UNIVERSITA
DEGLI STUDI
DI TORINO

INFN
Istituto Nazionale di Fisica Nucleare

107° CONGRESSO NAZIONALE
della SOCIETÀ ITALIANA DI FISICA

Silicon detectors for timing measurements

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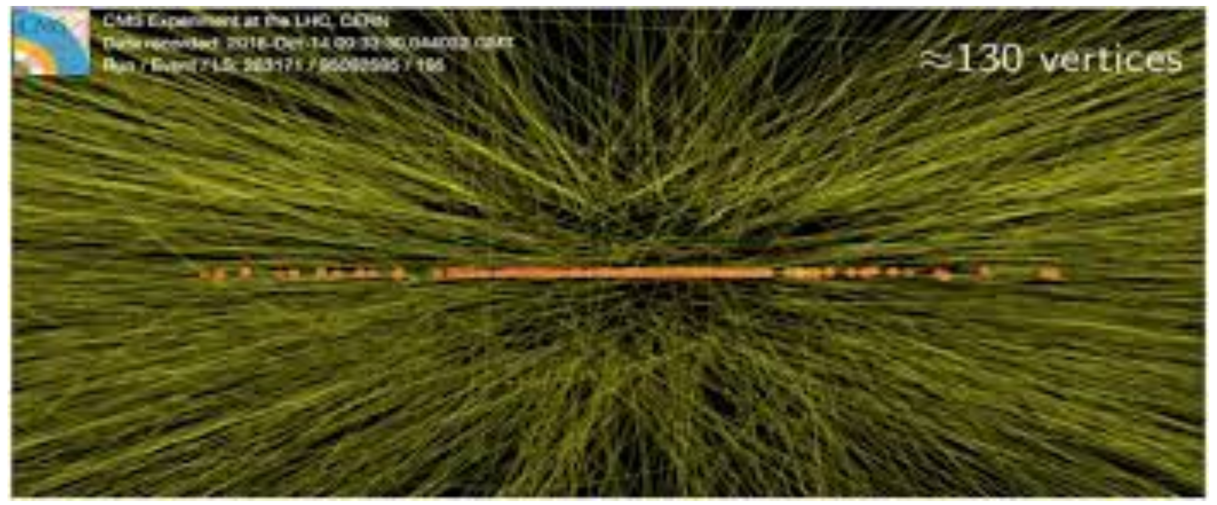
Timing measurements in future experiments

Future colliders will be characterised by environments with high collision density

→ difficulties in reconstruction and particle identification due to tracks coming from overlapping vertices

→ Near future example: High Luminosity LHC starting in 2026

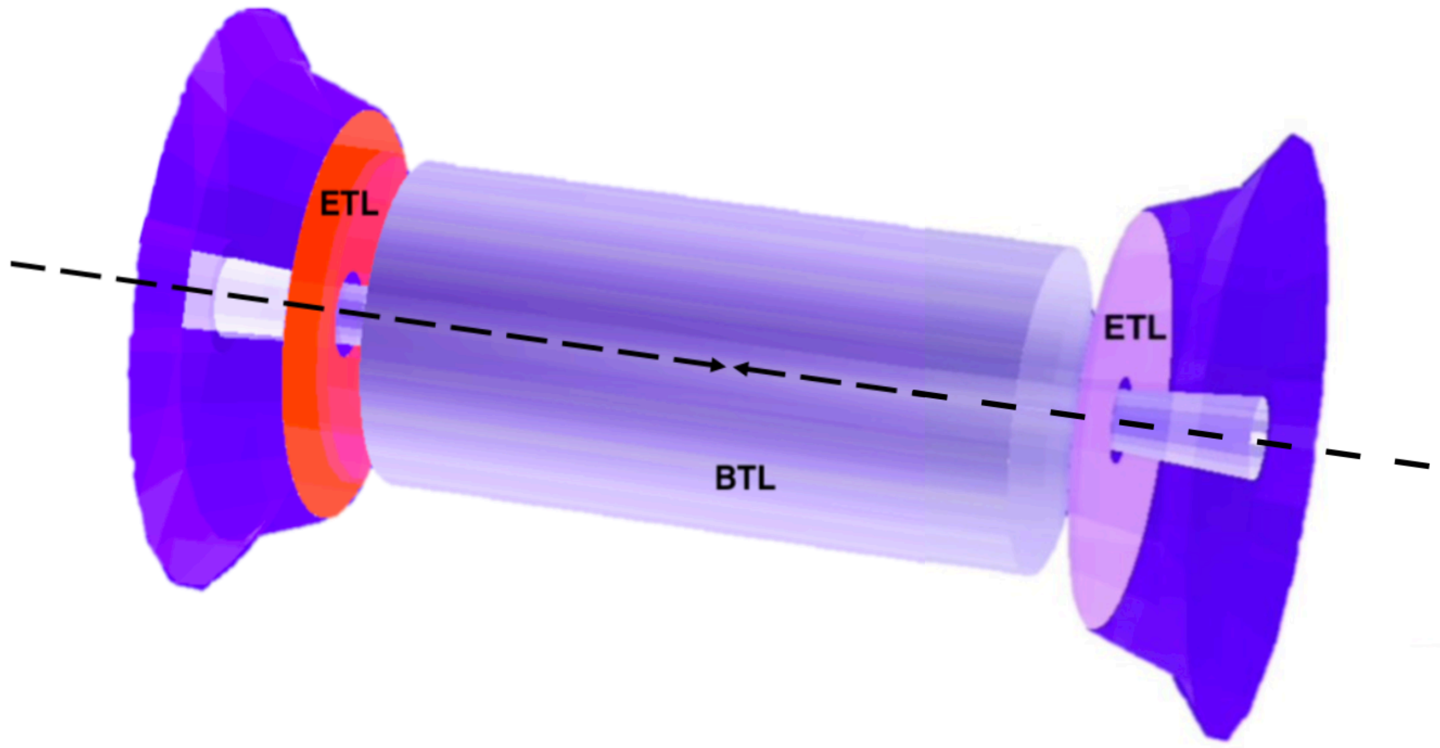


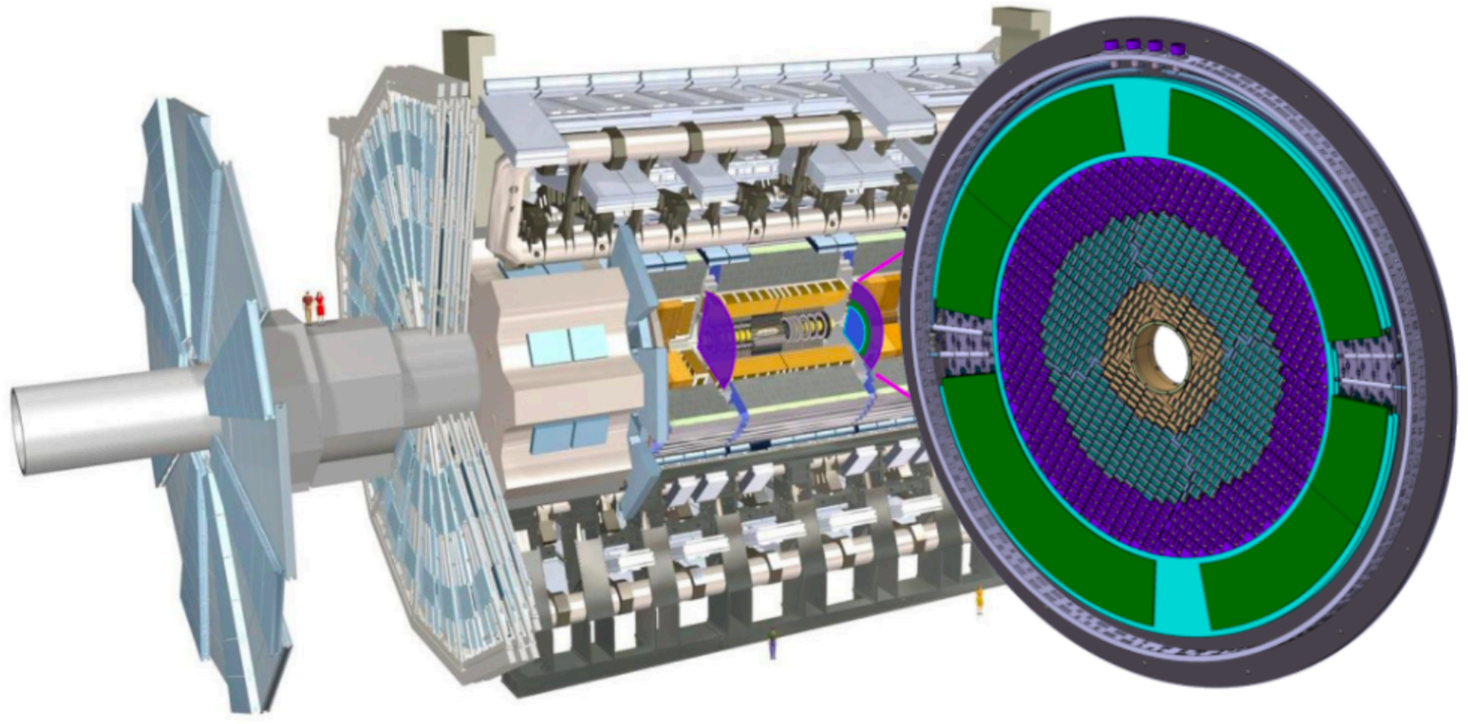
At High Luminosity LHC, experiments need to maintain their performances in a new harsh environment

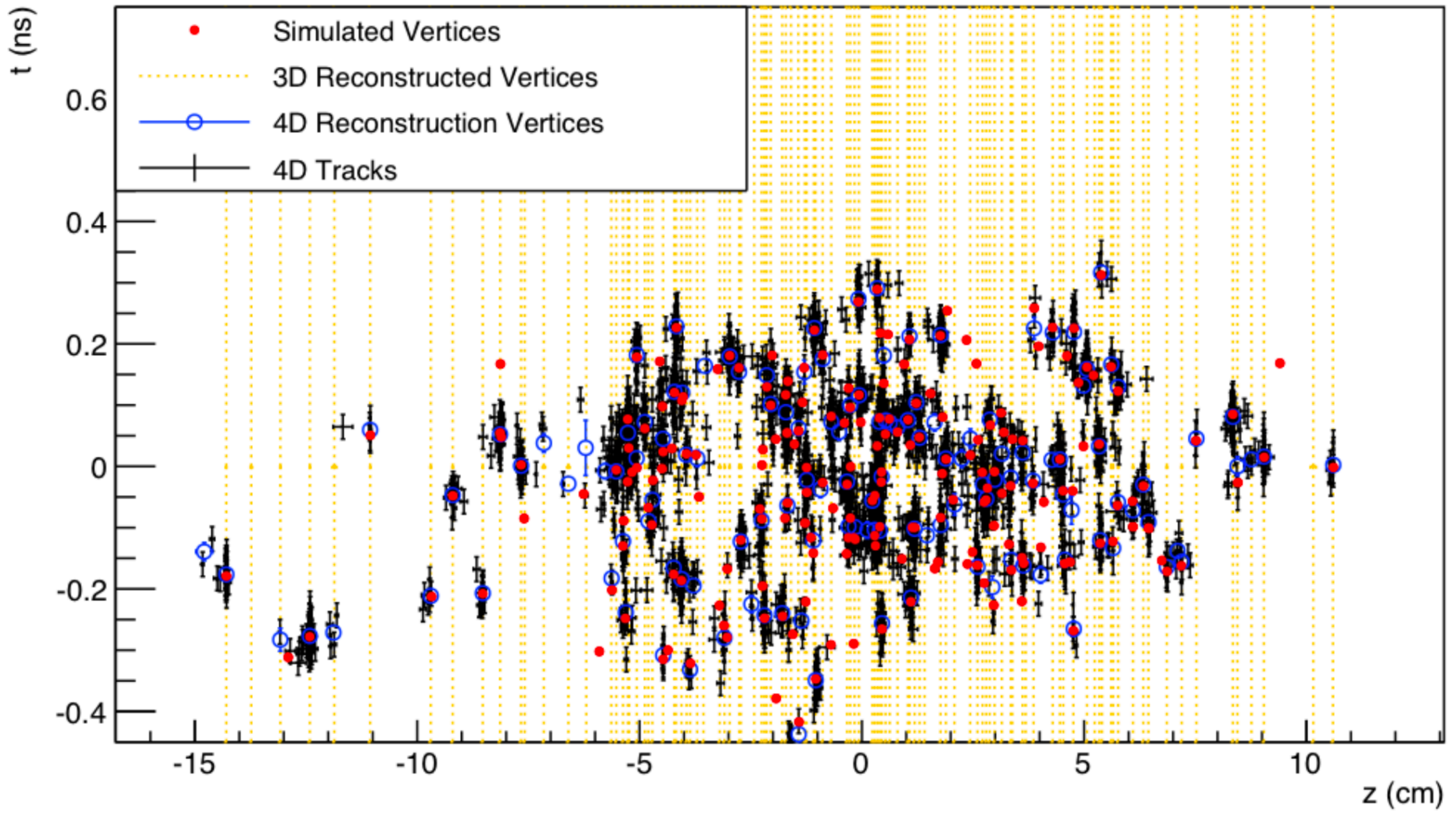
→ additional timing information to improve pile up rejection and particle identification

