# Recent Advances in UFSD design


**UFSD group**

**INFN – Torino-Genova, Univ. of Turin, Univ. of Piemonte Orient,**

**FBK-Trento, Univ. of Trento, Univ. of California at Santa Cruz.**

**Extensive collaborations with other groups and within the RD50 CERN collaboration**

PRIN 4DInSiDe

AIDA Innova

# UFSD state-of-the art

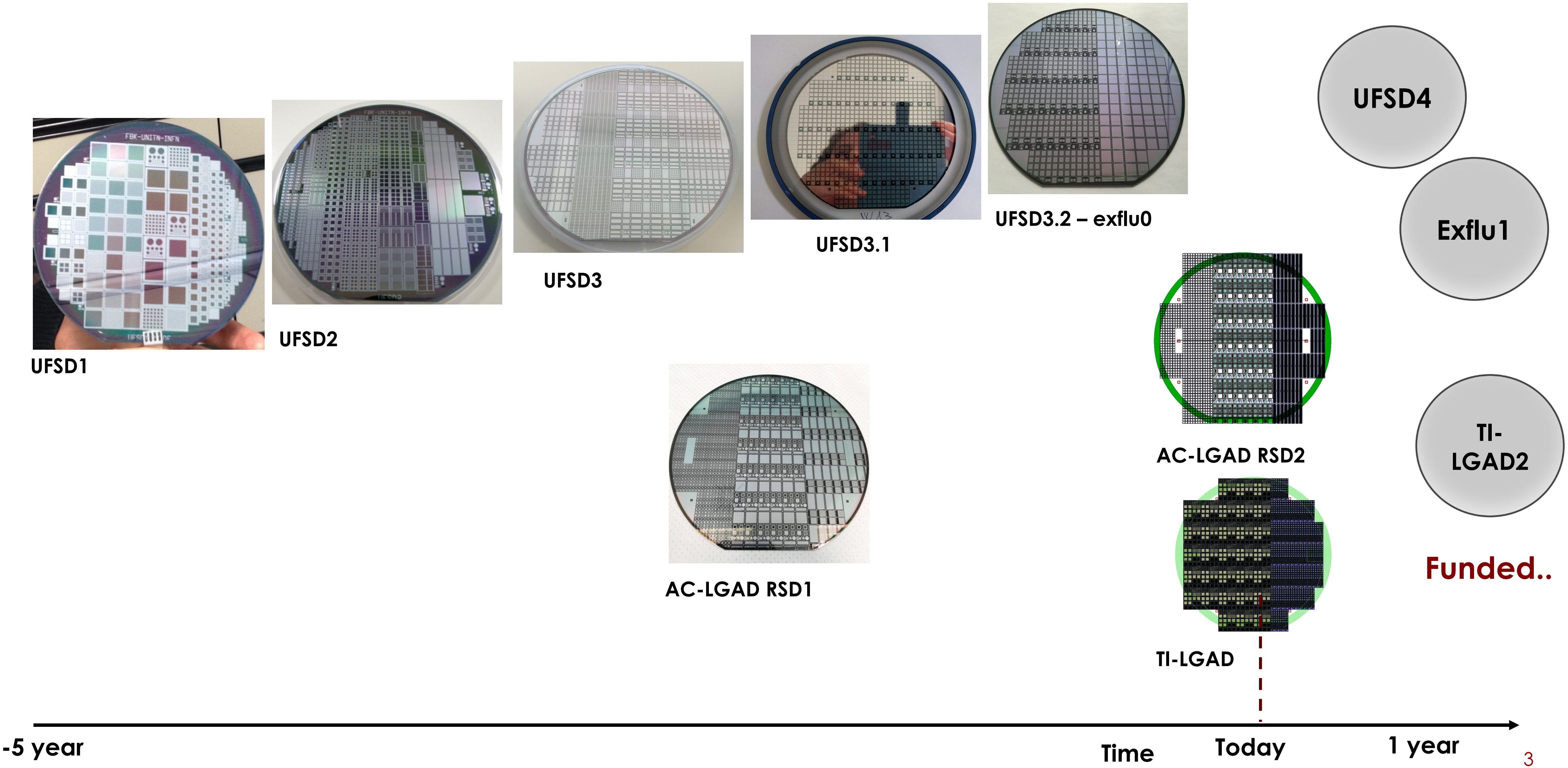
**After several years of intense R&D, ATLAS and CMS have (almost) finalized the designs of the silicon sensors of their timing layers.**

