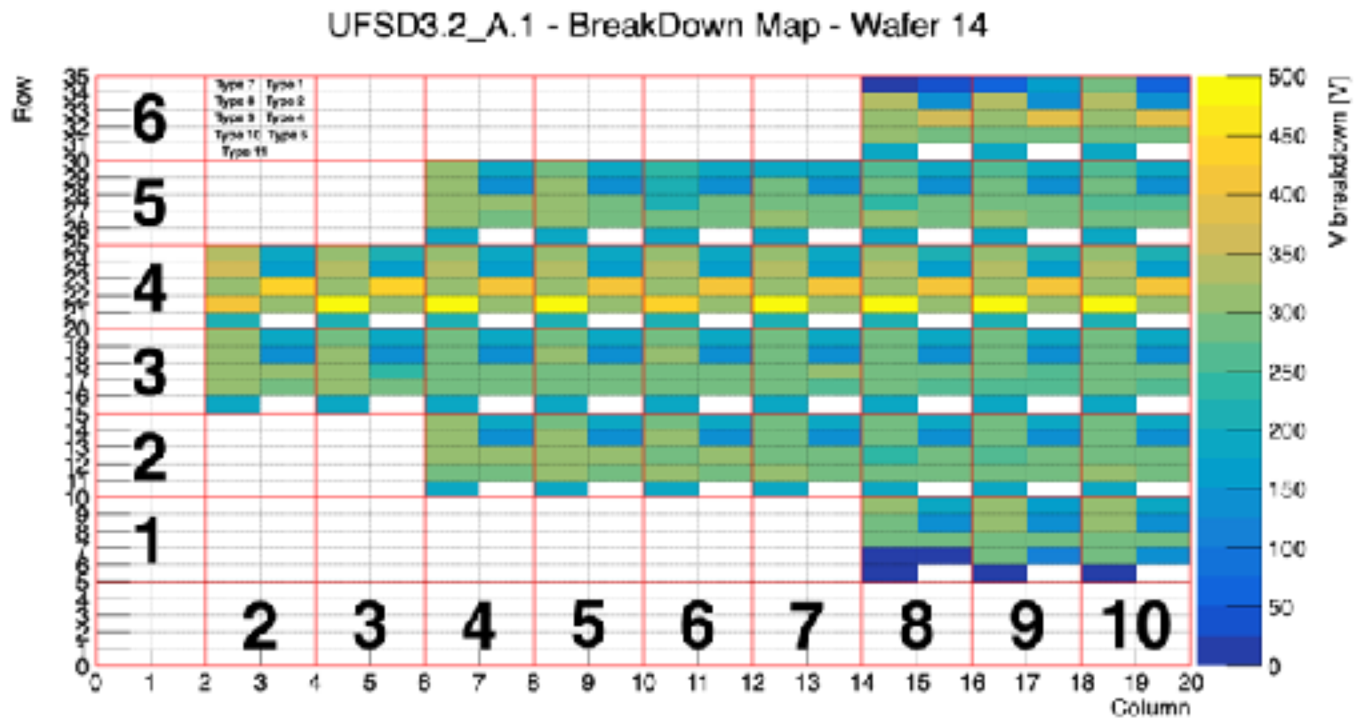
Laboratory measurements: uniformity

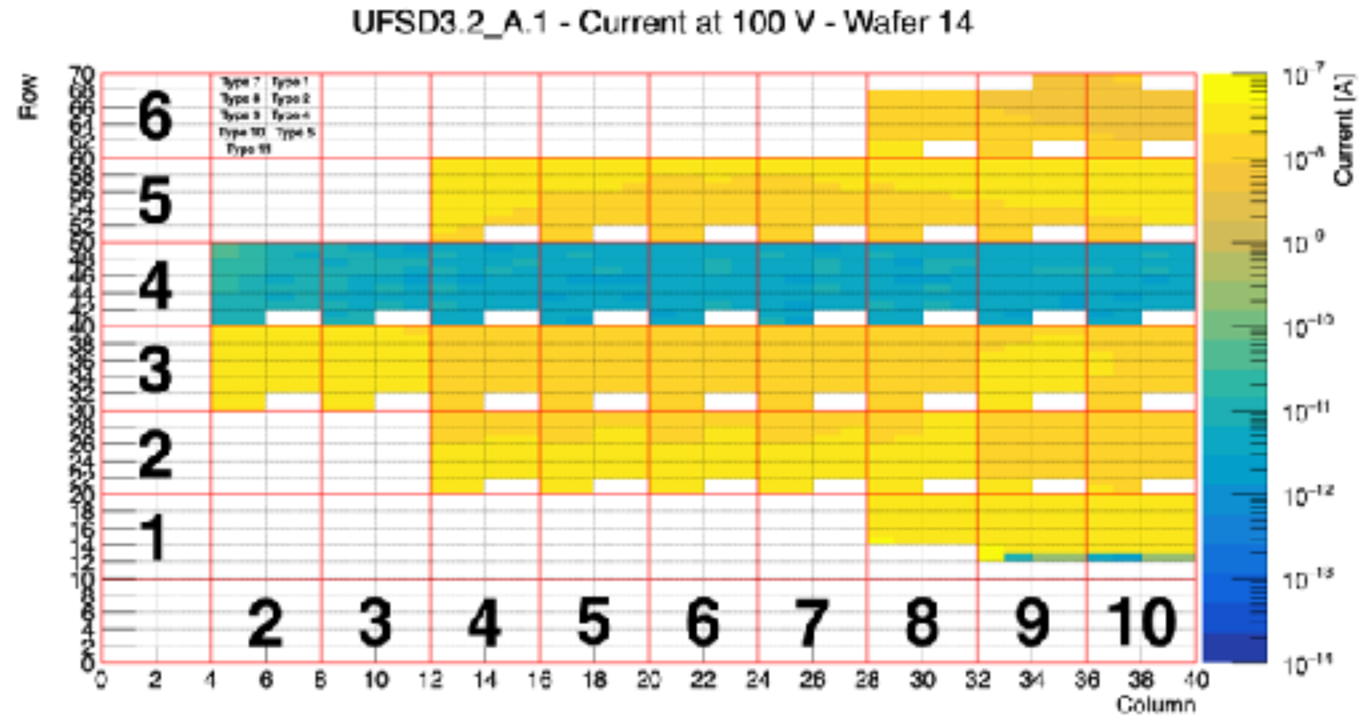
*Devices are tested **on wafer** at FBK and as **single structures** in Torino*

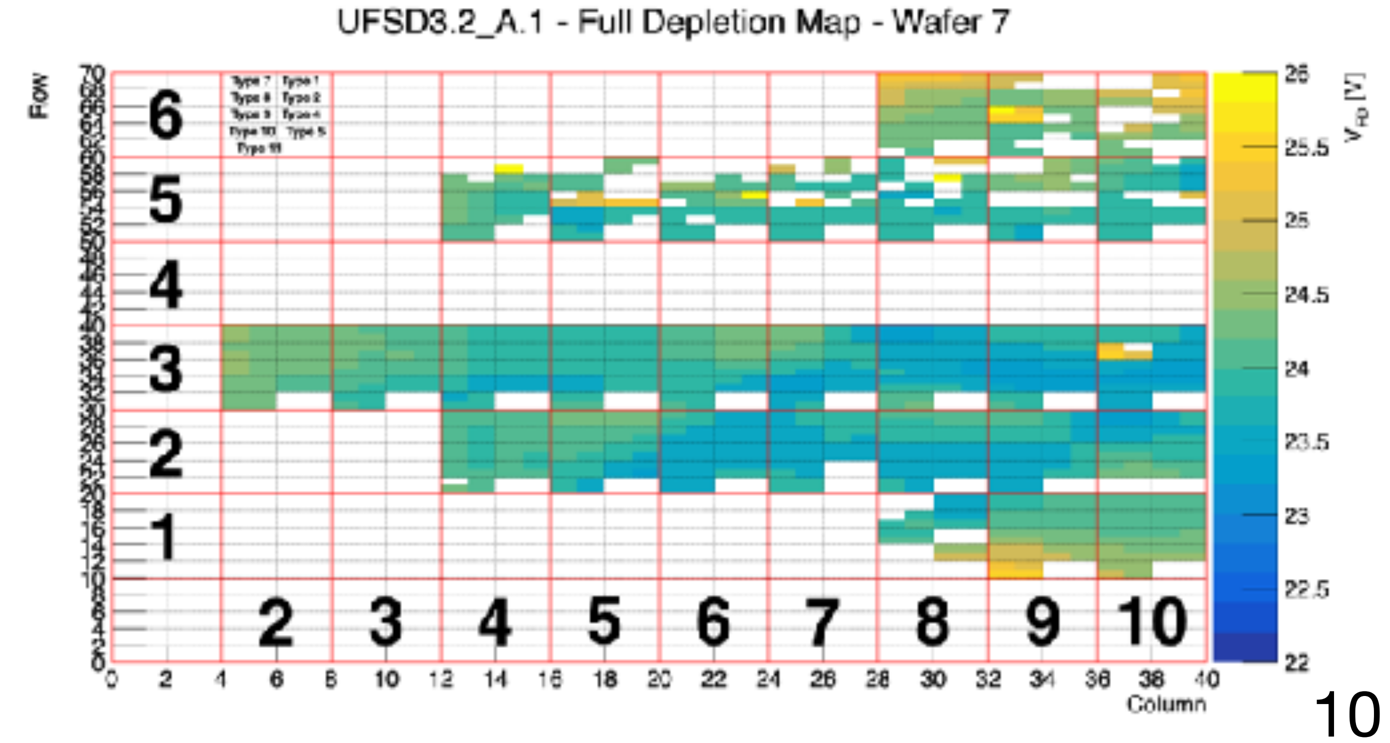


For each wafer and device type we consider:

- ***breakdown** maps and distributions for every structure or pad*
- ***leakage current** distributions of every single pad at **a fixed value of bias***
- ***depletion voltage** distributions of each pad, extracted from C(V)s*







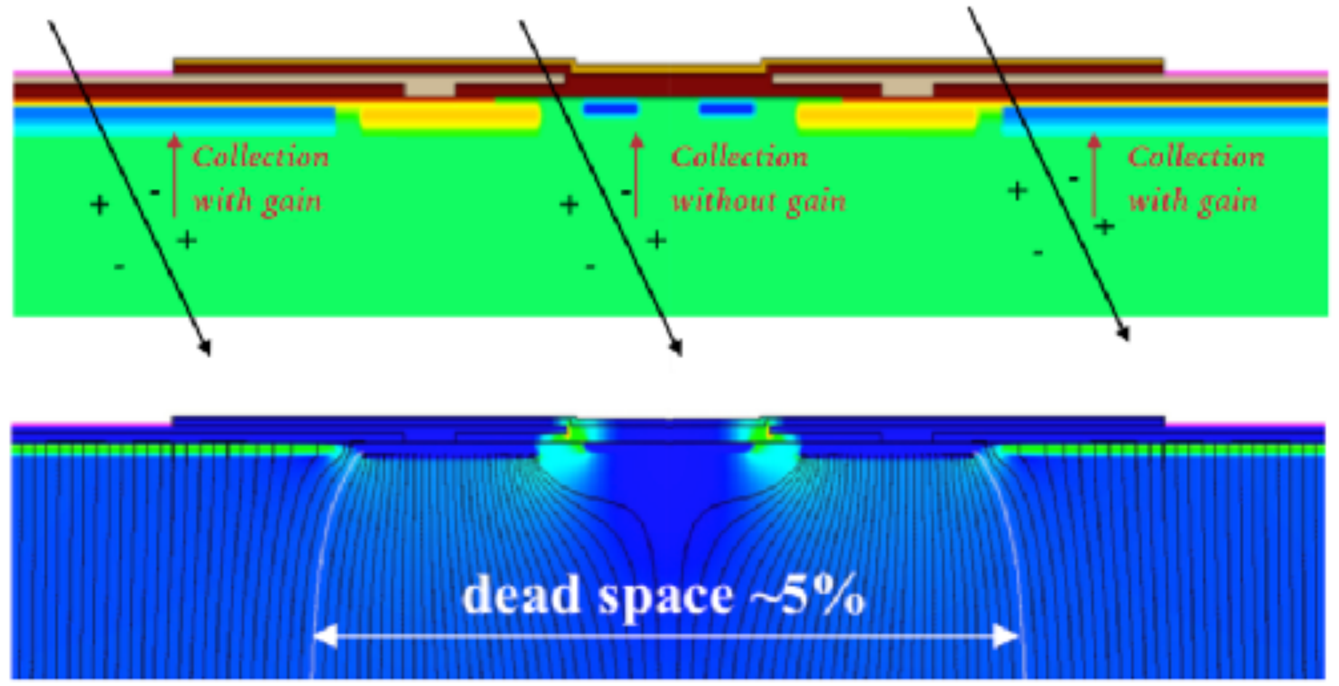
***Yield** is evaluated as the ratio of good pads on the total number of measured pads*