→ creation of timing layers in High-Lumi LHC experiments with $\sigma_t \sim$ **few tenths ps**

- ✳ Minimum Ionizing Particle Timing Detector for CMS
- ✳ High Granularity Timing Detector for ATLAS
- ➡ foreseen ALICE3



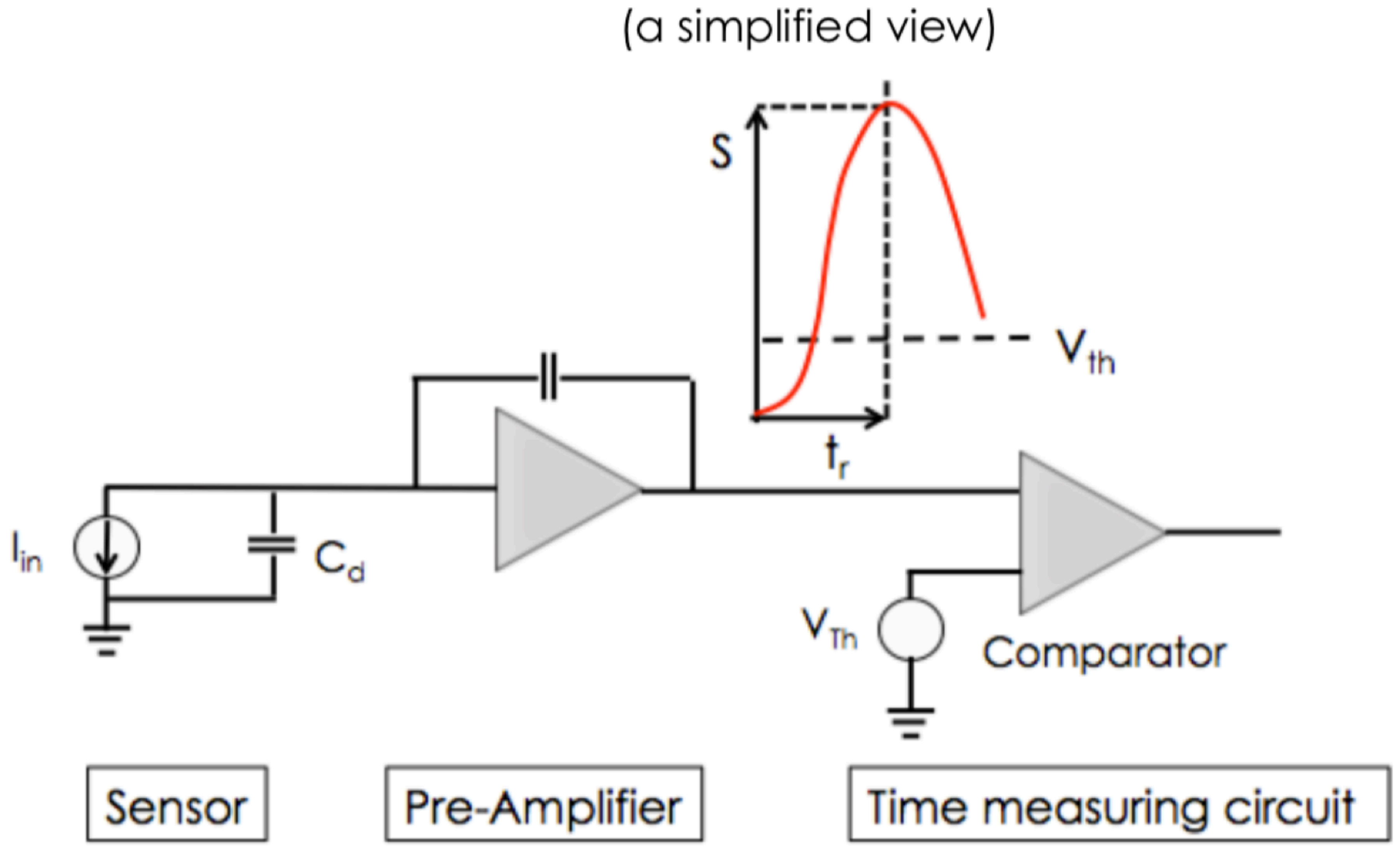




Timing resolution

The design of the perfect silicon detectors depends on timing resolution

$$\sigma_t^2 = \sigma^2_{\text{Non-unifom Ionization}} + \sigma^2_{\text{Jitter}} + \sigma^2_{\text{TimeWalk}} + \sigma^2_{\text{TDC}}$$



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

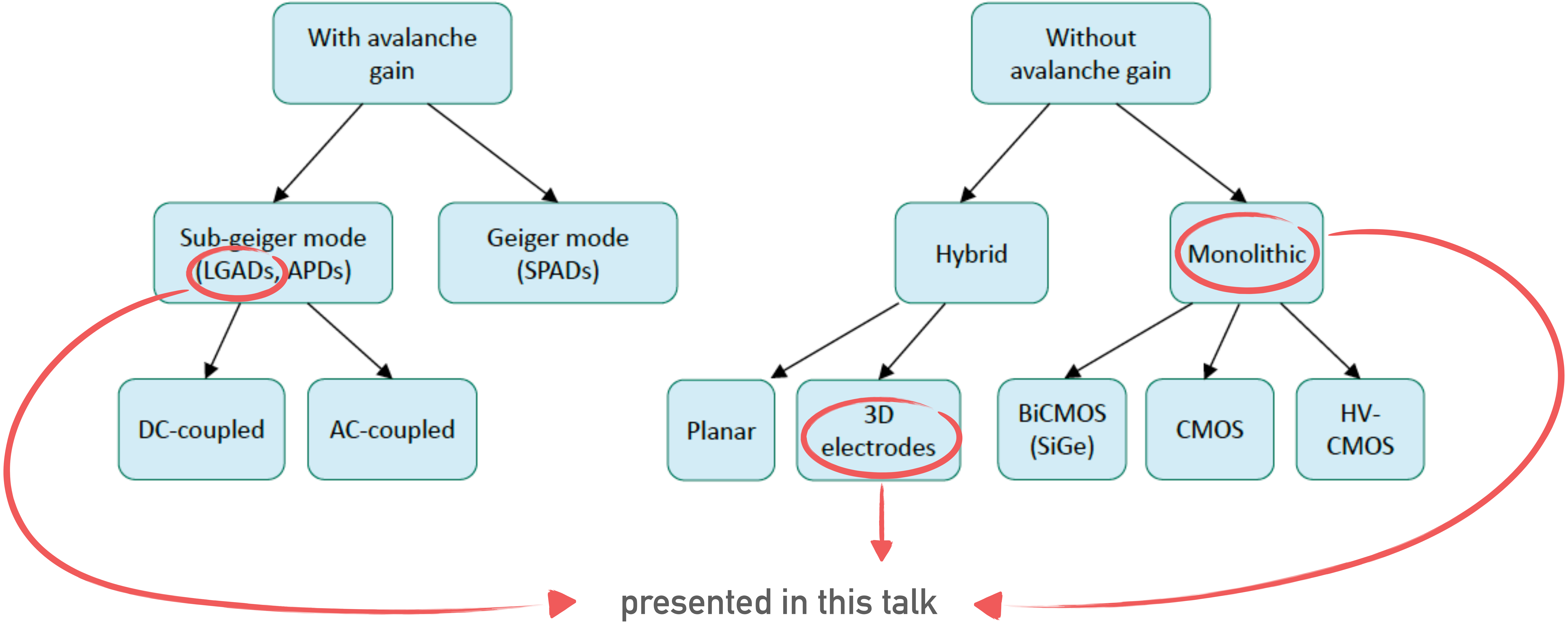
Minimized with:

- Low input capacitance → detector + detector-amplifier interconnection
- Large signal → gain
- Short signal rise time → fast charge collection, fast amplifier

→ Dependent on sensor design

Timing detectors

Several families of silicon detectors for picosecond timing have been designed so far

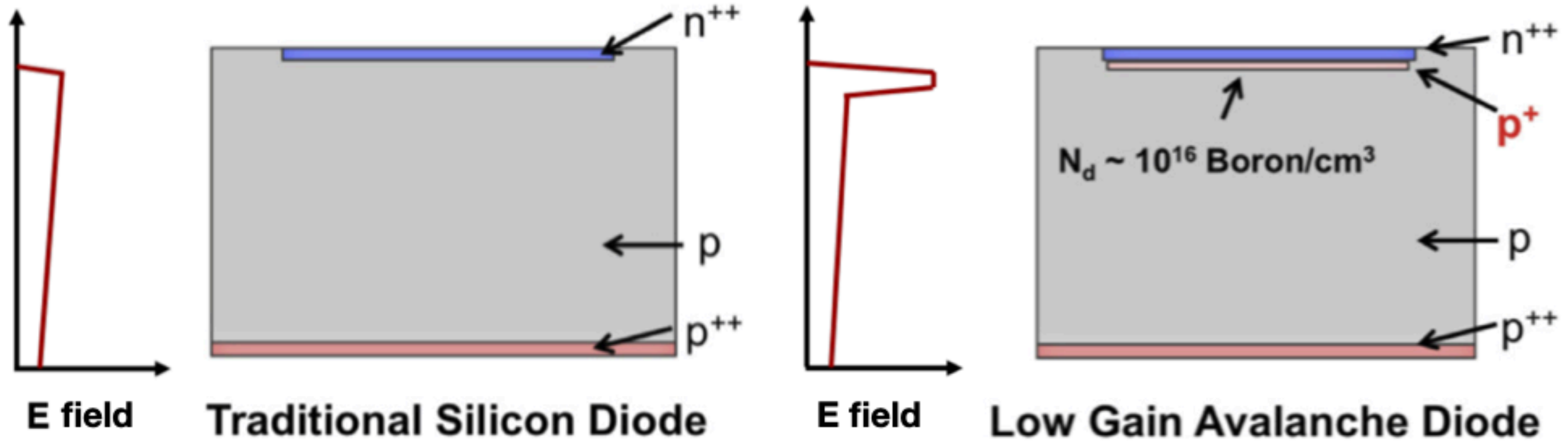


Ultra-Fast Silicon Detectors

Ultra-Fast Silicon Detectors (UFSDs) project: production of innovative silicon sensors based on the Low-Gain Avalanche Diode (LGAD) technology and optimised for timing measurements

LGADs

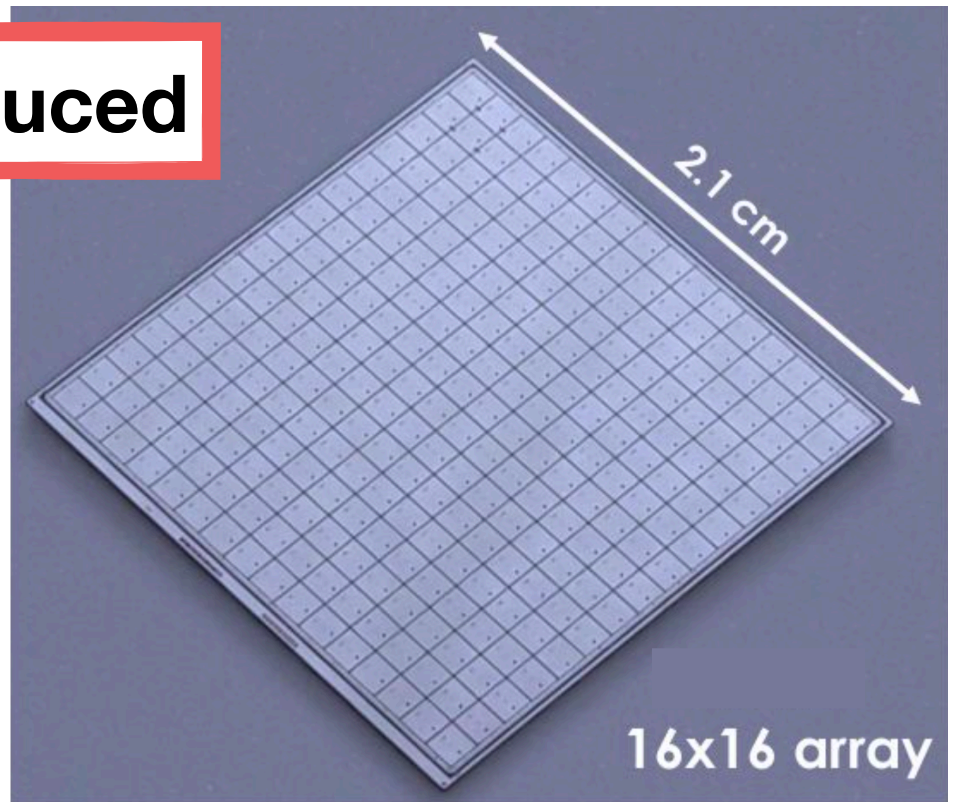
- Additional highly-doped thin implant near the p-n junction
  → gain layer
- High local electric field allowing charges multiplication
- Gain must be moderate to maximise signal/noise ratio



UFSD design for CMS Endcap Timing Layer:

- Large multi-pads arrays
  → Segmentation through gain termination structures
  → Interpad distance 50-100 μm
- Gain uniformity
- Timing resolution $\sigma_t \sim 30$ ps
  → Fast and large signals
- Fluences range up to $\phi \sim 1.7e15\ n_{eq}/cm^2$ ($2.5e15\ n_{eq}/cm^2$ with 50% safety factor)

Already produced



UFSD timing resolution

How to obtain a timing resolution $\sigma_t \sim 30$ ps with UFSDs?