Besides the number of pads (15x15 in ATLAS – 16x16 in CMS), the two designs are very similar:

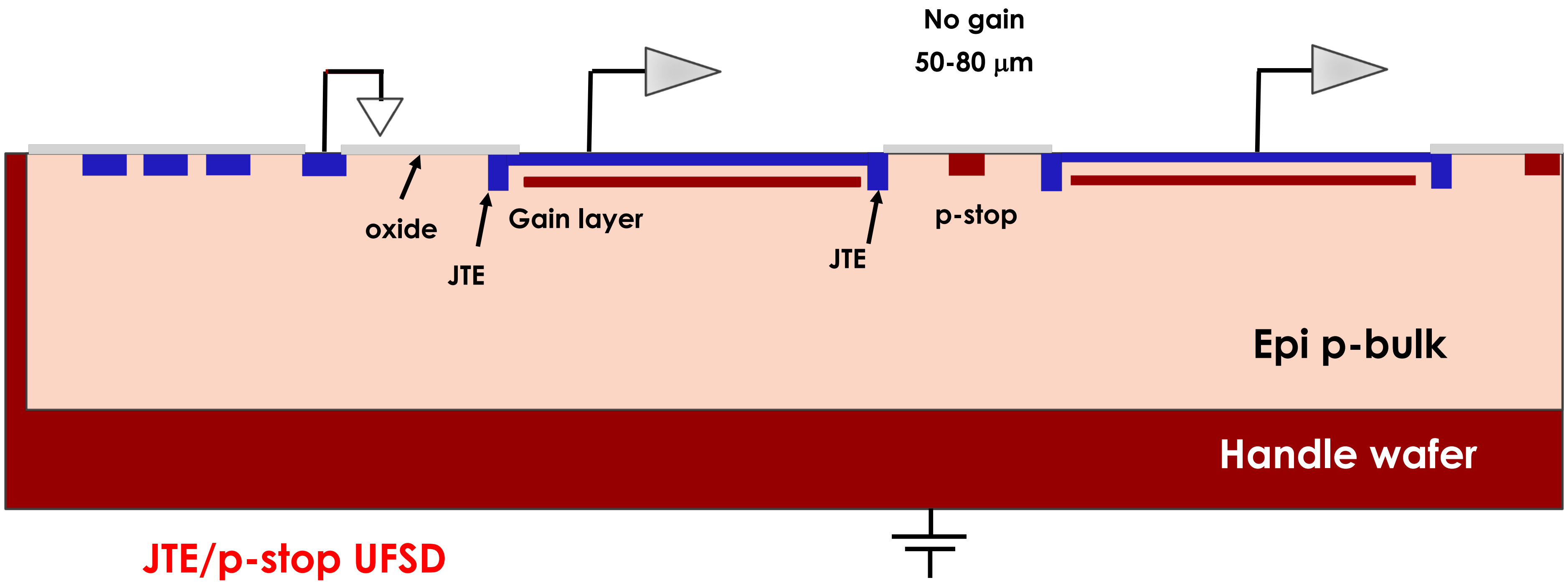
- The sensors are 45-55 $\mu$m thick <100> high-resistivity p-doped epitaxial, on a handle wafer of about 300 $\mu$m
- Each pad is 1.3 x 1.3 $mm^2$ ==> position resolution = 1.3 mm/sqrt(12) = 375 $\mu$m
- The total surface of the timing layers to be built is about 25 $m^2$

➢ **Within this talk, these designs define the UFSD state-of-the-art**

# The path to the present state-of-the art UFSD



# UFSD for ATLAS and CMS

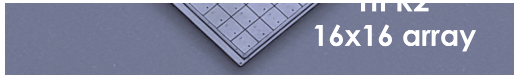



**JTE/p-stop UFSD**

- Very well tested
- will be used up to ~ 2 E15 n/cm2
- Gain ~ up to 40 when new ==> up
- Signal duration ~ 1 ns
- Low noise
- Rate ~ 50-100 MHz
- Good production uniformity

**Shortcomings:**

- **Large no-gain area between pads ==> not suitable for 4D tracking**
- **Intrinsic temporal resolution ~ 25-30 ps due to Landau noise**
- **Total material budget ~ 200-300 μm of silicon**
- **Rad hardness too low for the next generation of hadron colliders**
- **Poor spatial resolution**