→ *Yield for UFSD3 matrices ranges between **99.3 and 99.9%***

***Uniformity** depends on the spread of depletion voltage value within a wafer*

→ *Depletion voltage spread in the last productions is **~1%***

Laboratory measurements: interpad distance



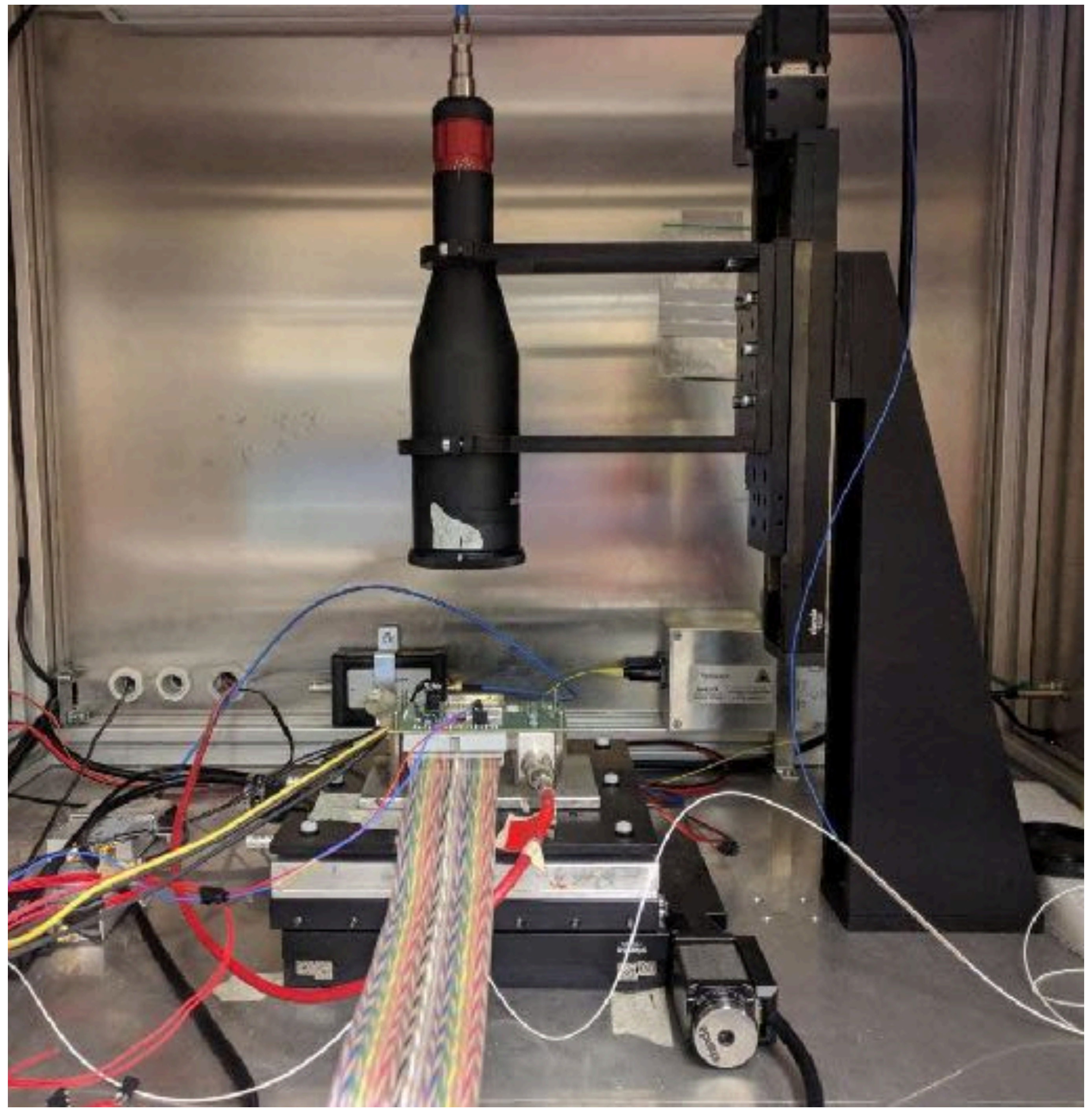
In UFSDs it is necessary to implement ***gain termination structures***

→ ***"no-gain" region*** *without charges multiplication*

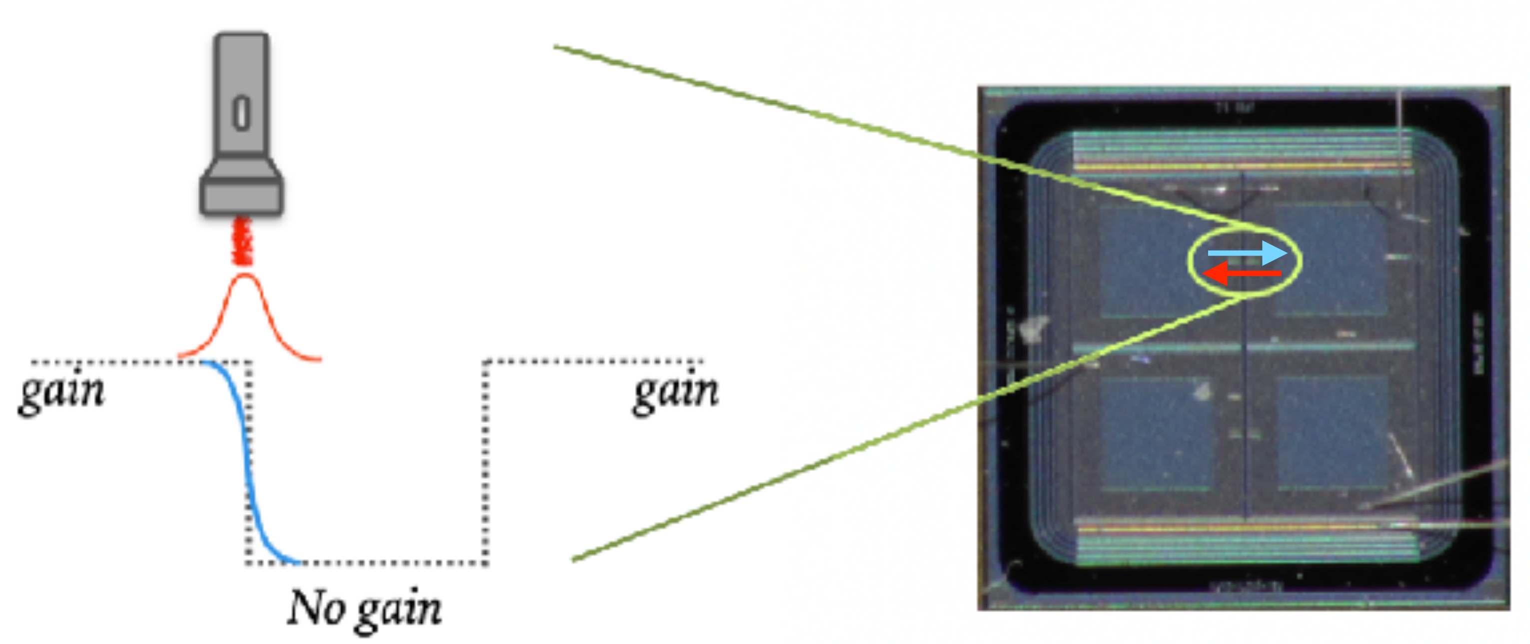
UFSD interpad design aims to ***reduce the no-gain area while maintaining a good production yield***

No-gain area width measured with ***Transient Current Technique setup***

- ***Analysis of current signal*** *induced in the detector*
- ***Picosecond IR laser*** *with* ***~10 μm spot*** *(FWHM)*
- *DUT mounted on moving stages with* ***micrometrical precision***
- *Dedicated acquisition software in LabVIEW*



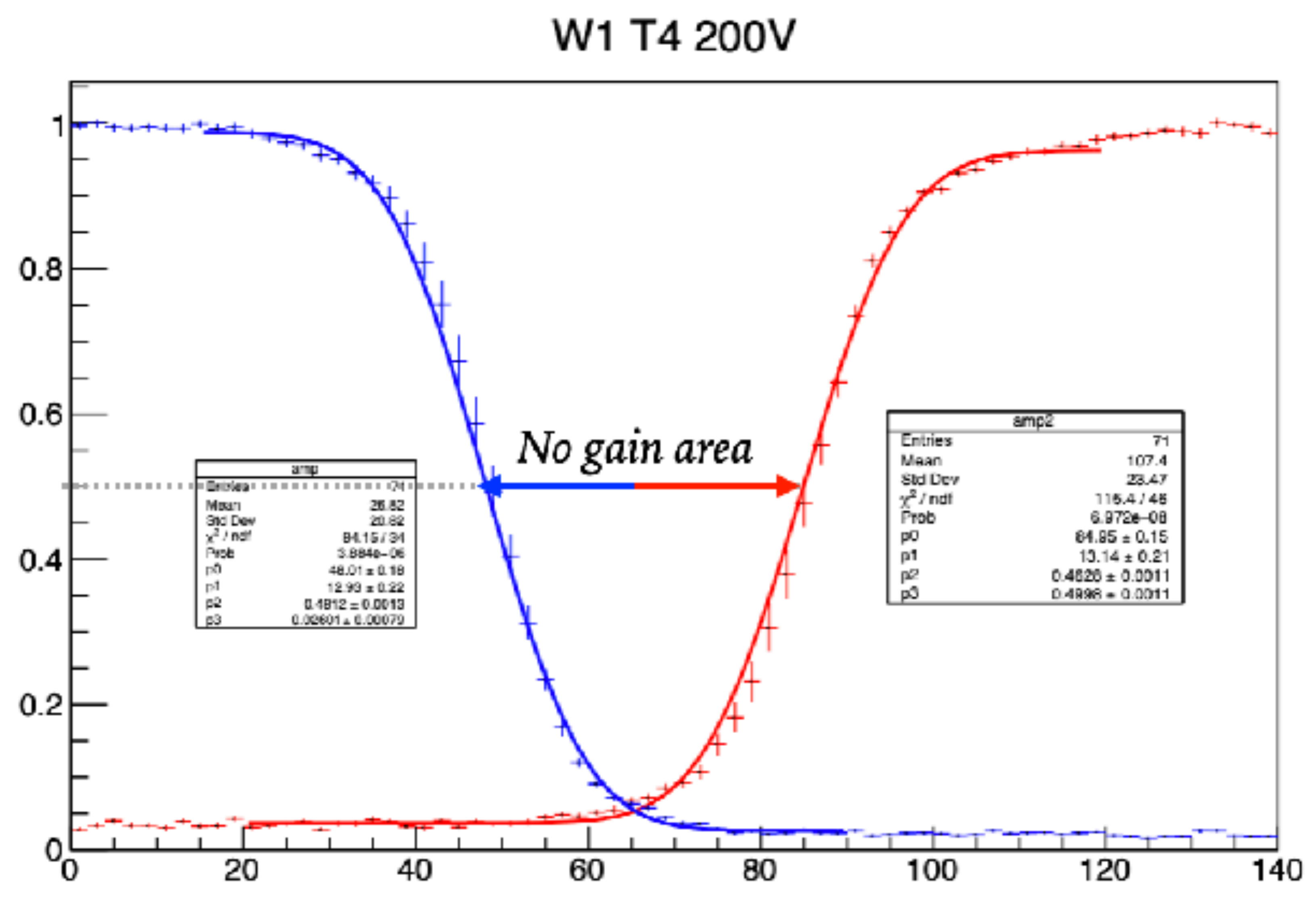
Laboratory measurements: interpad distance