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

- N → moderate gain and low-noise electronics
- dV/dt → fast and large signals → thin sensors with internal gain

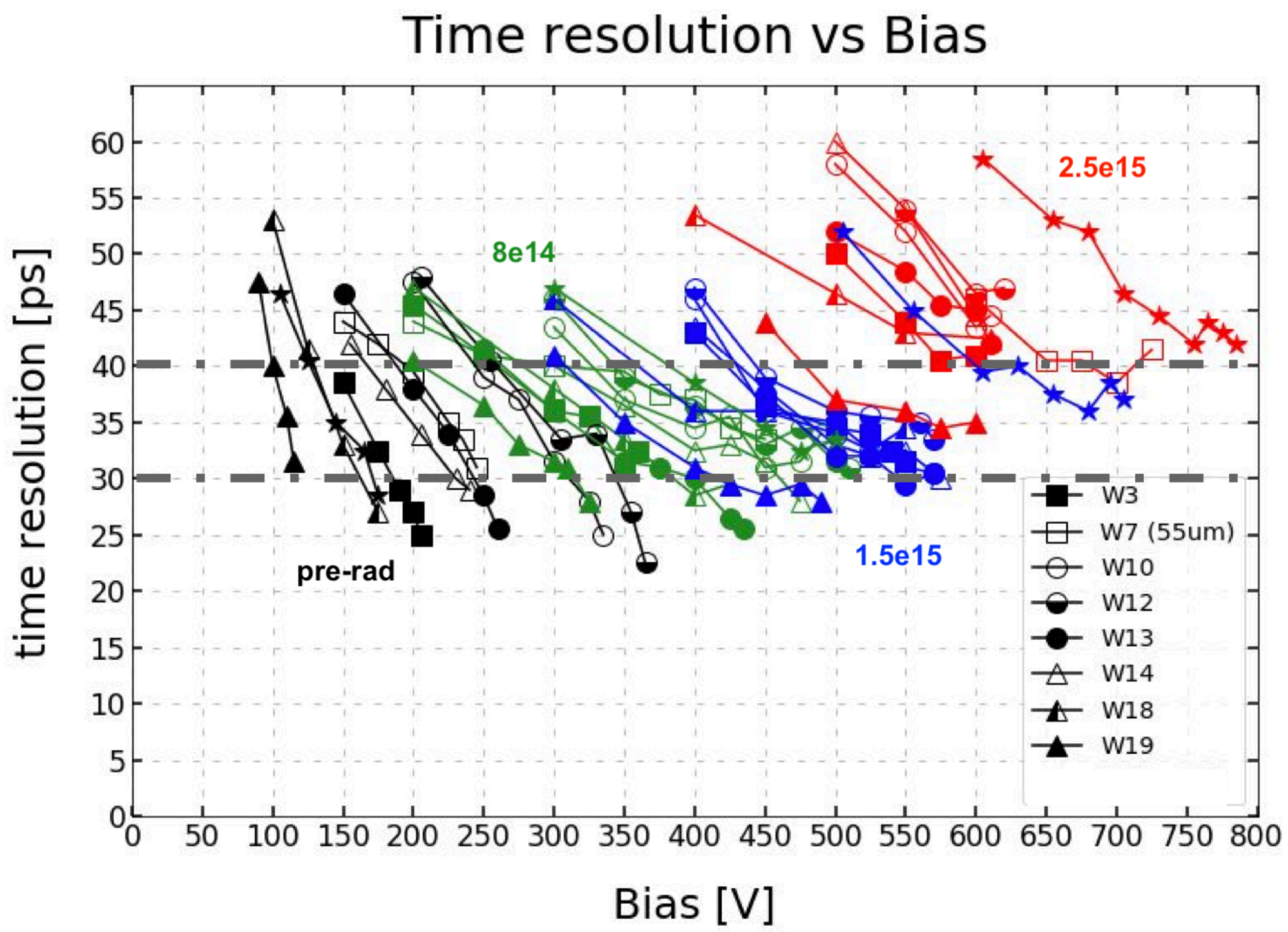
} decreases with gain

$\sigma_{Non-uniform\ Ionization}$ → thin sensors

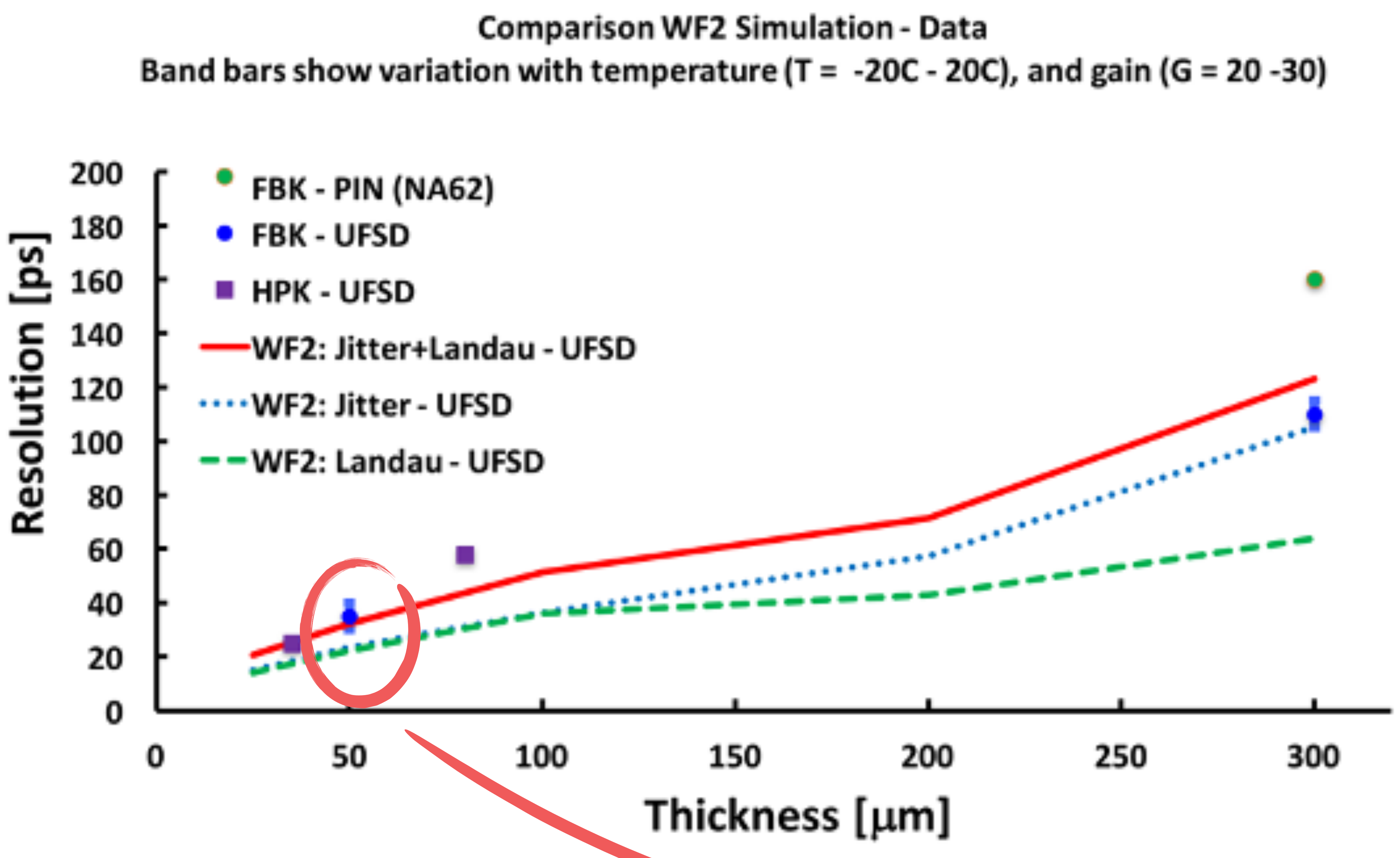
constant with gain

Laboratory measurements on the latest UFSD prototypes show the most performant sensors deliver a sufficient amount of charge and can reach $\sigma_t \sim 30$ ps when new and $\sigma_t \sim 40$ ps at the highest irradiation point

→ Timing resolution and radiation hardness within requirements of CMS and ATLAS



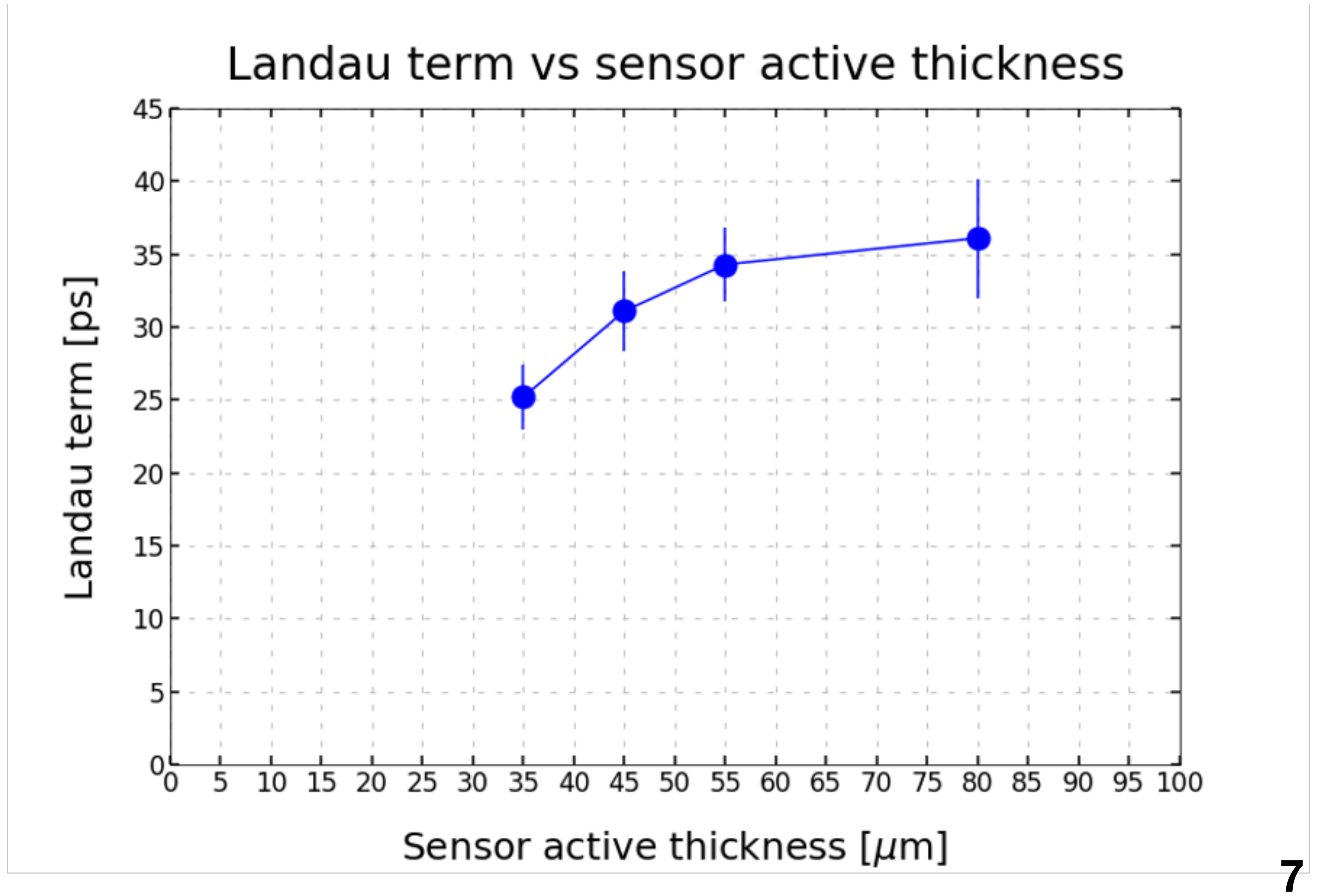
How can we do better?