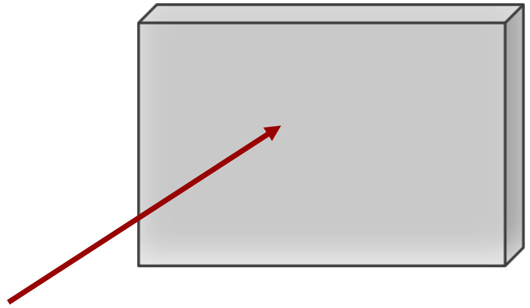
# Developments in UFSD designs

**Improvements of the UFSD design will allow their use in many more applications**

1) Very small no-gain distance ==> 4D tracking
2) Improved radiation resistance ==> inner layer of HL-LHC and beyond
3) Improved temporal resolution
4) Reduced material budget ==> future ee $\mu\mu$ experiments
5) Improved position resolution (AC-LGAD/RSD) ==> 4D tracking

# 1) Very small no-gain distance

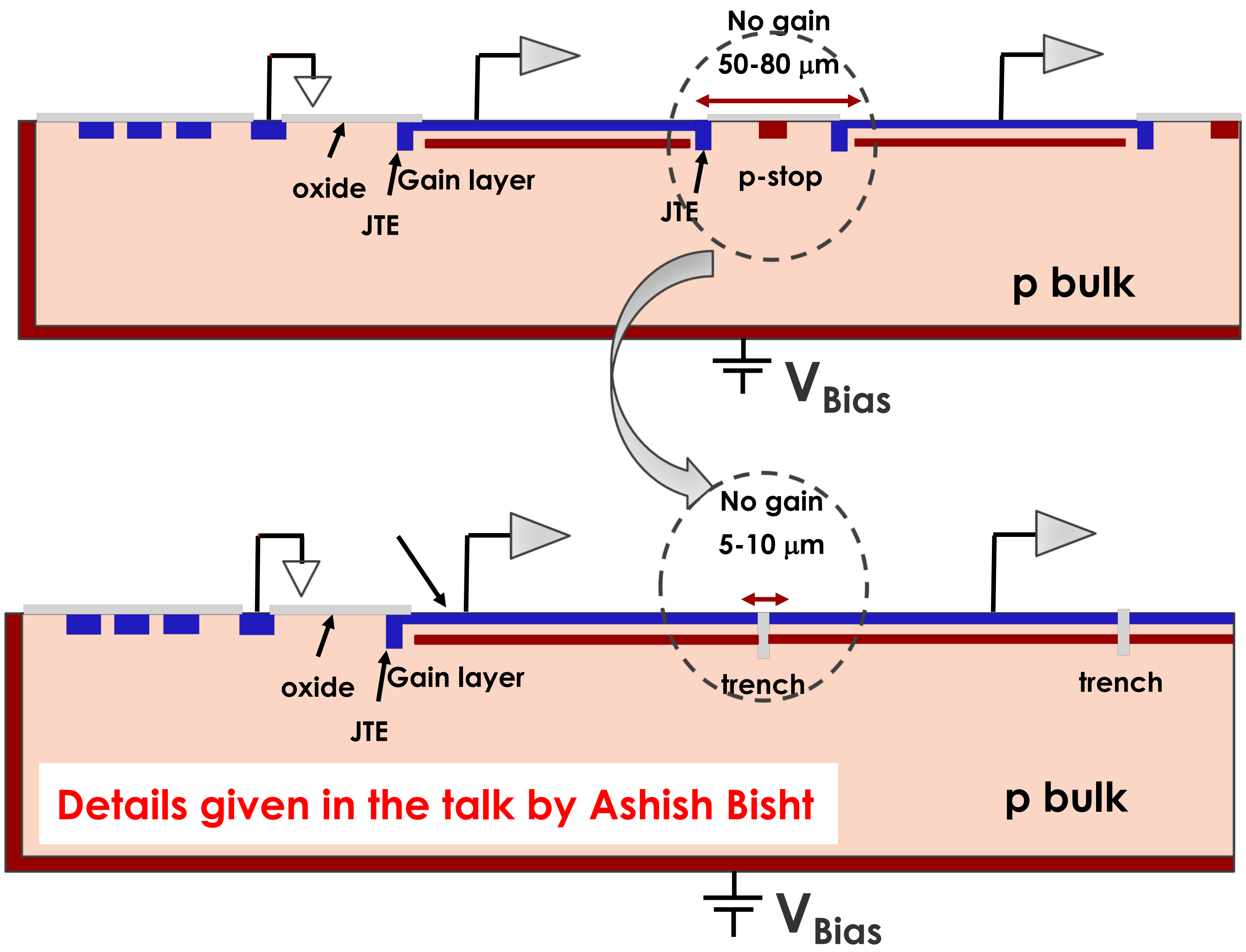
Up to now, activities using UFSD are focused on "timing layers", i.e. a layer that provides the time to a track