No gain distance measured by performing a ***1D scan*** *with the laser along the optical window between two pads*

Charge vs laser position behaves like an ***S-curve***

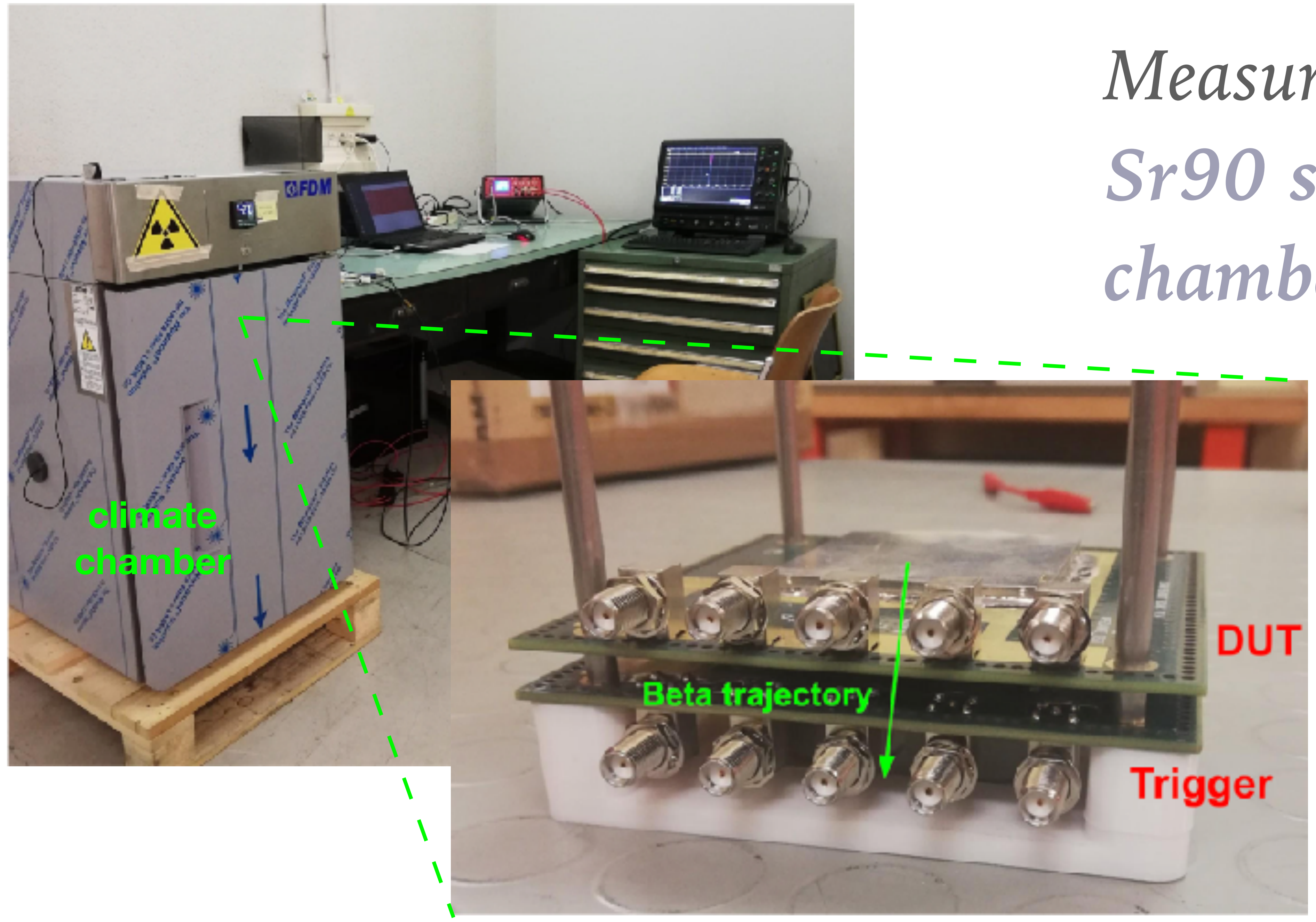
→ *convolution of* ***gain layer step function*** *and laser* ***gaussian beam profile***



Interpad area is evaluated as the ***distance between the points at 50% of the S-curve maximum*** *for the two measured pads*

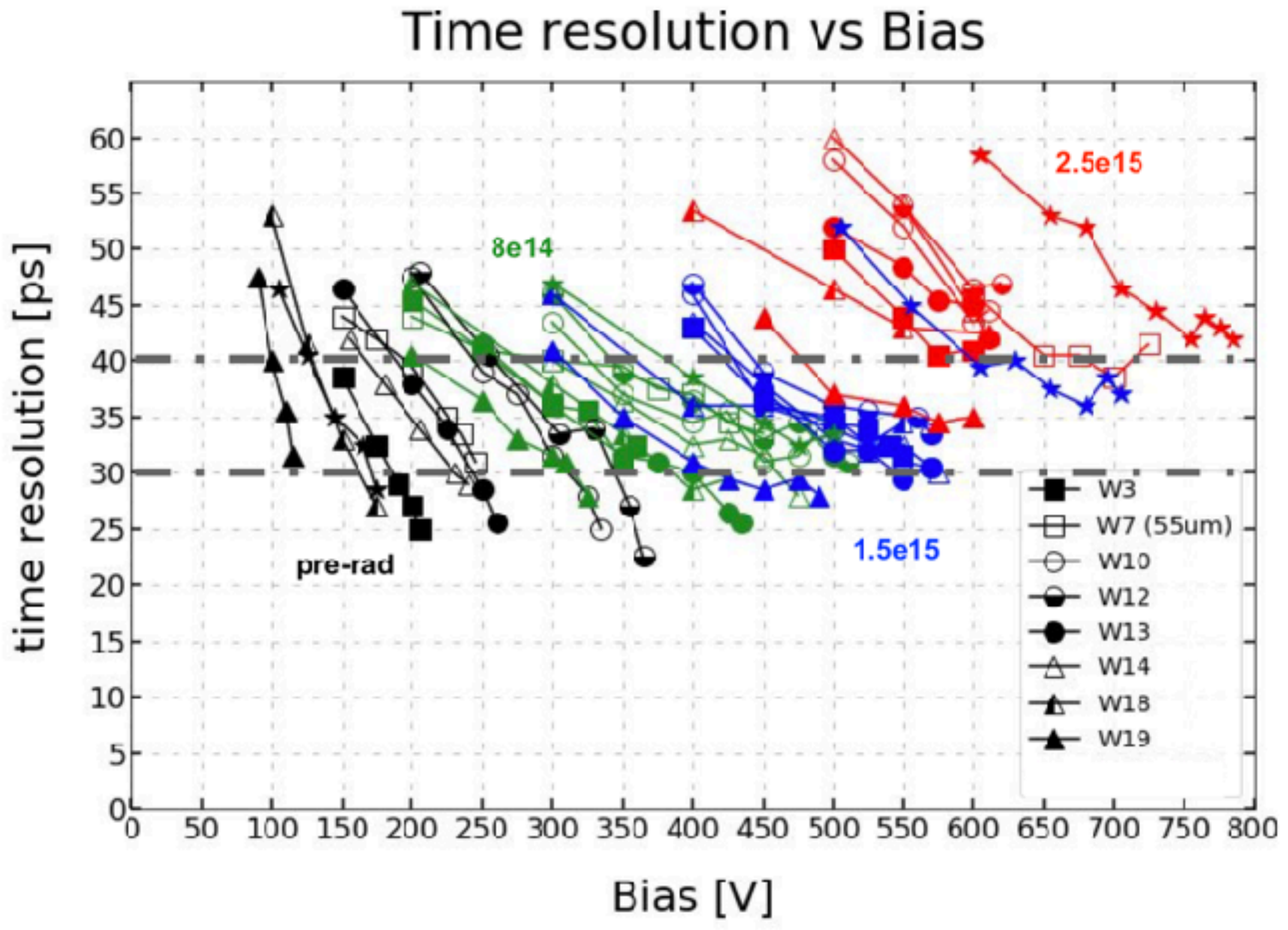
Interpad distances from the latest FBK production ***range between 35 μm and 70 μm***

Laboratory measurements: timing resolution



*Measurements performed with the **Torino Beta-source setup** based on a **Sr90 source** and provided with a **DUT+trigger telescope** in a **climate chamber** and an automated DAQ and analysis system*

*All UFSD3.2 wafers can deliver a **charge >20 fC** and reach a **time resolution of ~30 ps** when new*



***Irradiated** sensors deliver a **charge >10 fC** and reach a **time resolution of ~30 ps** up to 1.5e15 n_eq/cm^2, while reach ~5 fC of charge and 40 ps resolutions at 2.5e15 n_eq/cm^2*

R&D campaign: summary

Results from laboratory measurements show we managed to achieve:

- ✓ ***Excellent*** *production* ***yield*** *and gain* ***uniformity***
- ✓ *Interpad designs with* ***no-gain area <50 µm***
- ✓ *Timing resolution of* $\sigma_t \sim 30$ ***ps*** *for new prototypes*
- ✓ ***Radiation resistant sensors*** *with ~40 ps time resolution at the highest irradiation point*
- ✓ *Large and uniform signals* ***delivering the required amount of charge*** *before and after irradiation*