In UFSDs, time resolution decreases for thinner sensors

UFSD state-of-the-art: 45-55 µm sensors largely tested

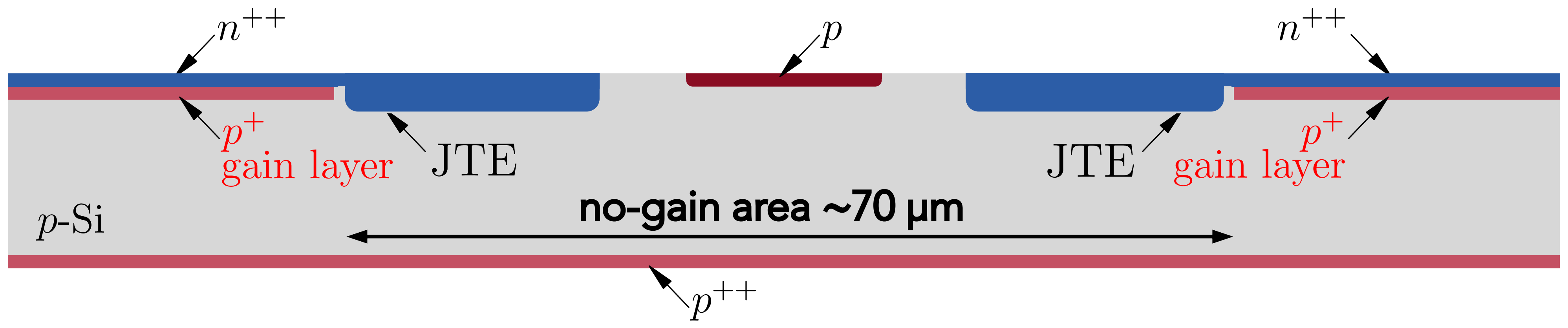
→ Current sensor choice for CMS and ATLAS timing layers



Sensors with 25 and 35 µm active thickness have been manufactured within the FBK ExFlu0 production

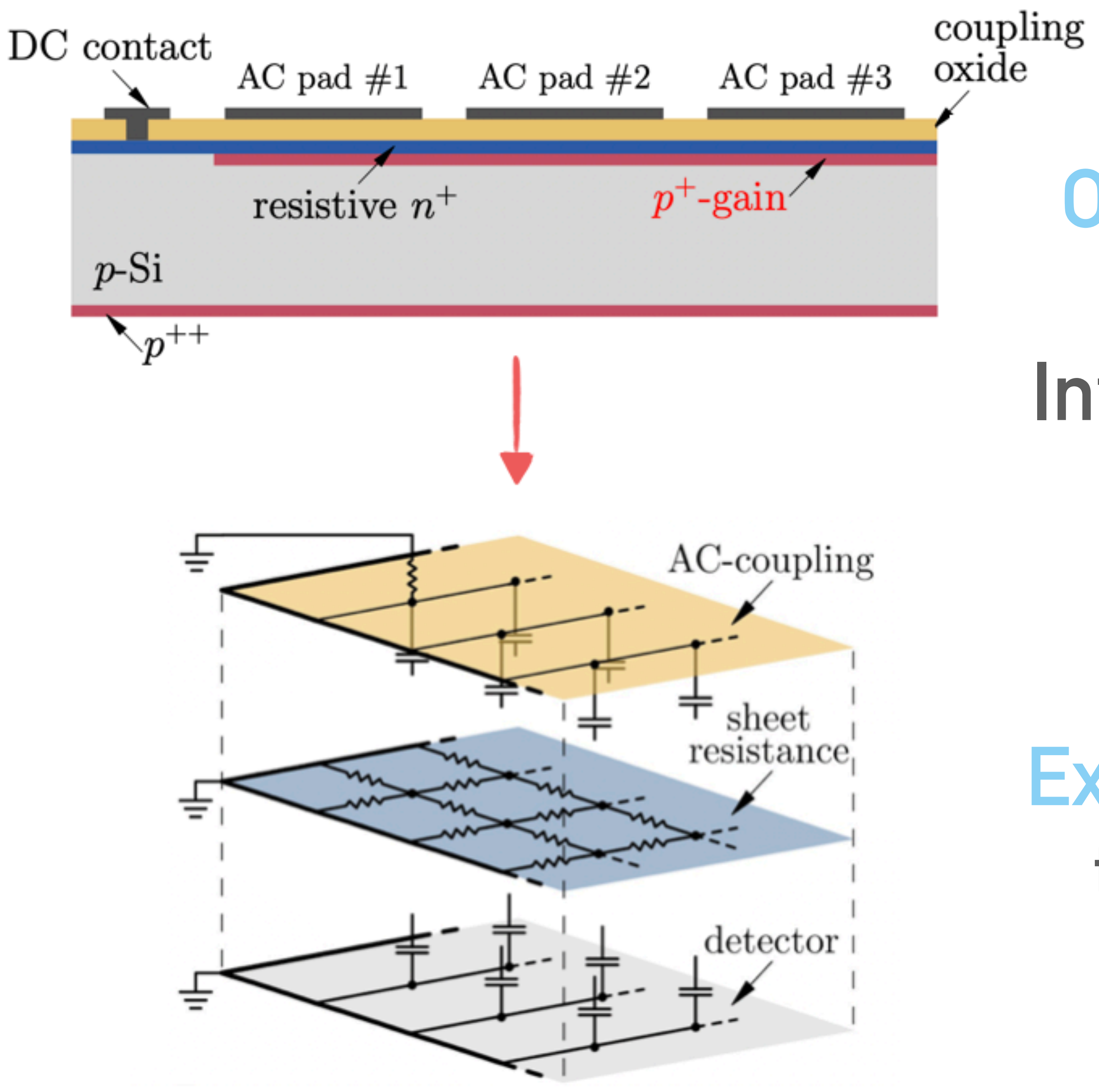
→ 15-20 ps resolution looks achievable with thinner sensors

100% fill factor LGADs



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

Resistive AC-Coupled Silicon Detectors (RSD)



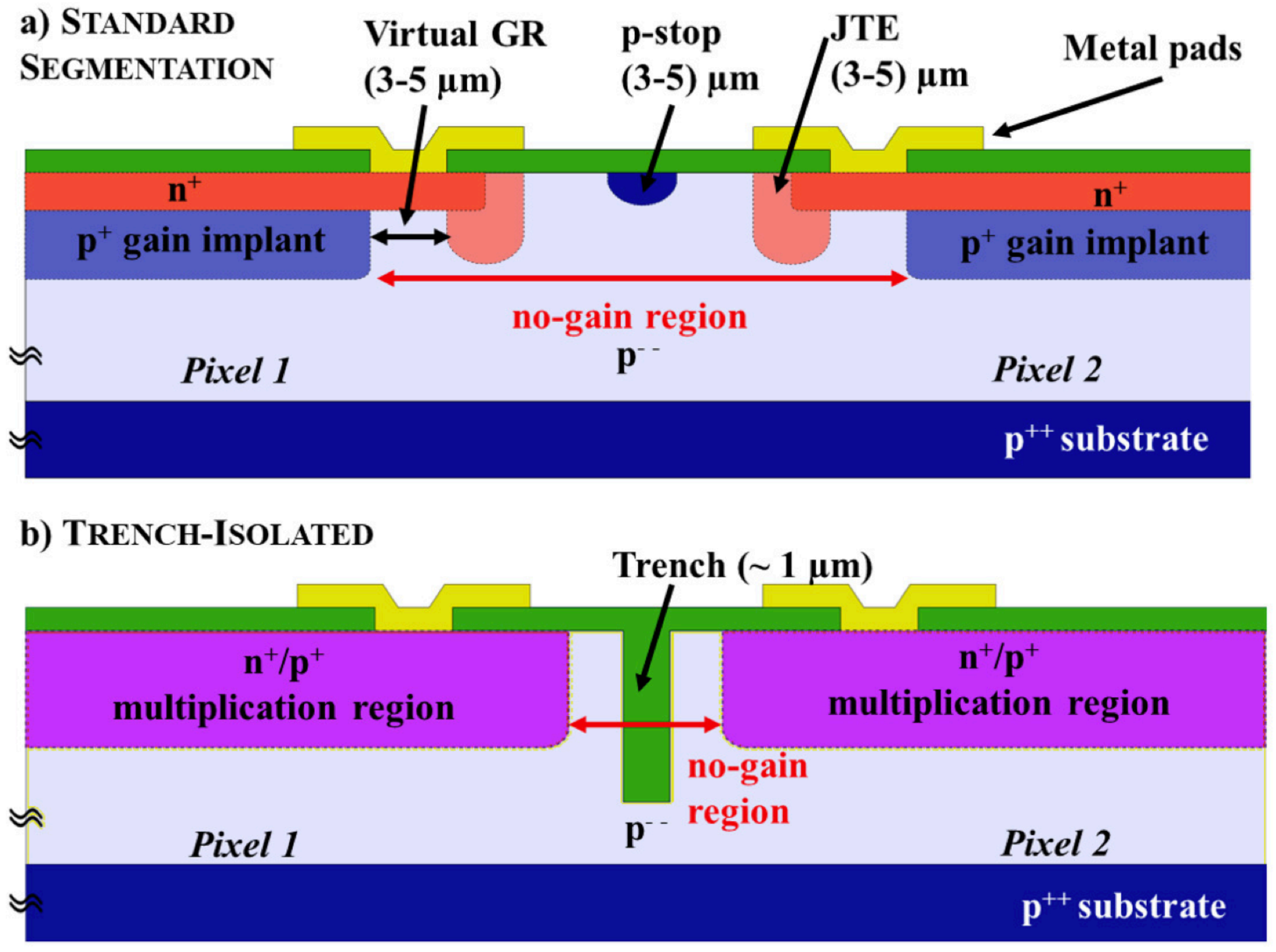
One continuous gain layer

Introduction of AC coupling and resistive read-out in silicon detectors

Excellent spatial resolution thanks to charge sharing

Trench Isolated (TI) LGADs

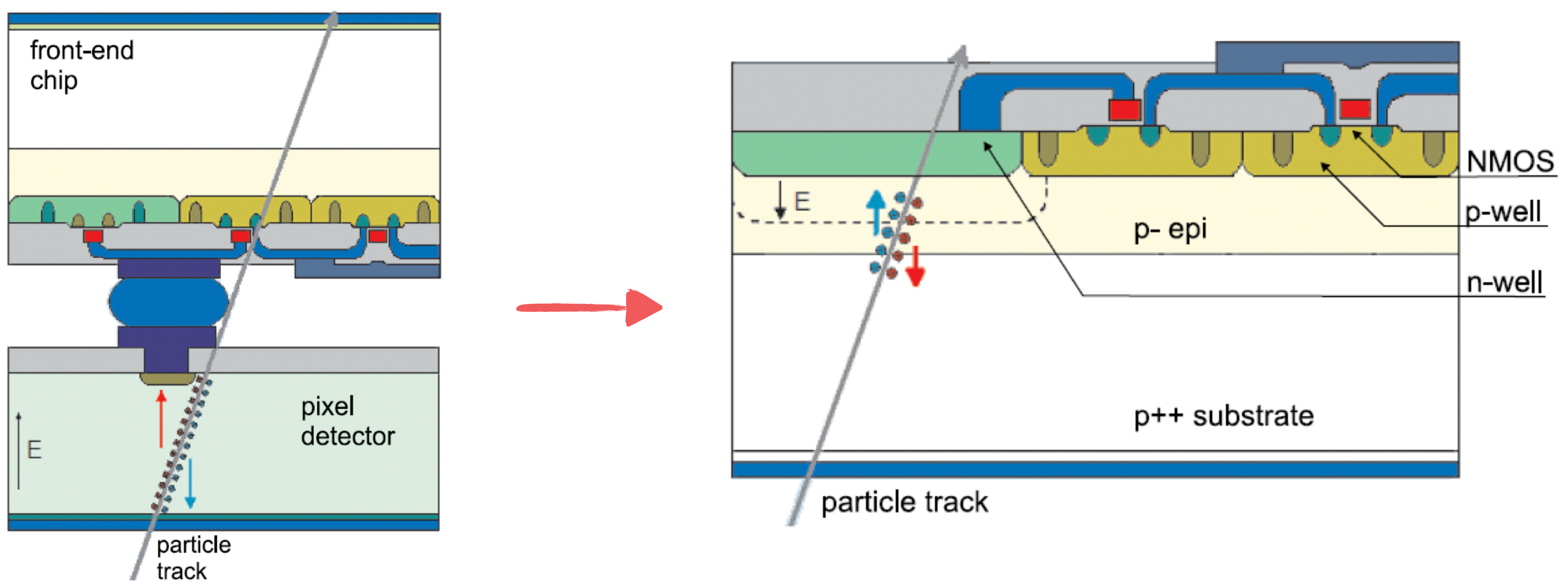
Gain termination implants replaced with a trench



Monolithic sensors

Monolithic sensors combine the sensing layer and its readout circuitry in a single integrated circuit

- Low capacitance
- Excellent signal/noise ratio
- Radiation hardness
- Low material budget