**4D trackers requires sensors with small pixels and almost 100% fill factors.**

This can be obtained only *with a re-design of the pad/gain isolation*, decreasing substaintially the inter-pad (no-gain) distance.

# Towards 100% fill factor: Trench Isolated LGAD




**Details given in the talk by Ashish Bisht**

**No-gain region ~ 50-80 μm**

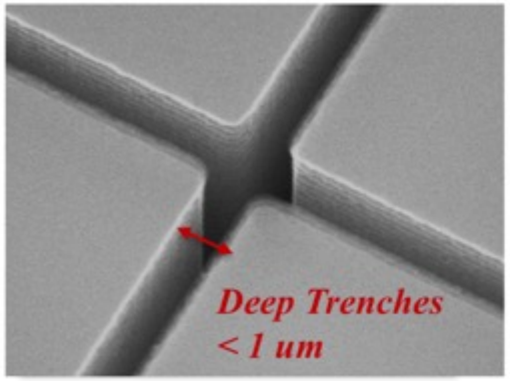
**➔ cannot use UFSDs for small pixels**

**Solution: use trenches for pad isolation**

**➔ No-gain region ~ 5 – 10 μm**

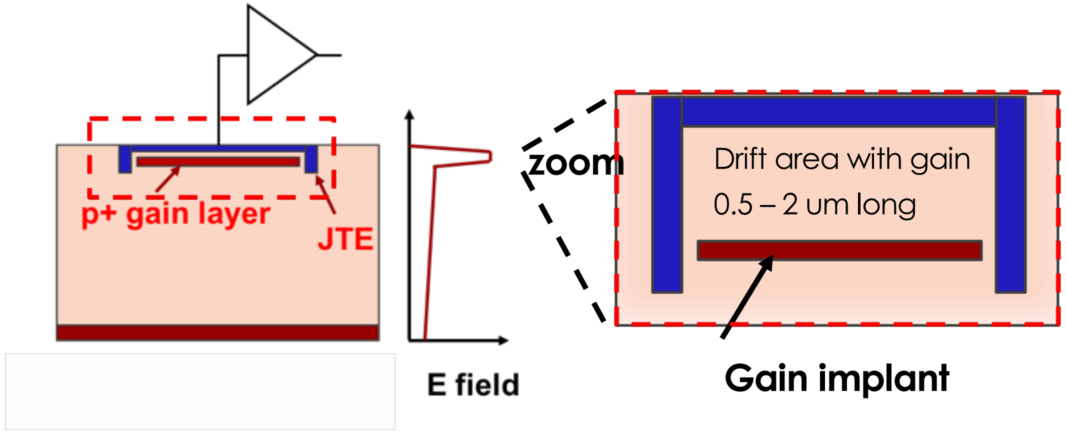
**RD50-TI production**

| Interpad design | Interpad distance [μm] |
|---|---|
| V1_1TR | $2.7 \pm 0.2$ |
| V2_1TR | $6.5 \pm 0.2$ |
| V3_1TR | $7.9 \pm 0.1$ |
| V4_1TR | $10.6 \pm 0.2$ |
| V2_2TR | $8.9 \pm 0.2$ |
| V3_2TR | $10.3 \pm 0.1$ |