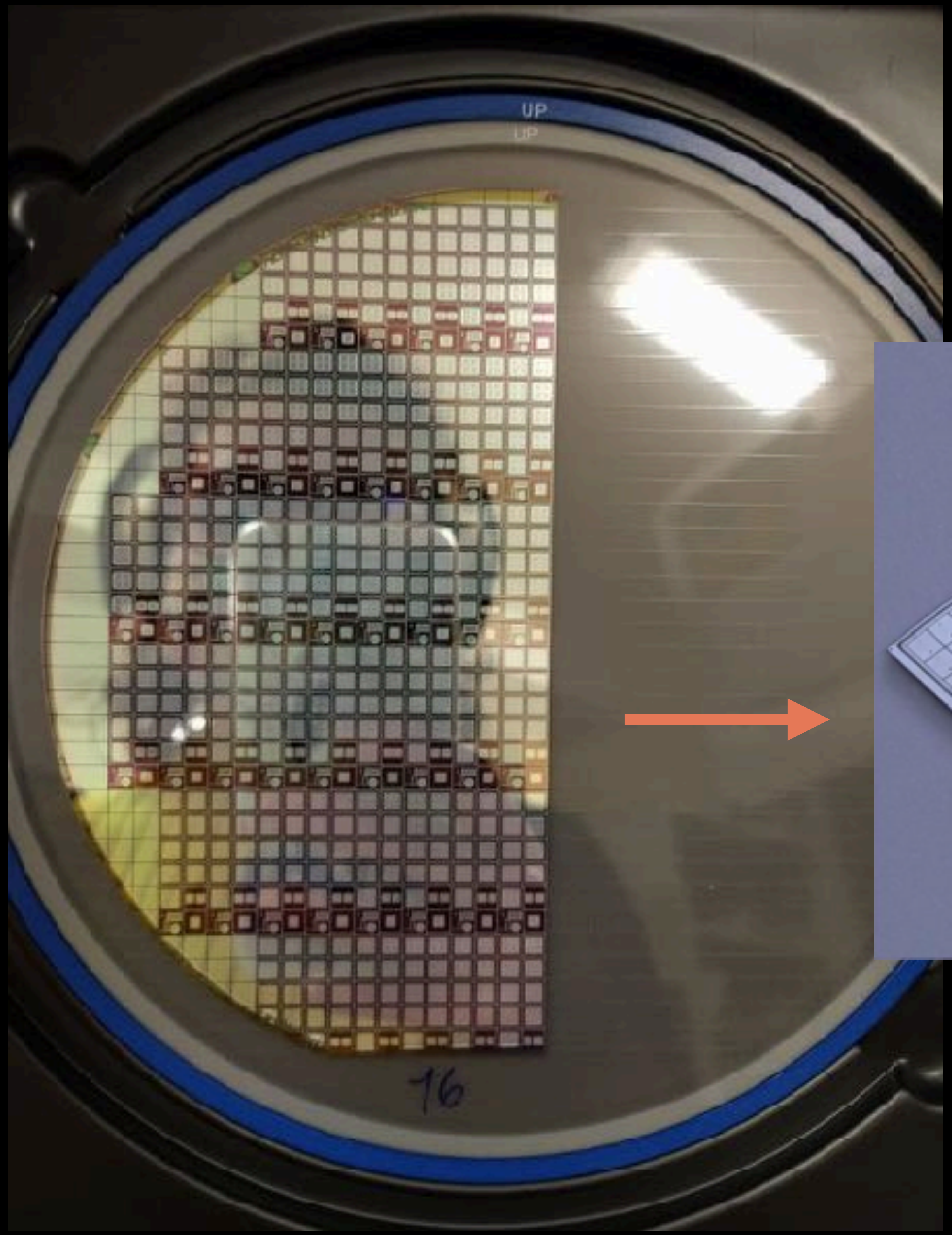
As the conclusion of this R&D campaign, ***the final design of the sensors for the CMS ETL*** *has been obtained*

→ ***CMS is presently in the process of ordering 15*** m^2 ***of UFSD sensors!***

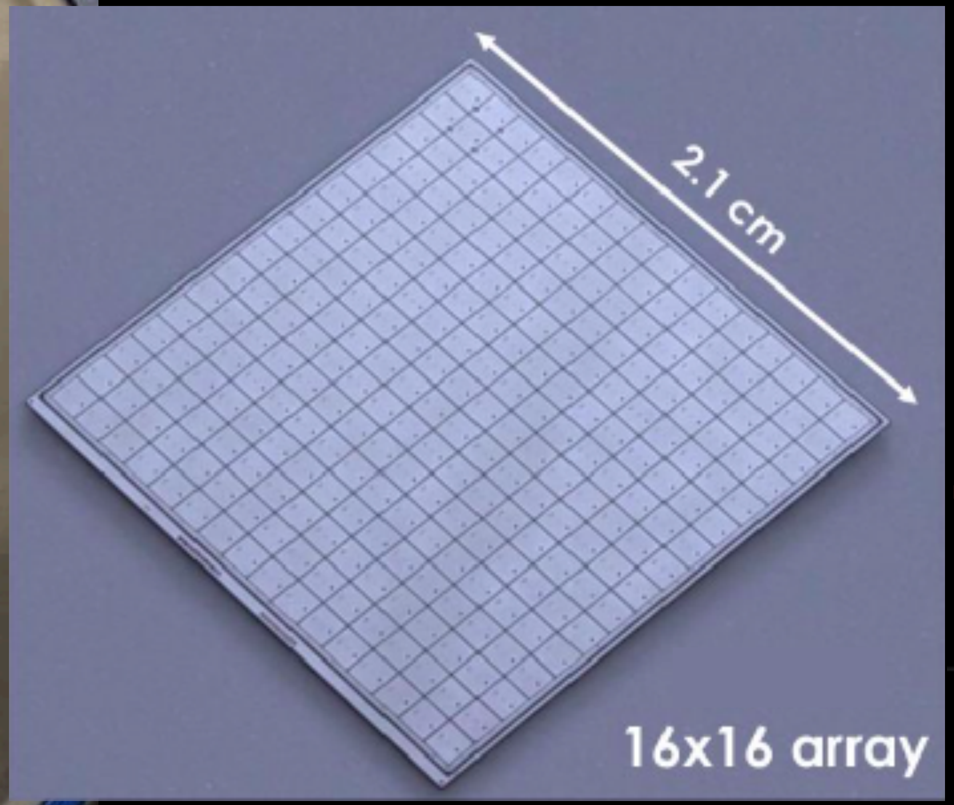
From hardware to software

The CMS Timing Layer is a **brand new detector** that will be installed in the experiment in 2026

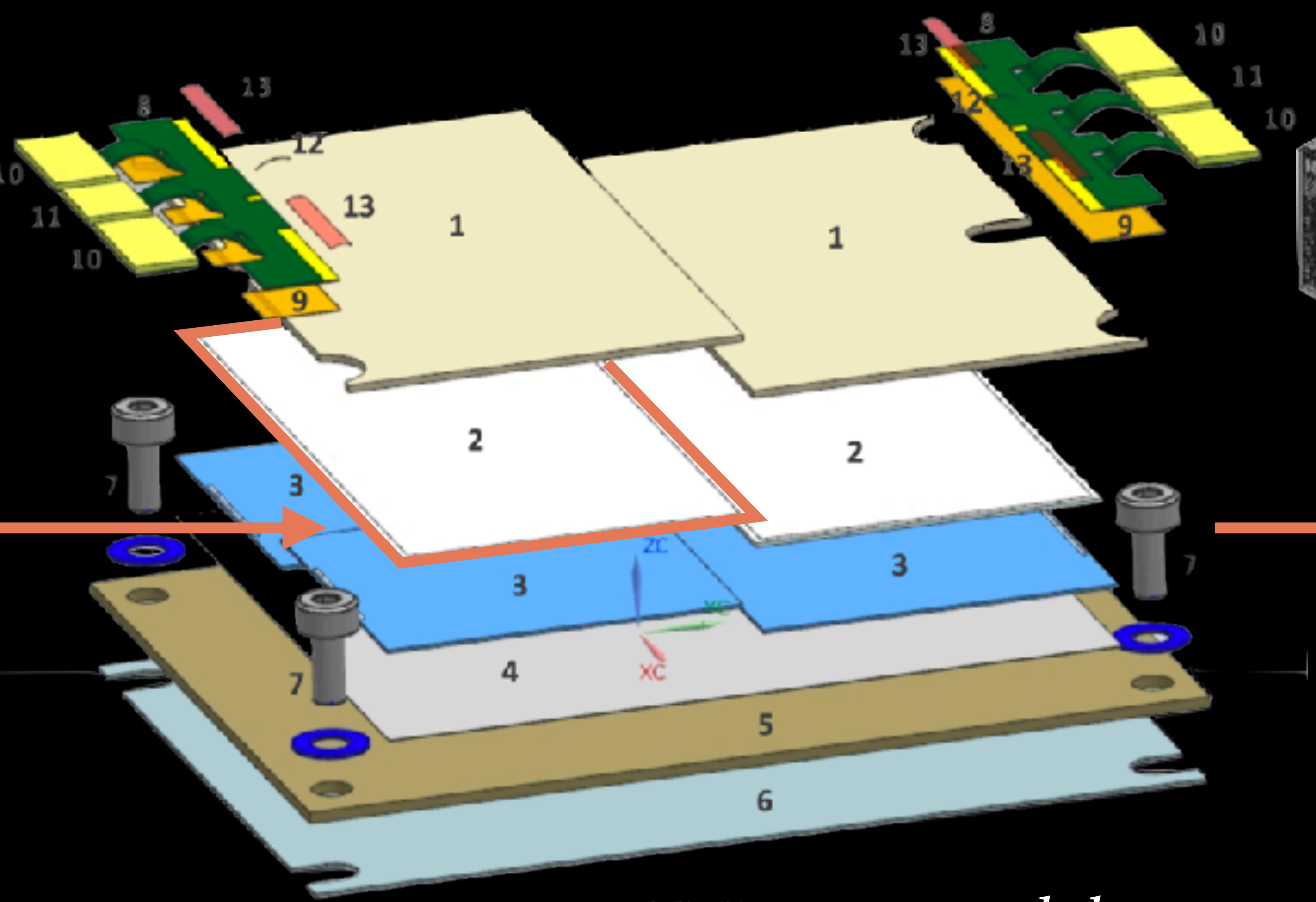
→ My PhD work includes the **implementation of the detector geometry inside CMSSW the CMS software environment**