New field, multiple possible approaches based on two technologies: CMOS and SiGe

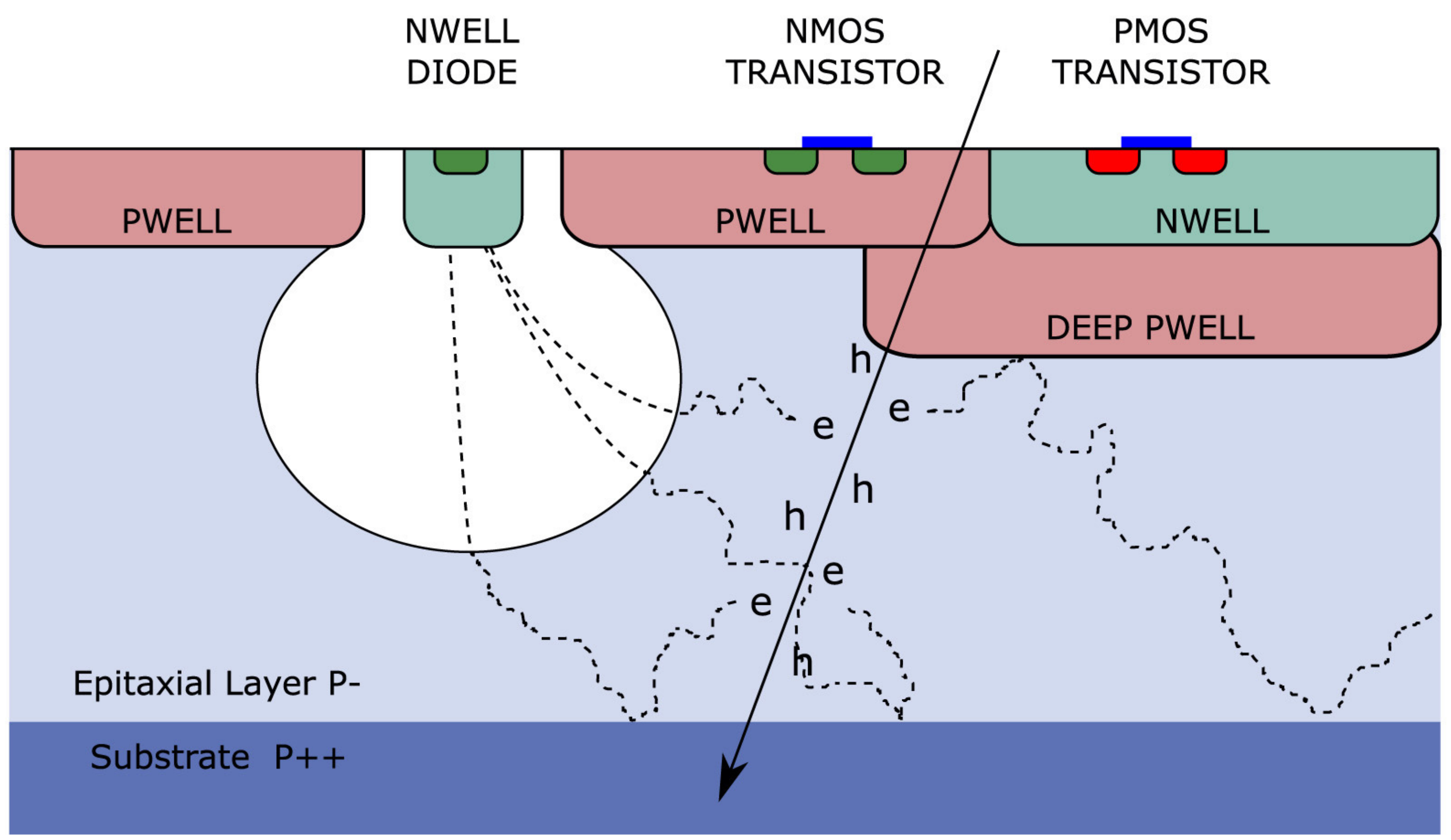
- CMOS Monolithic Active Pixel Sensors (MAPS)
  → ALICE 3 TOF detector
- High Voltage CMOS (HV-CMOS)
  → CACTUS with Depleted MAPS
- Fully Depleted MAPS
  → ARCADIA
- Monolithic CMOS sensors with small collection diodes
  → ATTRACT project FASTPIX
- Monolithic SPAD arrays

- SiGe BiCMOS
  → ERC project MONOLITH
  → SNSF project FASER
  → ATTRACT project MonPicoAD

CMOS MAPS in the ALICE experiment

ALICE experiments is using CMOS MAPS for the upgrade of the Inner Tracker System (ITS)
→ ALPIDE sensors

Evolution of TowerJazz 180 nm CMOS Imaging Process:
- 25-µm thick epitaxial layer with high resistivity on p-type substrate
- Small n-well collection electrode in the center of the sensing volume → low capacitance
- Deep p-well provides shielding of full CMOS circuitry



UPGRADE

Timing application in future Time-Of-Flight barrel detector of ALICE3 experiment:

- Goal: TOF timing resolution of ~20 ps
- Large-size MAPS: up to $21 \times 21\ cm^2$
- Sensors thinned to 20-40 µm
  → large area curved sensors
  → unprecedented low material budget: $0.5\ \%\ X_0$ per layer

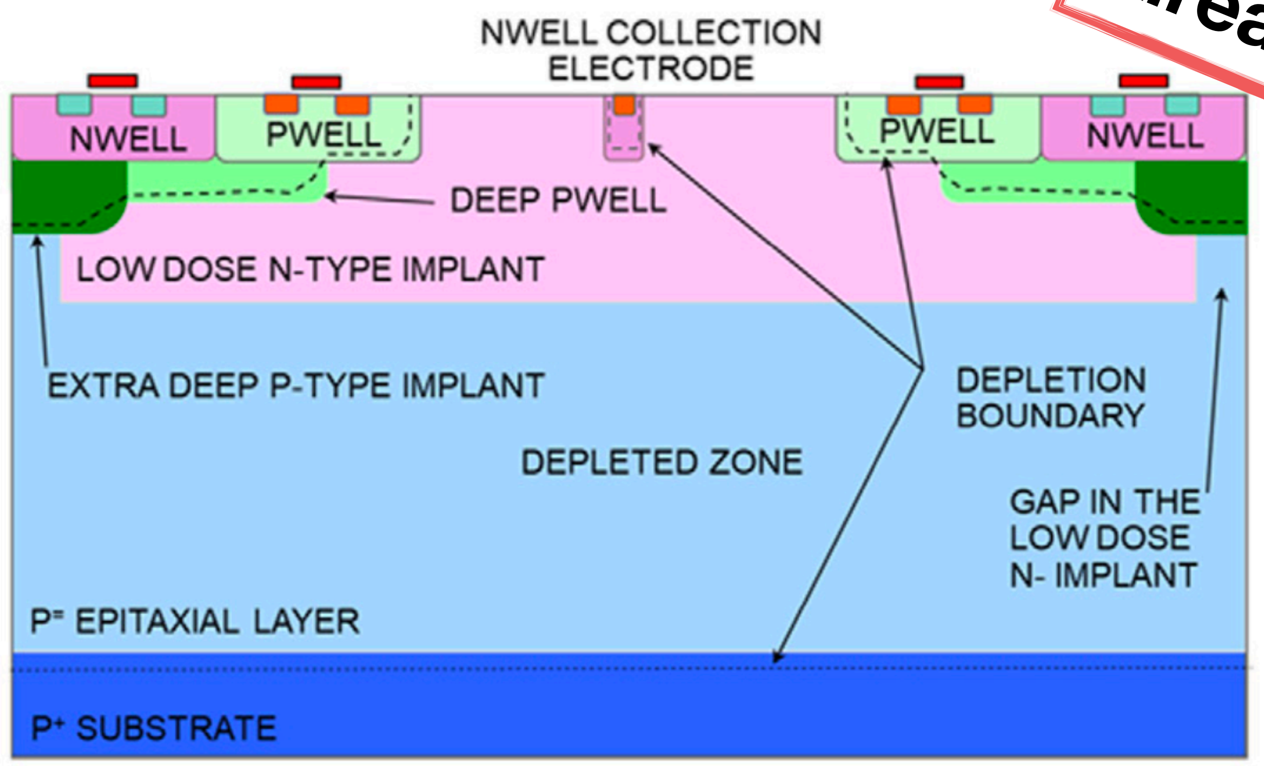
The CMOS family for fast timing

Goal: achieve fast collection time using fully depleted CMOS and high uniform electric fields

→ junction modified to reproduce the field of a parallel plate capacitor

FASTPIX

- Based on CMOS 180 nm
- Highly resistive p-type 25 μm-thick epitaxial layer
- Full lateral depletion
- Small hexagonal electrodes with ~10 μm pitch
- 3D micromachined structures

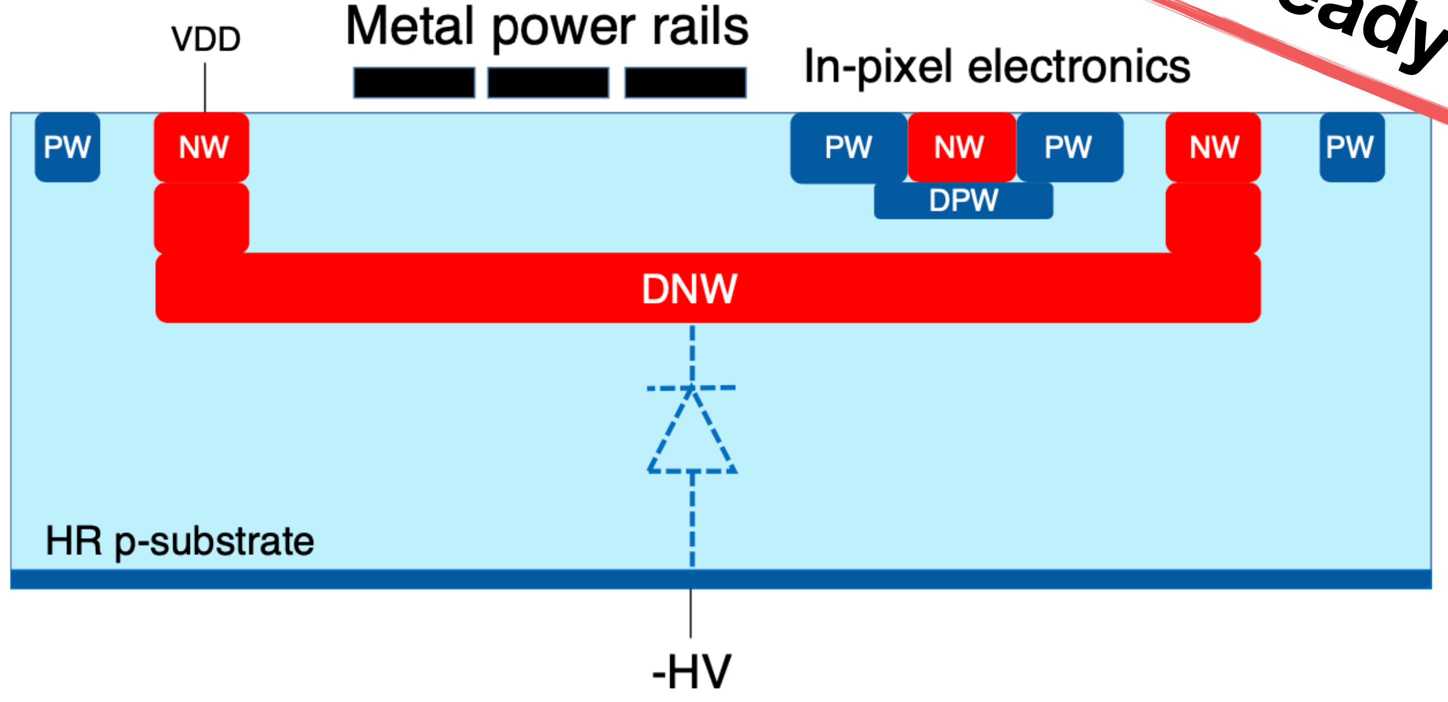


Already produced

CACTUS

CMOS ACtive Timing μ Sensors

- Based on 150 nm CMOS
- High Voltage CMOS
- High resistivity 200 μm-thick substrate
- Electronics inside the pixel
- Large collecting diodes with $\sim 1\ mm^2$ pitch
- ~100 ps time resolution