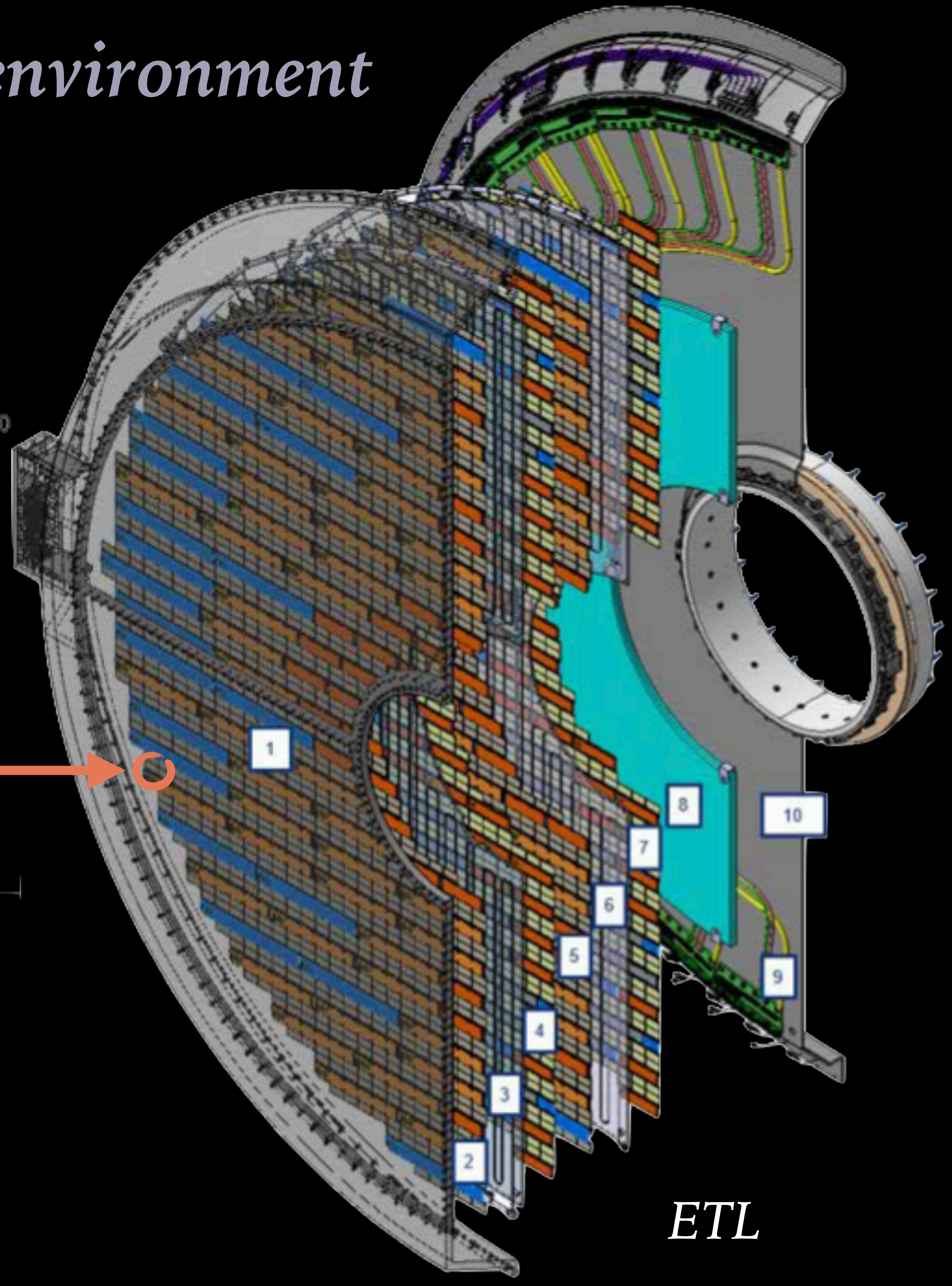
R&D productions



Final sensor



ETL sensor module

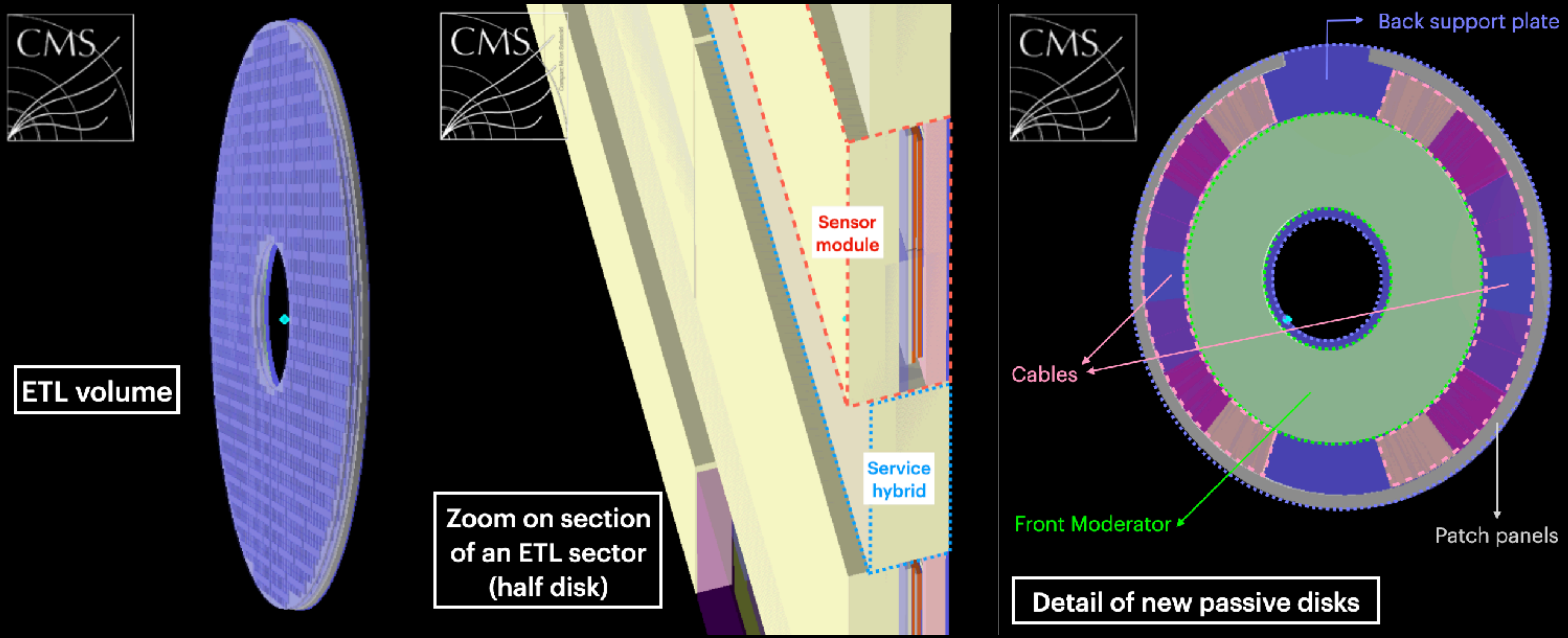


ETL

Simulation of the Endcap Timing Layer

Definition of ETL geometry including active and passive disks, with sensor modules and services

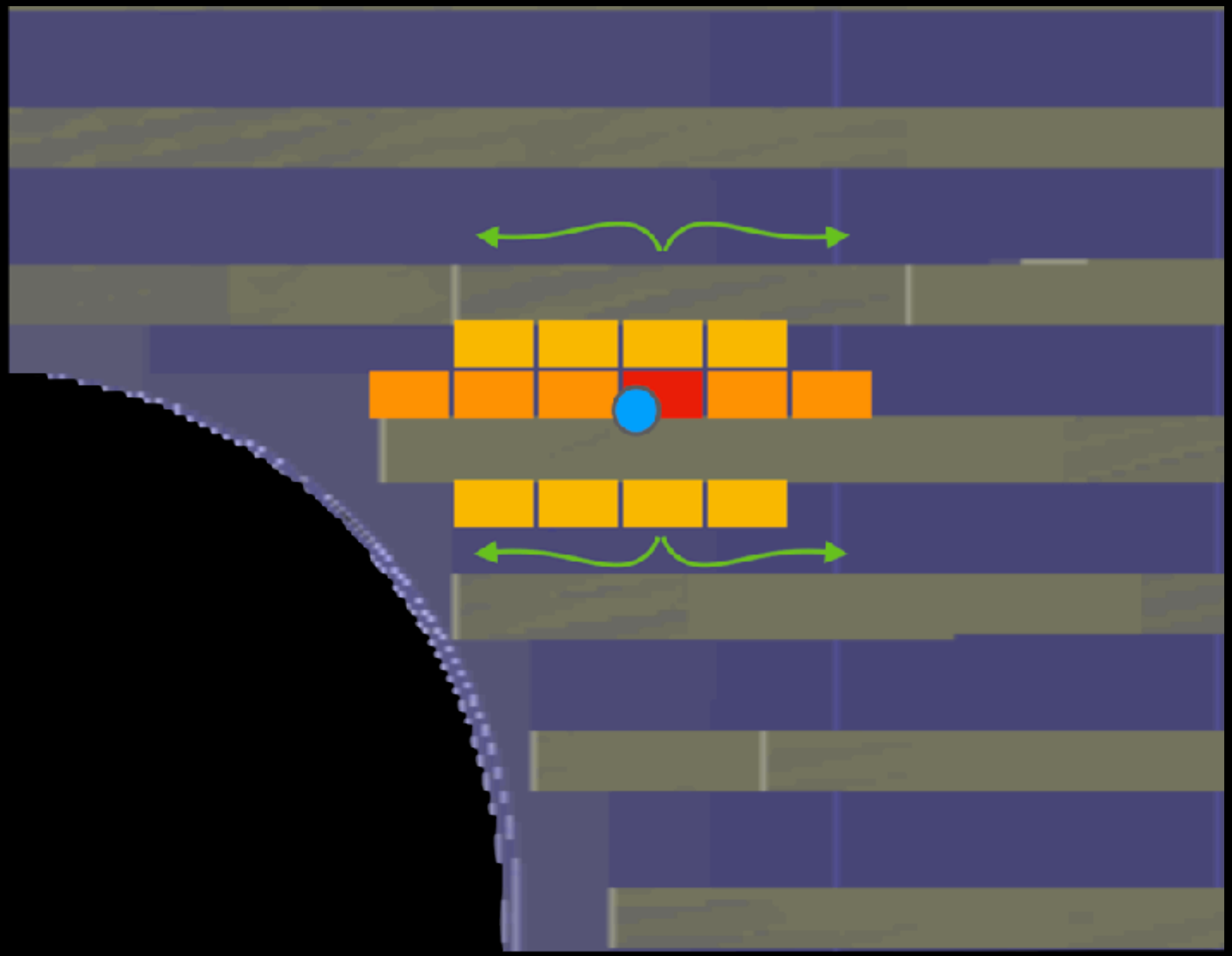
All future simulations and physics analyses concerning ETL will use Montecarlo tools based on this geometry



Simulation of the Endcap Timing Layer

*Implementation of a **new navigation algorithm** used to identify all the modules compatible with the point in which reconstructed tracks cross ETL disks*

- ***Identification of the "minimum"**: closest module to the track*
- ***Shift on the left and on the right** of the minimum and check if there are compatible modules in the same row*
- ***Move to the module above and below** the minimum and, if it's compatible, check if there are other compatible modules on its left and its right*
- ***Repeat** the procedure until no more compatible module is found*



Conclusions and future plans

CMS Endcap Timing Layer will be installed in 2026 for High Luminosity LHC and instrumented with Ultra-Fast Silicon Detectors

*On the **hardware** side:*

✓ *Laboratory studies performed to **finalise the layout of the ETL sensor***

➡ *Next: conclusion of R&D phase and production of **final batch** for the experiment, preparation for **module assembly***

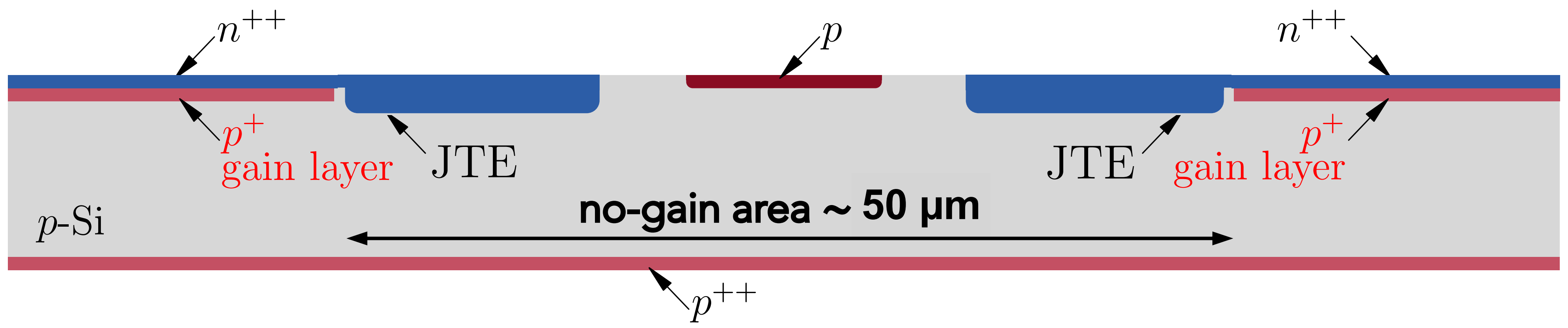
*On the **software** side:*

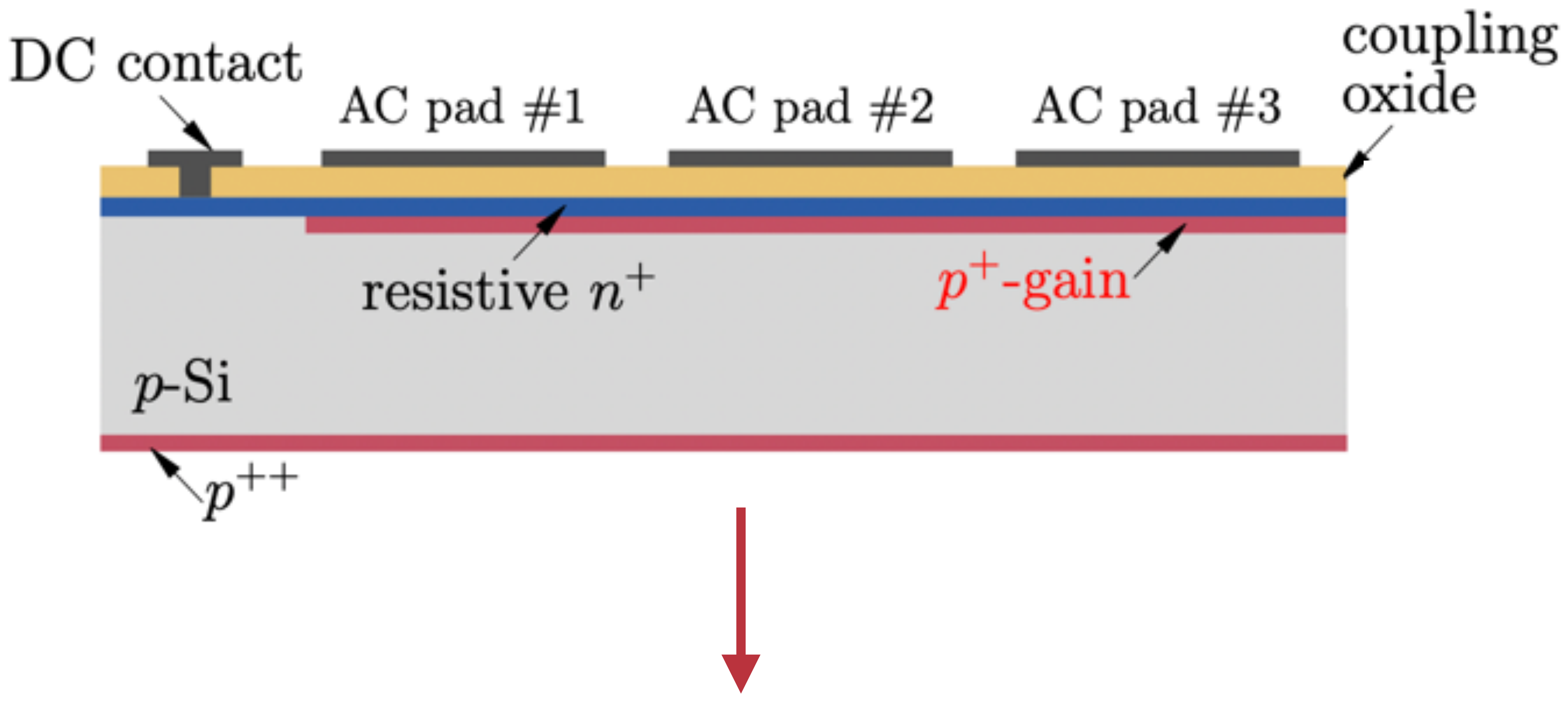
✓ *Implementation of **ETL geometry in CMSSW** with algorithms useful for analysis*

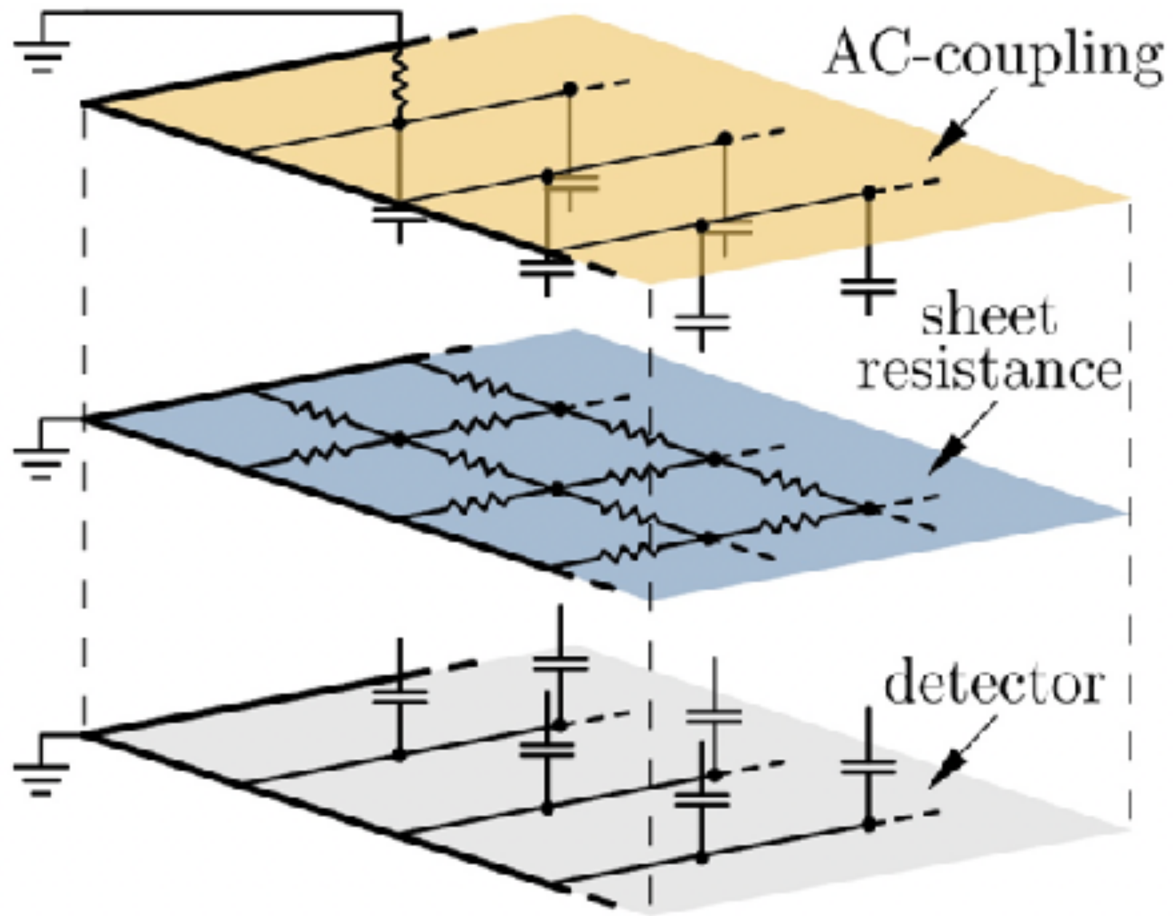
➡ *Next: simulation of the **benefits provided by the timing layer** to the CMS reconstruction capabilities focusing on **specific Higgs analyses***

Evolution of the sensor design

In the current UFSD design, isolation structures between readout pads represent a no-gain area for signal collection







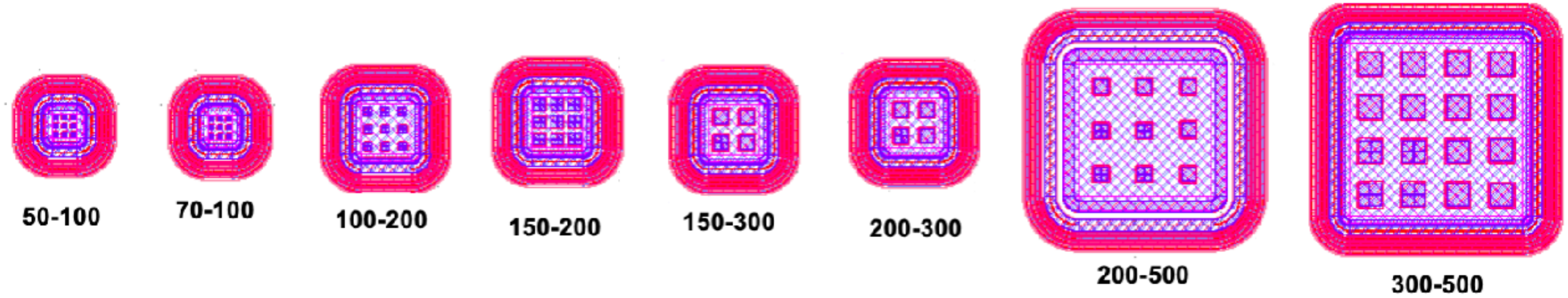
Resistive AC-coupled LGAD (RSD) *are designed as detectors with 100% fill factor*

- ***One continuous gain layer***
- *Segmentation of* ***read-out pads*** *defines spatial resolution*
- *Easy structure with a reduced number of edges, more resistant*

RSD measurements

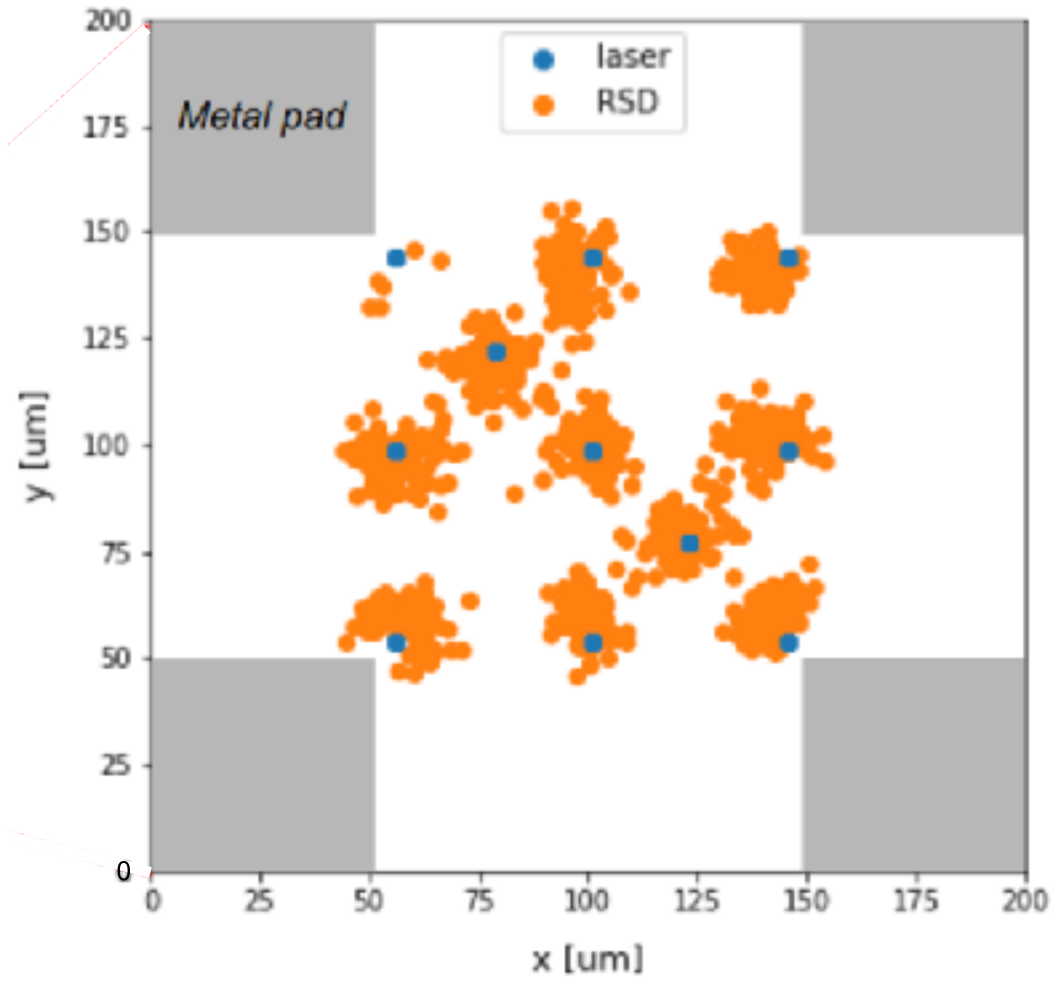
Several RSD matrices with different pad-pitch geometry (but same resistivity) have been measured:

- *at the **Laboratory for Innovative Silicon Sensors** in **Torino** with a Particulars TCT setup, where data have been used to develop the analytical model for hit reconstruction and evaluate spatial resolution and jitter*
- *at the **Fermilab Test Beam Facility** with a 120 GeV/c proton beam, for further studies on RSD signal properties and to measure their timing resolution*



Resistive AC-Coupled Silicon Detectors: Principles of operation and first results from a combined analysis of beam test and laser data, M. Tornago et al, https://doi.org/10.1016/j.nima.2021.165319

RSD performances



Laser measurements show that RSD can reach a ***very good spatial resolution****, up to a factor 10 better than the corresponding binary read-out precision (pad size/$\sqrt{12}$)*

pad-pitch geometry	spatial resolution [μm]
50-100	4.3
70-100	2.5
100-200	4.8
150-200	4.4
150-300	7.2
200-300	5.3
200-500	16.5
300-500	14

Timing resolution results are ***compatible with the best LGAD performances*** *obtained at the same gain*

	single pad	3 pad	4 pad
100-200 laser	45 ps	-	22 ps
100-200 test beam	50 ps	44 ps	-
190-200 test beam	35 ps	42 ps	-

$\sigma_t^2 = \sigma_{\mathrm{Jitter}}^2$

$\sigma_t^2 = \sigma_{\mathrm{Landau}}^2 + \sigma_{\mathrm{Jitter}}^2$

Resistive AC-Coupled Silicon Detectors: Principles of operation and first results from a combined analysis of beam test and laser data, M. Tornago et al, https://doi.org/10.1016/j.nima.2021.165319

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*On the **software** side:*

✓ *Implementation of **ETL geometry in CMSSW** with algorithms useful for analysis*

➡ *Next: study of improvements brought by timing information in **specific Higgs analyses***

***UFSD evolutions**:*

- ***RSD**, towards 100% fill-factor with AC-coupling ⟶ **more in Luca Menzio's talk***

Publications

- *“Resistive AC-Coupled Silicon Detectors principles of operation and first results from a combined laser-beam test analysis”, M. Tornago et al., NIM A, Volume 1003, July 2021, 165319*
- *“Demonstration of 200-, 100-, and 50- µm Pitch Resistive AC-Coupled Silicon Detectors (RSD) With 100% Fill-Factor for 4D Particle Tracking”, M. Mandurrino et al., IEEE Electron Device Letters, vol. 40, no. 11, pp. 1780-1783, November 2019, DOI: 10.1109/LED.2019.2943242*
- *“Analysis and numerical design of Resistive AC- Coupled Silicon Detectors (RSD) for 4D particle tracking”, M. Mandurrino et al., NIM A, Volume 959, 163479, 2020*
- *“Experimental Study of Acceptor Removal in UFSD" , Y. Jin, H. Ren et al., NIM A, Proceedings of the 12th International "Hiroshima" Symposium (HSTD12) at Hiroshima, Japan, HSTD12, 2019*
- *“Silicon Sensors for Future Particle Trackers”, N. Cartiglia et al., NIM A, Proceedings of the 12th International "Hiroshima" Symposium (HSTD12) at Hiroshima, Japan, HSTD12, 2019*
- *“State-of-the-art and evolution of UFSD sensors design at FBK”, R. Arcidiacono et al., NIM A, Proceedings of the 12th International "Hiroshima" Symposium (HSTD12) at Hiroshima, Japan, HSTD12, 2019*
- *“Novel Strategies for Fine-Segmented Low Gain Avalanche Diodes” G. Paternoster et al., NIM A, Proceedings of the 12th International "Hiroshima" Symposium (HSTD12) at Hiroshima, Japan, HSTD12, 2019*
- *“Evolution of the design of ultra fast silicon detector to cope with high irradiation fluences and fine segmentation”, M. Ferrero et al., April 2020, Journal of Instrumentation 15(04):C04027-C04027*
- *“First application of machine learning algorithms to the position reconstruction in Resistive Silicon Detectors ”, F. Siviero et al., 2021 JINST 16 P03019*
- *“Next-Generation Tracking System for Future Hadron Colliders”, V. Sola et al., Proceedings of Science, Volume 373, The 28th International Workshop on Vertex Detectors (Vertex2019), September 2020*

CMS Author from 15/7/2020

Conference presentations and posters

- *"Characterization of the first RSD production at FBK", 35th RD50 Workshop, CERN, Geneva, 19th November 2019*
- *"Latest results on Resistive AC-Coupled Silicon Detectors (RSD) spatial and timing resolution", 36th RD50 Workshop, CERN (Virtual), 4th June 2020*
- *"Measurement of the Z boson cross section with τ" , CMS Virtual Data Analysis School, 30th September 2020*
- *"Resistive AC-Coupled Silicon Detectors: laser and beam test data analysis", IEEE 2020 Virtual Nuclear Science Symposium and Medical Imaging Conference, Boston (Virtual), 3rd November 2020*
- *"Performances of the latest FBK UFSD production", TIPP 2021 (Technology and Instrumentation in Particle Physics Conference),Vancouver (Virtual), 24-28 May 2021*
- *"Ultra-Fast Silicon Detectors for CMS Phase II upgrade", XXXII International Seminar of Nuclear and Subnuclear Physics "Francesco Romano", 11th. June 2021*
- *"The CMS MTD Endcap Timing Layer: Precision Timing with Low Gain Avalanche Diode Sensors", PANIC 2021 (22nd Particles and Nuclei International Conference), Lisbon (Virtual), 5th September 2021*
- *"Rivelatori al silicio per misure di tempo" (Invited Talk), 107° Congresso Nazionale SIF (Virtual), 17th September 2021*


UFSD
https://doi.org/10.1201/9781003131946
Positrons
Electrons
BANG
NW '21

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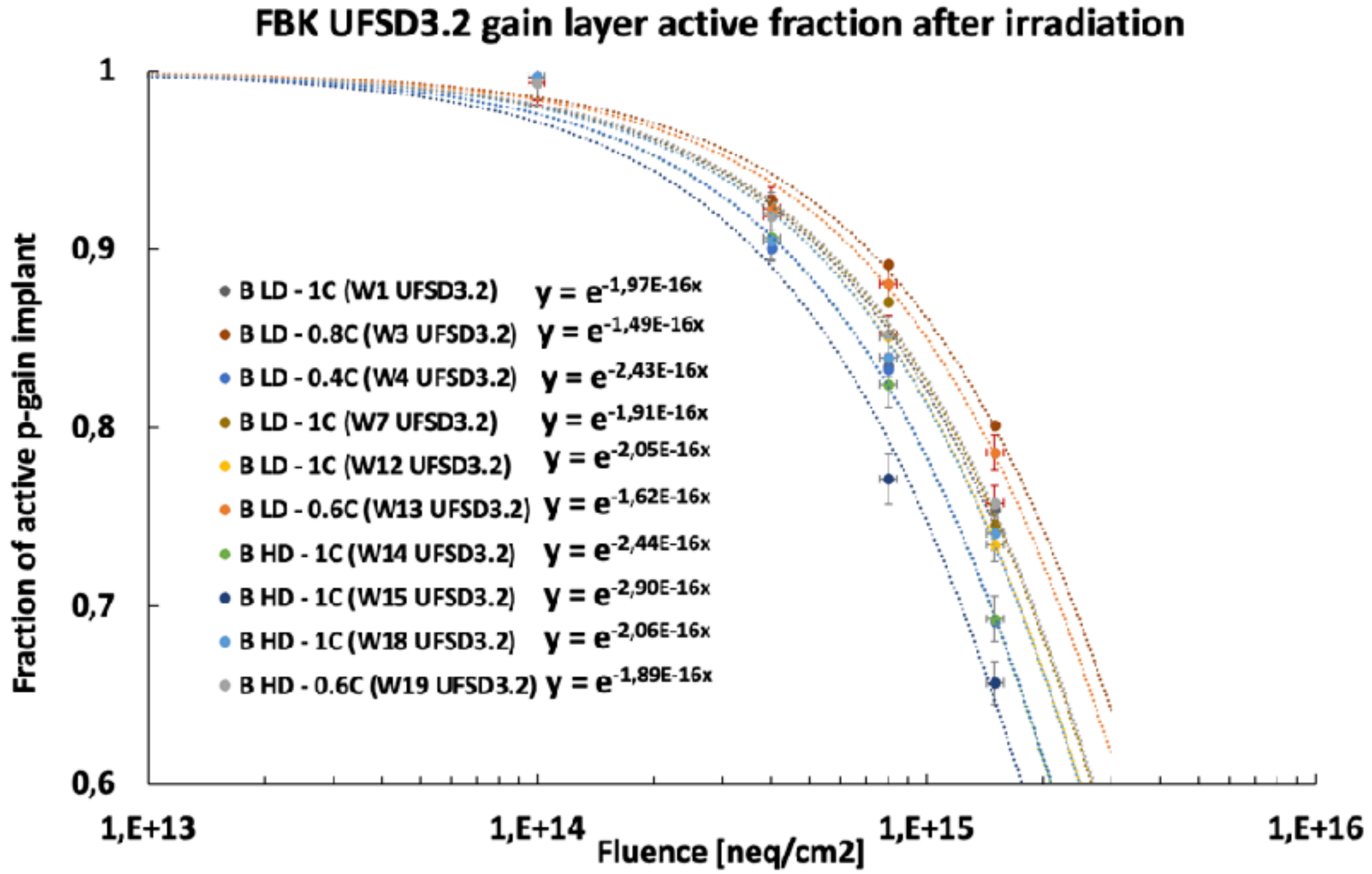
- *Horizon 2020, ERC - **Grant UFSD669529***
- *Horizon 2020, MSCA - **Grant number 654168 (AIDA-2020)***
- *U.S. Department of Energy **Grant number DE-SC0010107***
- ***Dipartimenti di Eccellenza**, University of Torino (ex L. 232/2016, art. 1, cc. 314, 337)*
- *Ministero della Ricerca, Italia , PRIN 2017, **progetto 2017L2XKTJ – 4DinSiDe***
- *Ministero della Ricerca, Italia, FARE, **R165xr8frt_fare***