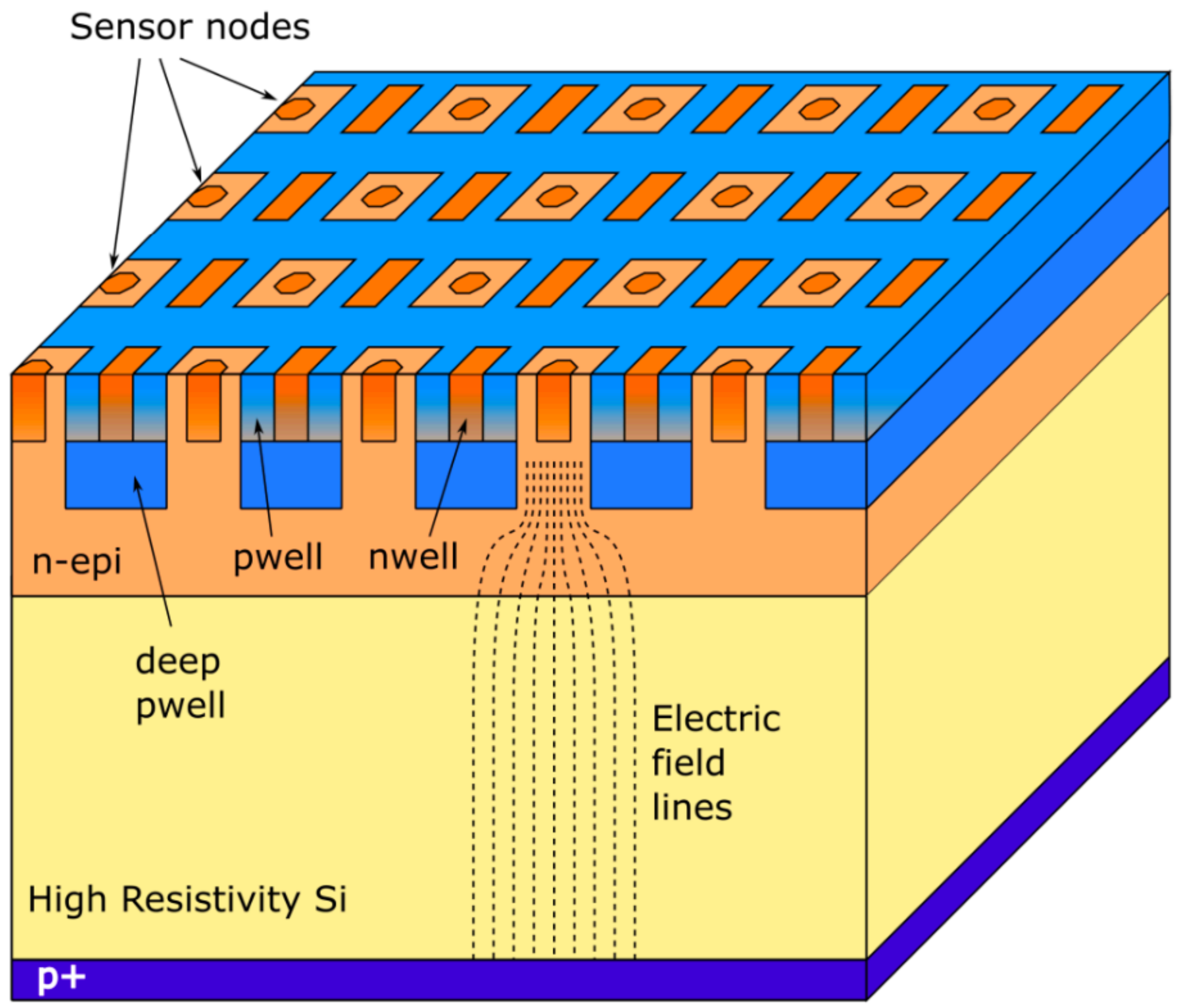


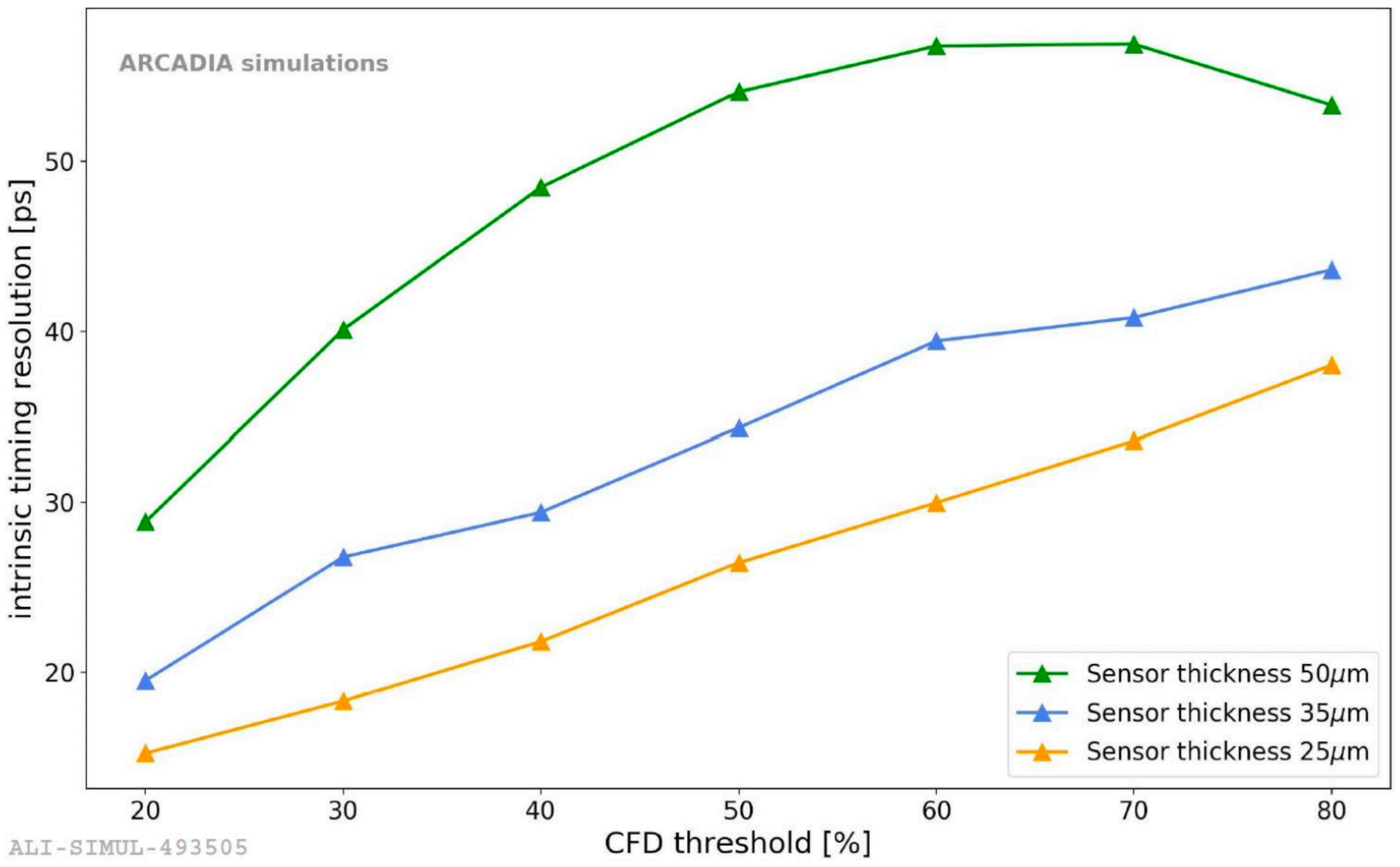
Already produced

The CMOS family for fast timing

ARCADIA

- Based on 110 nm CMOS
- Fully depleted MAPS
- Manufactured devices: 100- and 300-μm thick n-type active substrate
  25 and 50 μm pitch
- Under study: 25-, 35-, 50-μm thick active substrate
  10 and 50 μm pitch

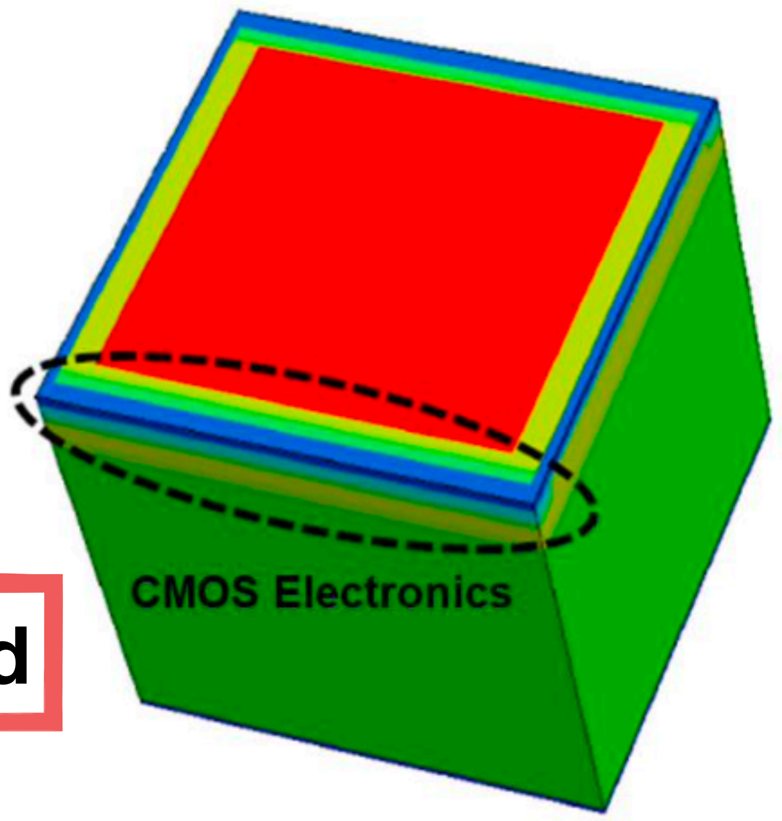




Latest simulations on new 50-μm pitch design:

- Uniform electric field
- Thinner substrates have a better timing resolution, down to ~15 ps

To be produced

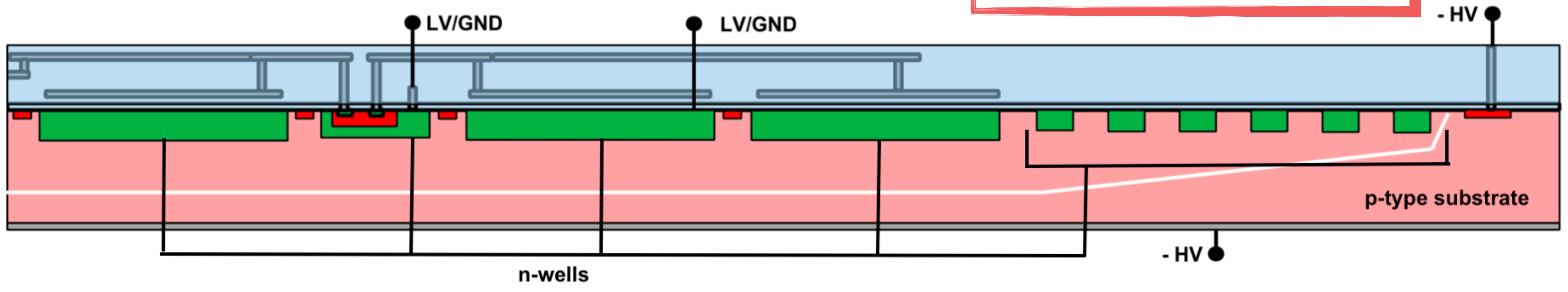


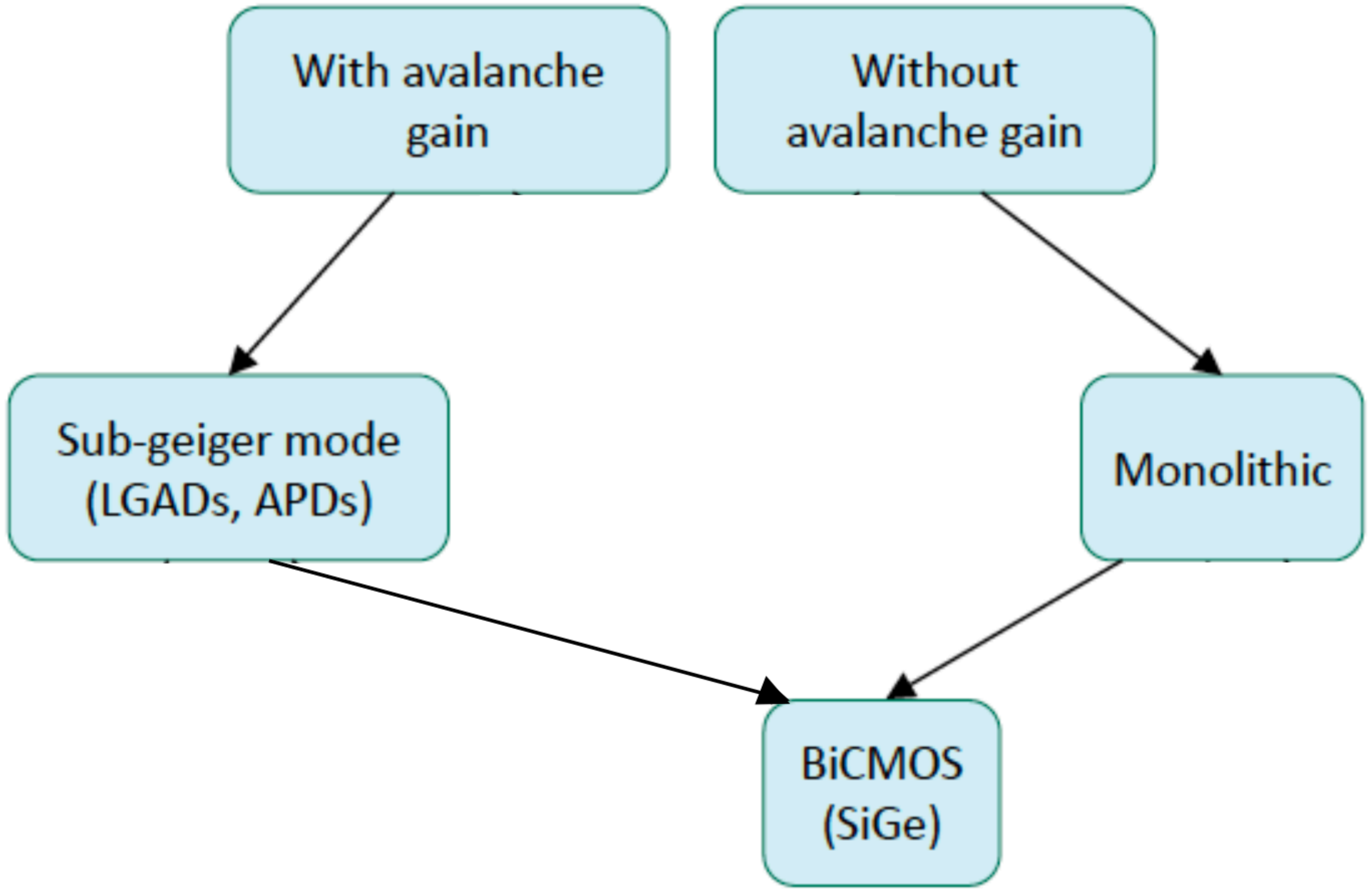
SiGe BiCMOS

SiGe BiCMOS benefit from the excellent properties of Silicon-Germanium, very fast and low-noise