Backup

Laboratory measurements: radiation resistance

*In an n-in-p device, one of the main radiation effect is the **deactivation of Boron acceptors** in the gain layer:*

$$N_A(\phi) = N_A(0)e^{-c\phi}$$

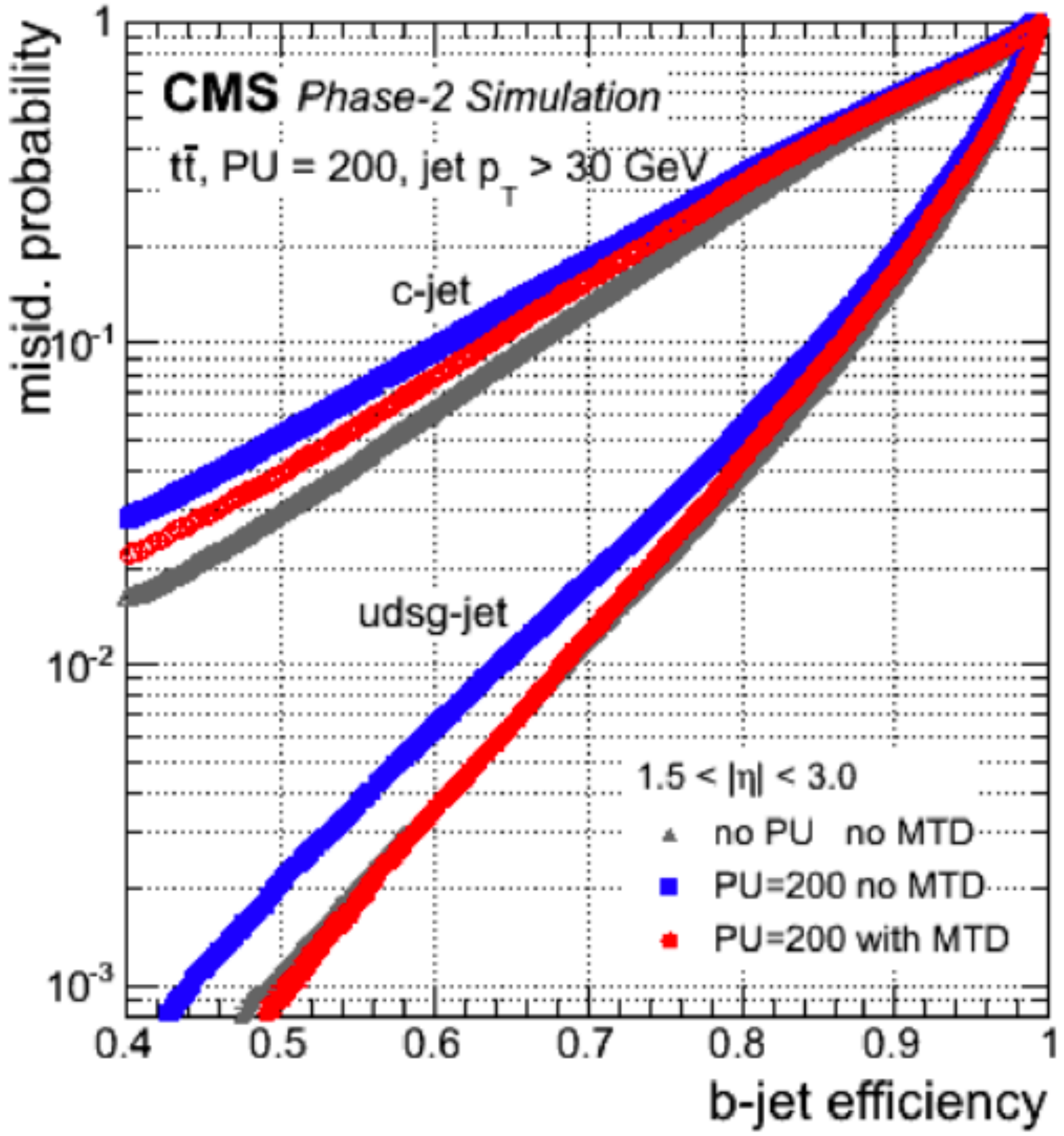


- *“c” factor obtained from gain layer active fraction vs fluence curves*
- *gain layer active fraction is calculated with gain layer depletion voltage extracted from CV measurements*
- ***Carbon dose which minimizes radiation damage is between 0.6*A and 1.*A***

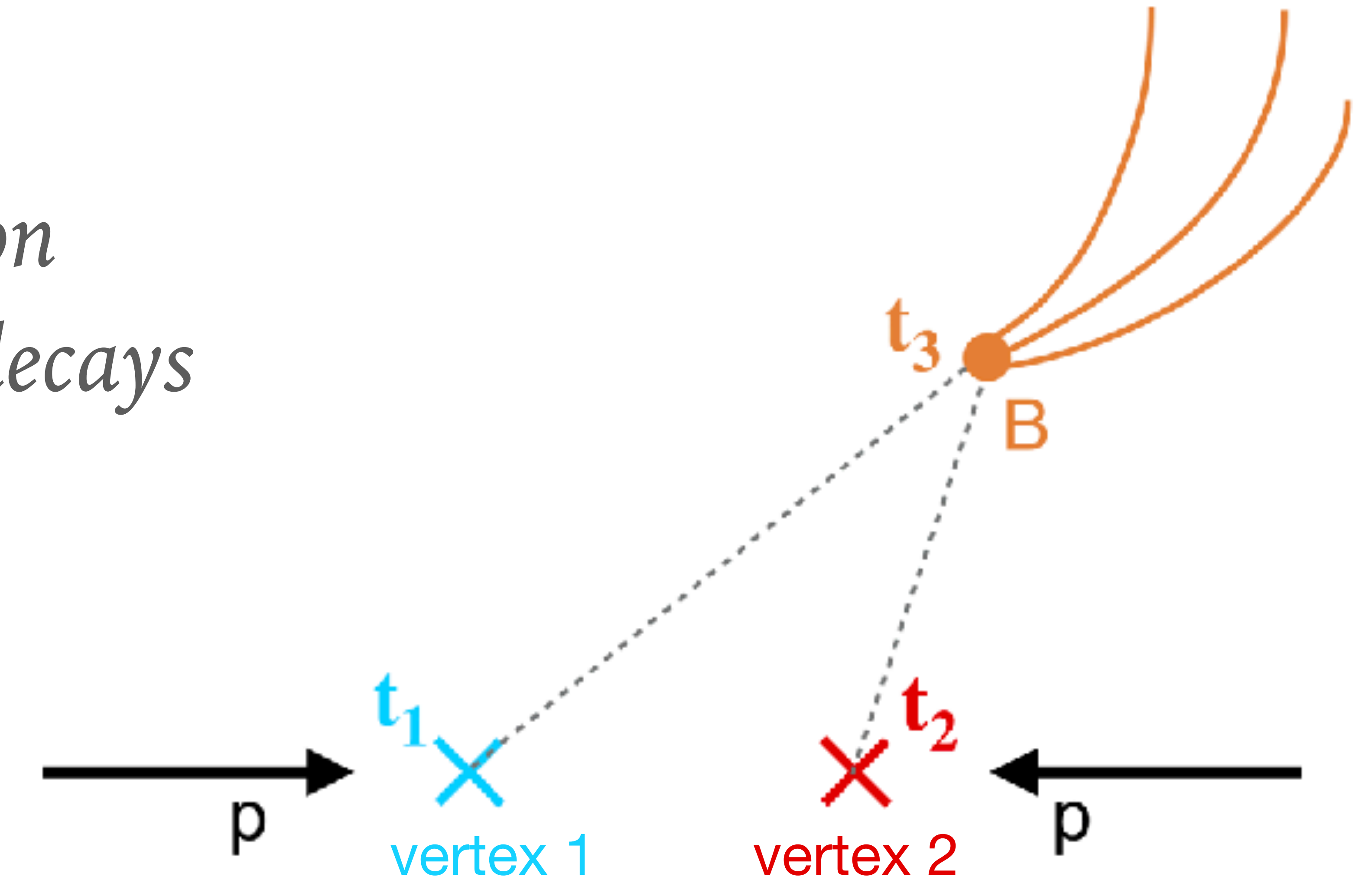
Impact of timing on physics analysis

Higgs boson characterization and *searches beyond the Standard Model* will benefit from the HL-LHC luminosity increase

*MTD is instrumental in **maintaining good resolution and reconstruction efficiency** for physics objects by providing additional timing information*



b-tagging: improvement in identification efficiency for jets produced by B meson decays based on vertices time consistency

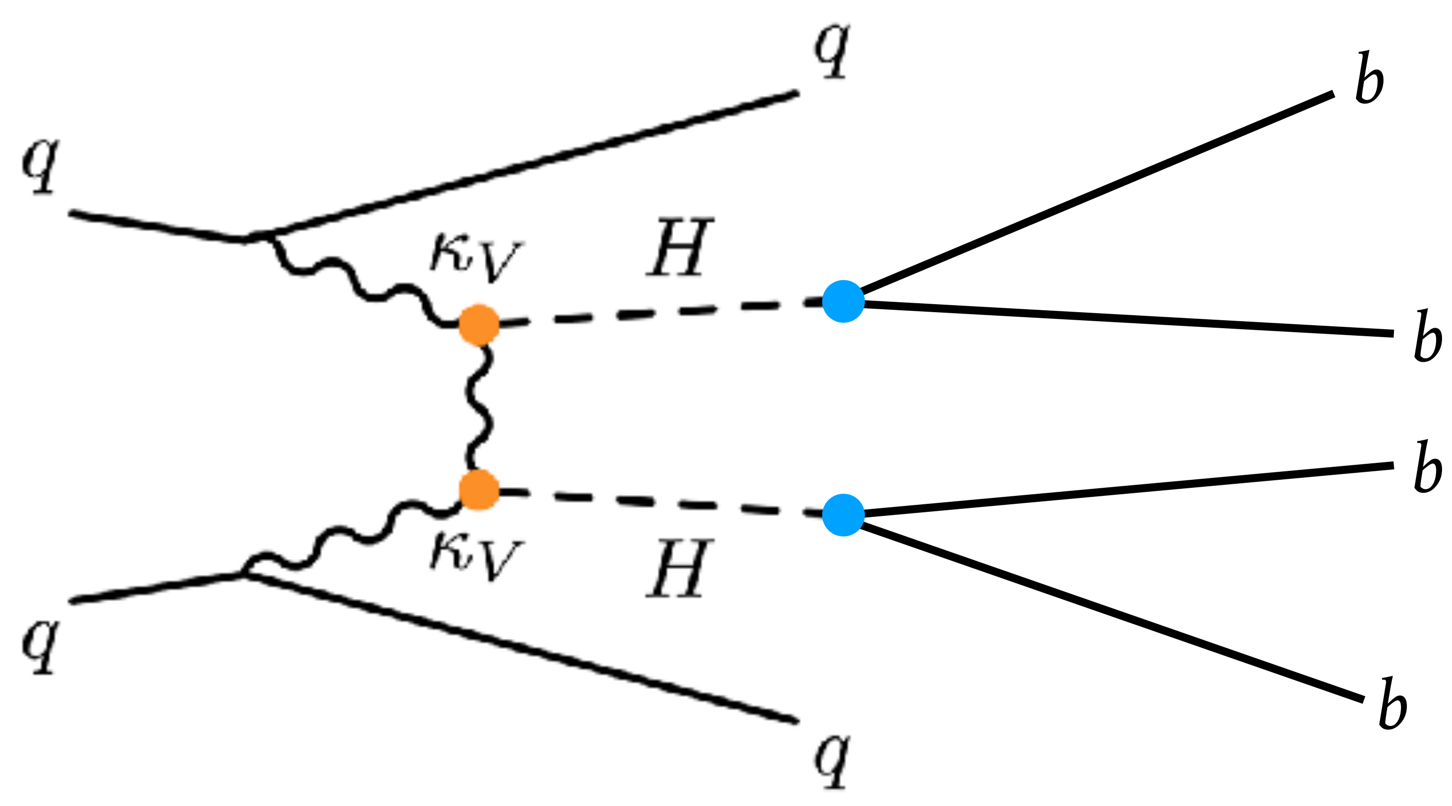


→ *Increase of statistics for physics analysis 10-20%*

Analysis studies in Torino

*Studies currently ongoing in Torino: **impact of MTD timing information in removing pile-up candidates from signal jets** considering a 200 pile-up scenario*

*Channel used as benchmark for the study: **VBF ⟶ HH ⟶ 4b***



- ***Vector Boson Fusion**:*
  - ***tagging of forward jets** with ETL*
  - ***coupling parameters** can be evidence of new physics beyond SM*
- ***Higgs pair production**: not yet observed, **Higgs self coupling measurement** would complete Higgs field characterization*
- ***beauty decay**: not the decay channel with the largest cross-section, but MTD improvements in efficiency are particularly noticeable as we have 4b in the final state*

⟶ *Efficiency contribution of timing **raised to the 4th power***