- Based on SiGe 130 nm BiCMOS
- Pixel matrix integrated inside the guardring
- Small hexagonal pixels: 65 and 130 µm side
- 60 µm-thick active substrate
- ~50 ps time resolution

Already produced





Future evolution of the SiGe BiCMOS technology:

LGADs + Monolithic SiGe BiCMOS

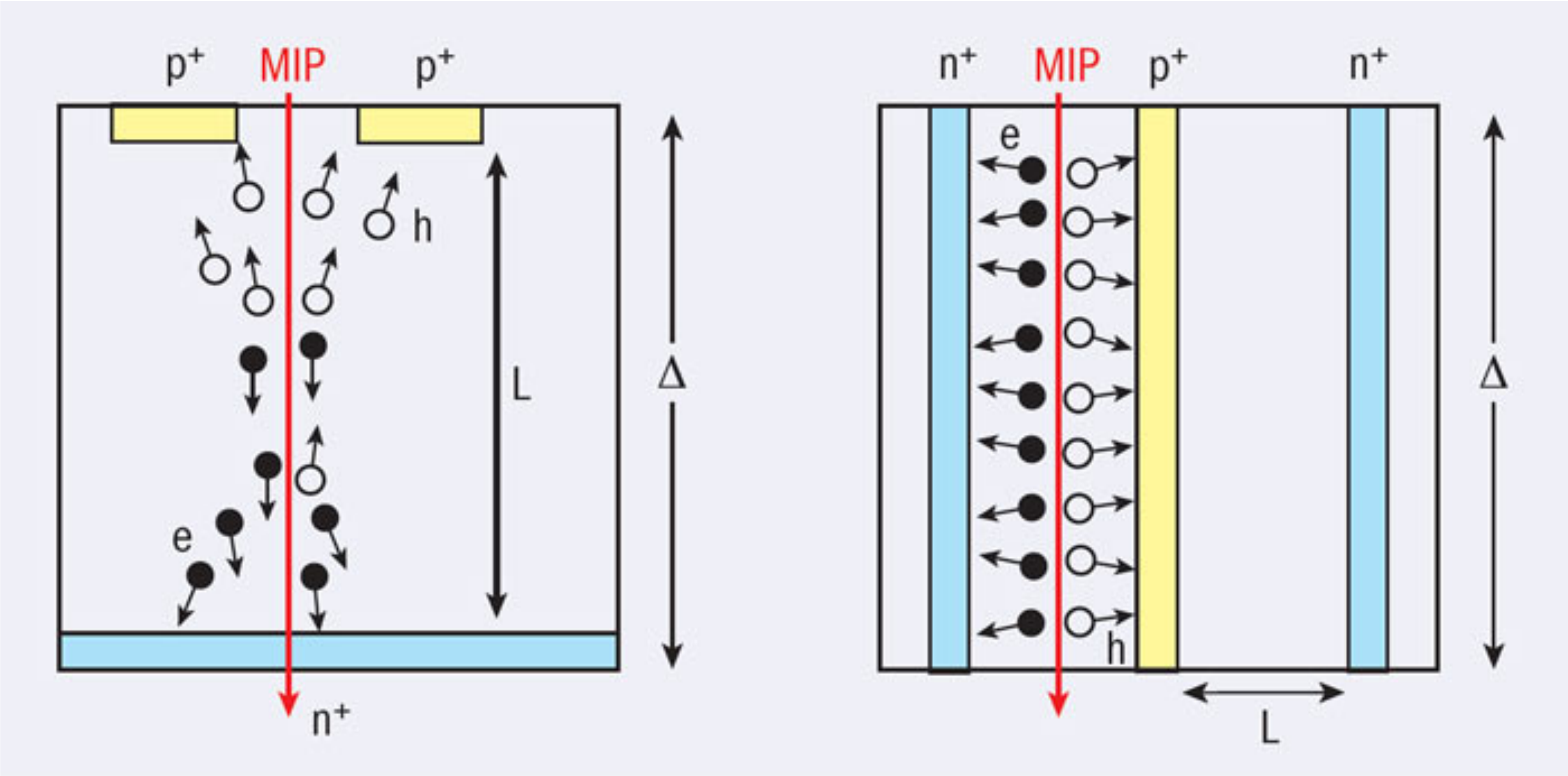
→ Monolithic Avalanche Detectors

Not produced yet

3D sensors

Collecting electrodes are placed close to the carriers generated by impinging particles
→ Separation of drift time and amount of charge

- Small pixels
  - → short drift distance
  - → low capacitance
- Thick active volume
- ~100% fill factor
- High radiation tolerance due to small cells
  - → detection efficiency unchanged up to $3e16\ n_{eq}/cm^2$
  - → tested working devices up to $3e17\ n_{eq}/cm^2$



Planar: $\Delta = L$ **3D:** $\Delta >> L$

3D sensors optimization for timing measurements:
designed to achieve constant weighting field and drift velocity
→ column and trench electrodes

Timing with 3D sensors: column 3D

Column 3D

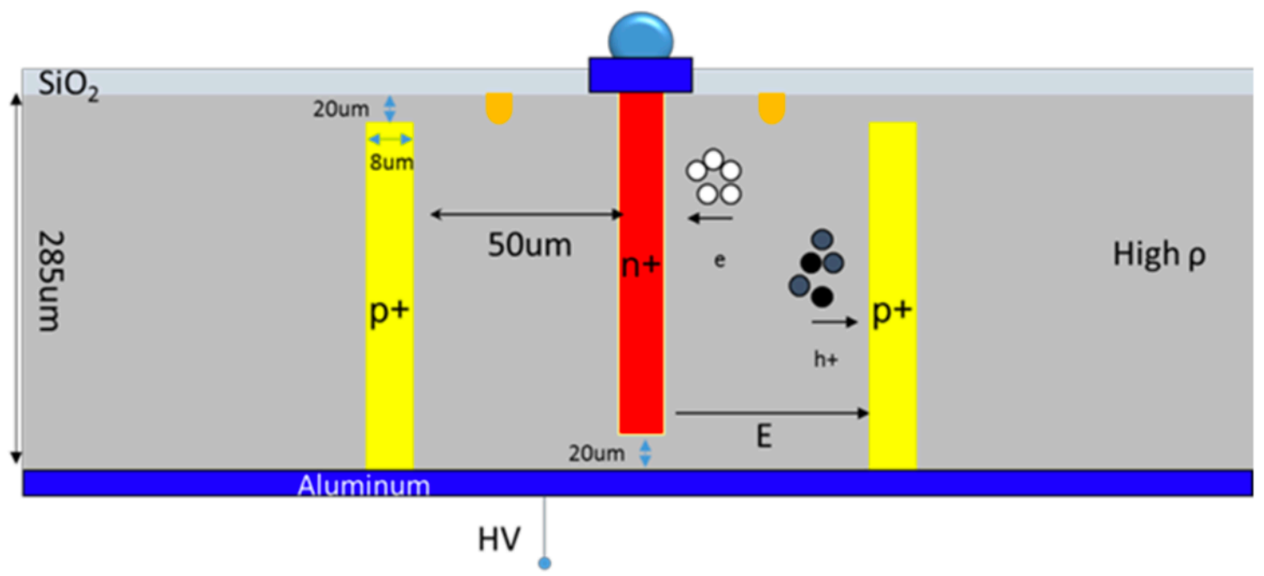
- High resistivity 300 μm-thick substrate
- 10 μm wide columns
- Electric field proportional to 1/r
- $25 \times 25\ \mu m^2$ and $50 \times 50\ \mu m^2$ cells

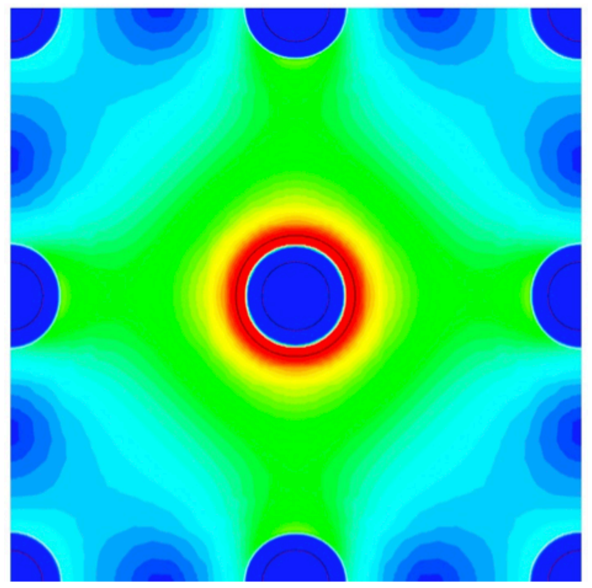
Time resolution measured for single cell:

✦ ~13 ps with $25 \times 25\ \mu m^2$ cell

✦ ~32 ps with $50 \times 50\ \mu m^2$ cell

No impact of radiation on detector performance





Trench 3D

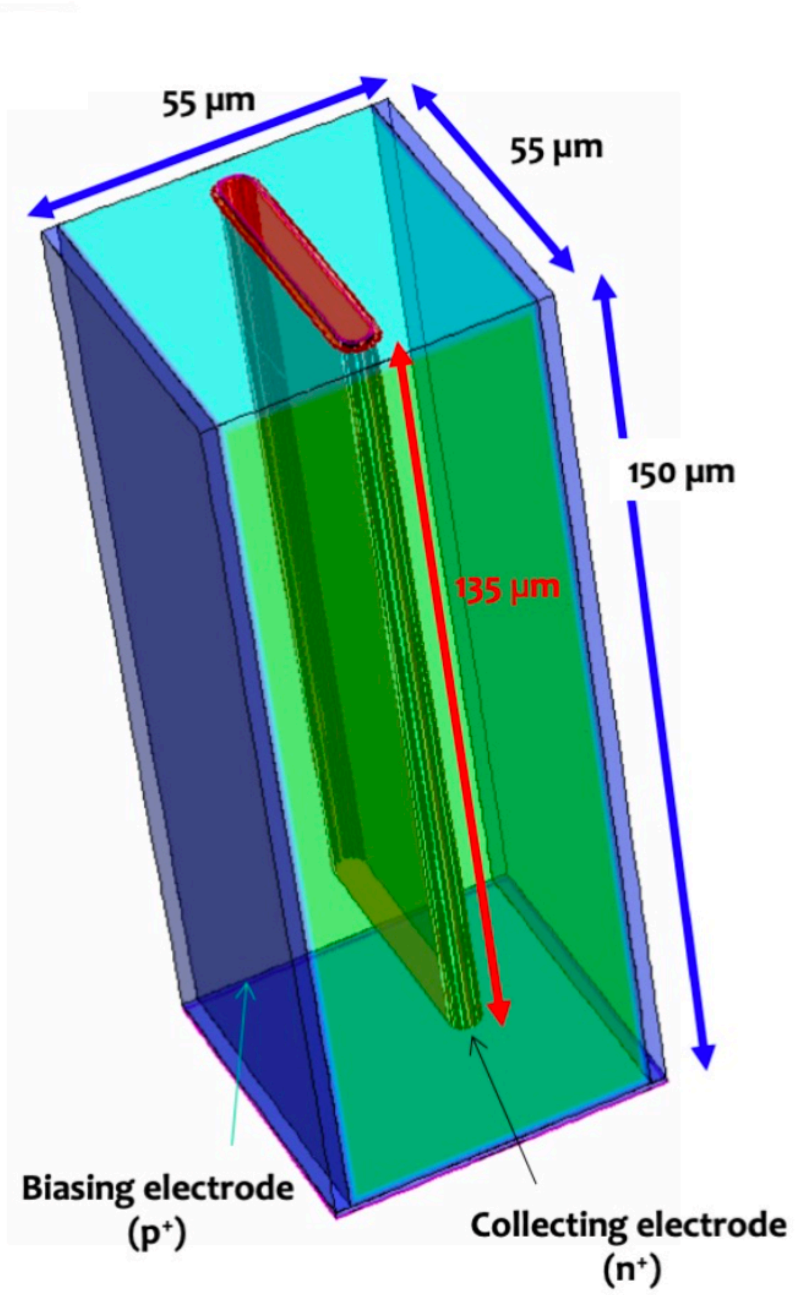
TimeSPOT project

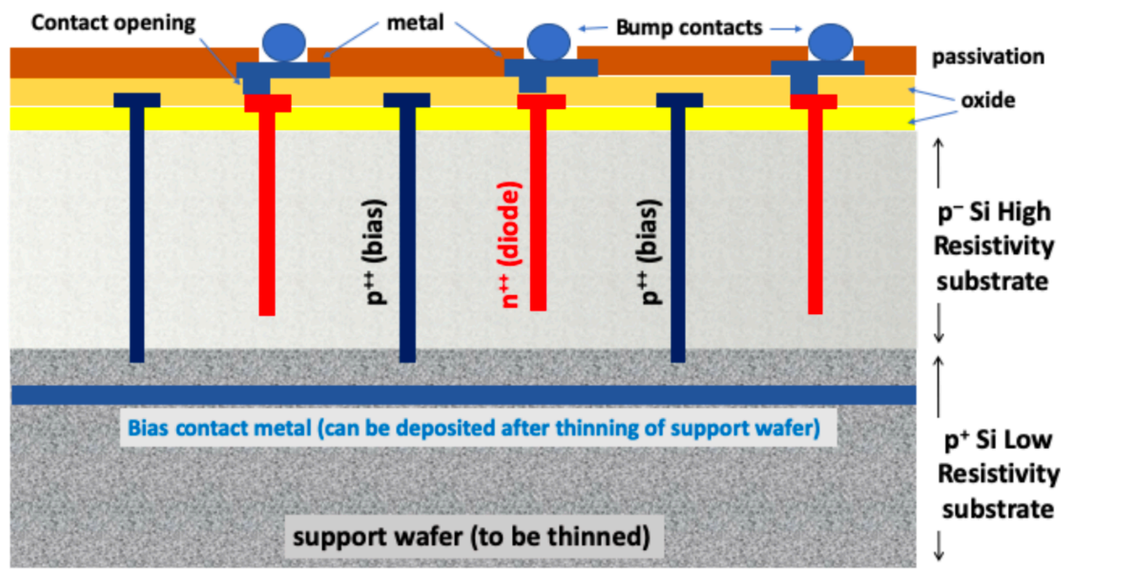
- 150 μm-thick active substrate
- $55 \times 55\ \mu m^2$ pixels
- 135 μm deep electrode
- Uniform electric field

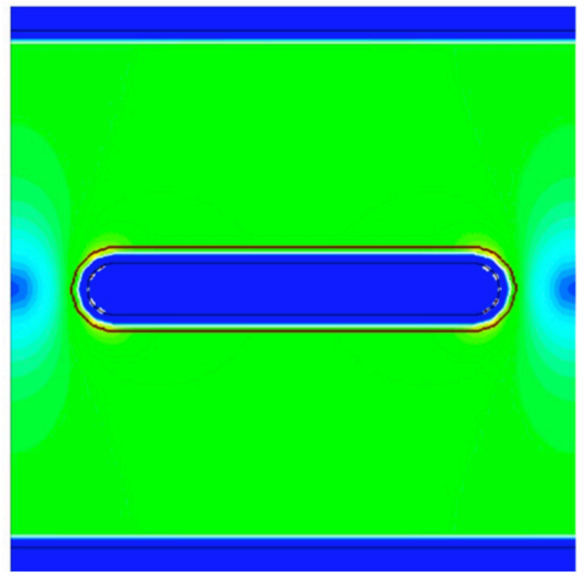
Time resolution measurements:

✦ ~18 ps from FE electronics

✦ ~15 ps from intrinsic resolution







Conclusions

Timing information will be fundamental for experiments at future colliders to perform particle identification and correctly benchmark tracking of single events in high density environments

Requirements for new timing detectors:

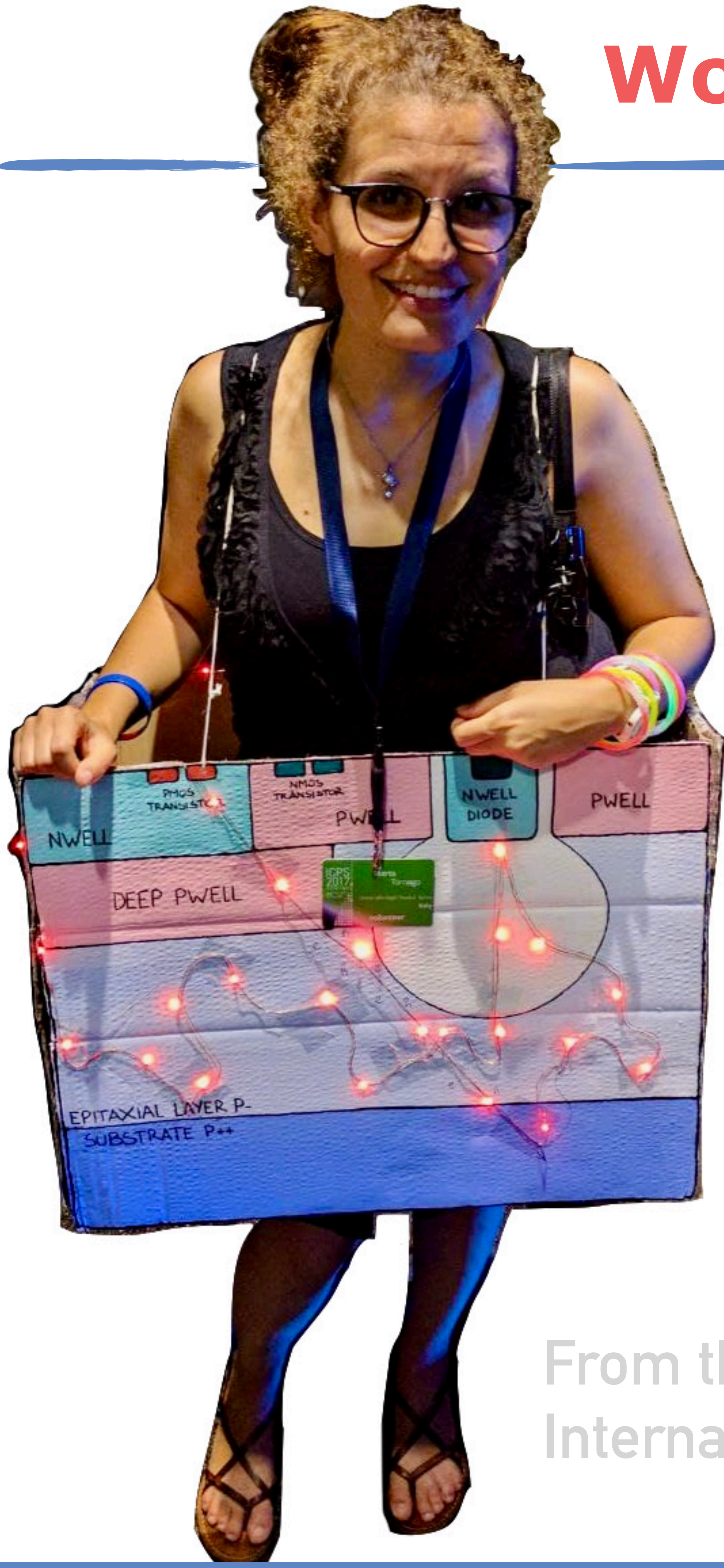
- Timing resolution of few tenths picoseconds
- ~100% efficiency
- Radiation hardness
- Low material budget and cost-effectiveness

Silicon sensors can meet the requirements with innovative technologies recently developed:

- Avalanche Gain sensors: Low Gain Avalanche Diodes chosen by the CMS Endcap Timing Layer
- Monolithic sensors: CMOS MAPS will instrument ALICE3 Time-of-Flight detector
- 3D sensors

Many active projects working on further new technologies such as Monolithic Avalanche Diodes

Working on UFSDs...



...dressed up like a MAPS!

Basically an example of an alive
Monolithic Avalanche Detector!

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From the Costume Party of the
International Conference of Physics Students 2017

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- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
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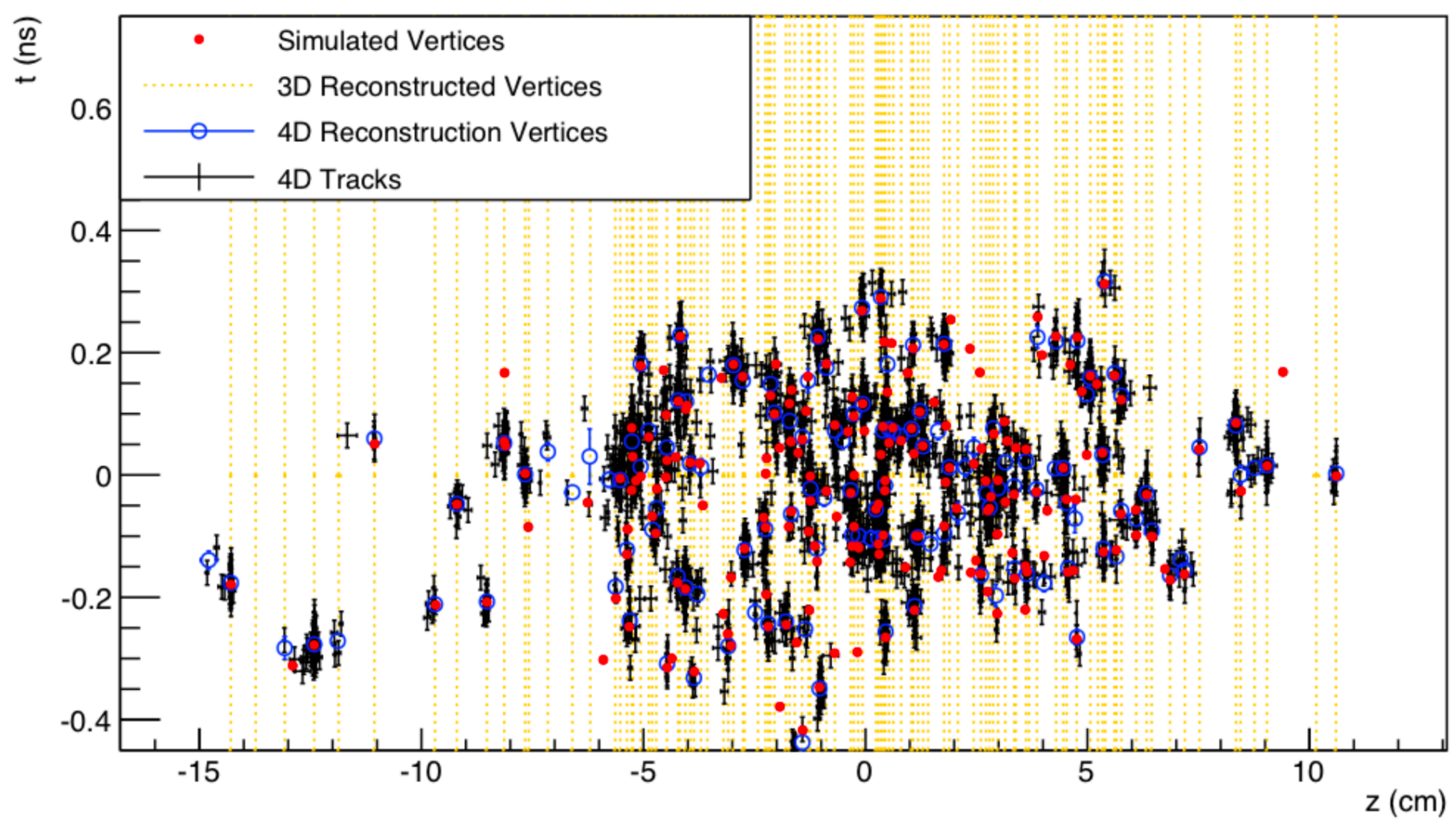
Backup

Impact of timing information

Timing layers will improve experiments performances in terms of pile up rejection and particle identification

Multiple events occurring in the same point in space but at different times

→ 4D tracking: association of timing information to reconstructed tracks



Poor resolution to separate different particles with present detectors

→ Introduction of time-of-flight

CMS:

proton identification and separation of charged k and π at low p_T

ALICE:

separation of low p_T electrons from hadrons