***→ The R&D to achieve small pixels is clear***

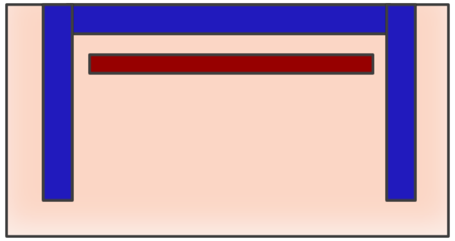
# 2) Improved radiation resistance



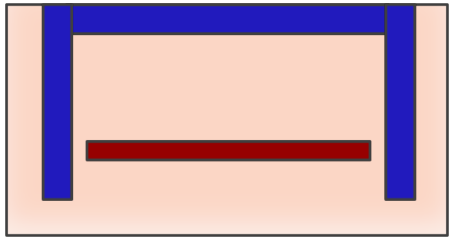

- Irradiation decreases the active doping of the gain implant

  **==> This effect is more damaging at low doping concentration**
- Vbias compensates the loss of Efield

**Can we design a more radiation resistant gain layer?**



**Shallow gain implant**



**Deep gain implant**

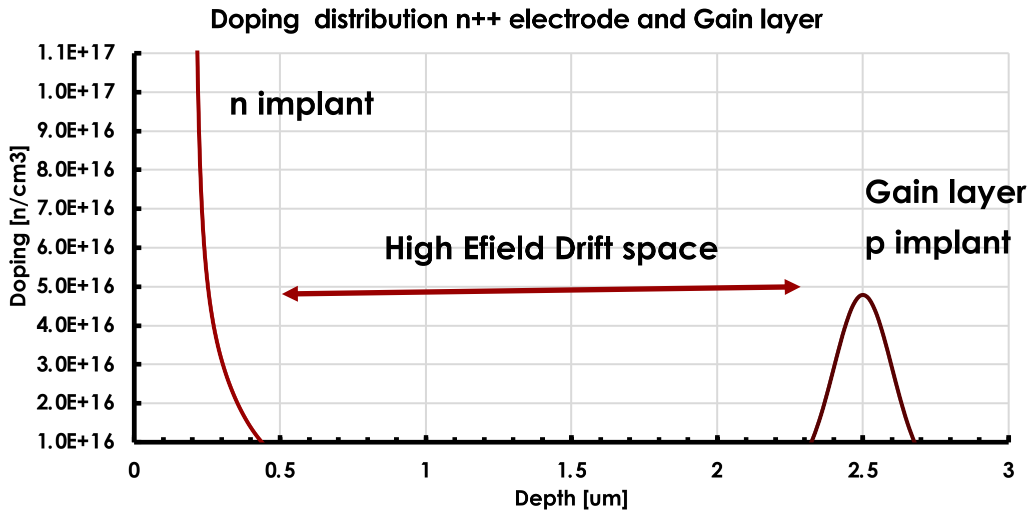
**Which geometry leads to better radiation resistance?**

# Gain layer: a parallel plate capacitor with high field

- *The doping of the gain implant is equivalent to the charge on the plates of a capacitor.*
- *the bias adds additional E field*

**Gain: exp(field * distance)**

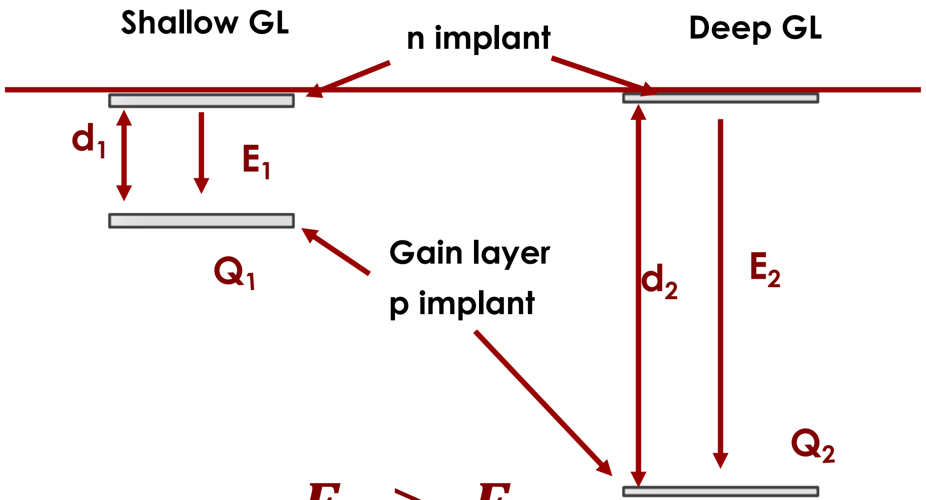
$$G \propto e^{\alpha * d}$$




**For equal gain implant doping, gain increases with implant depth**

**==> need to decrease the doping in deep implants**

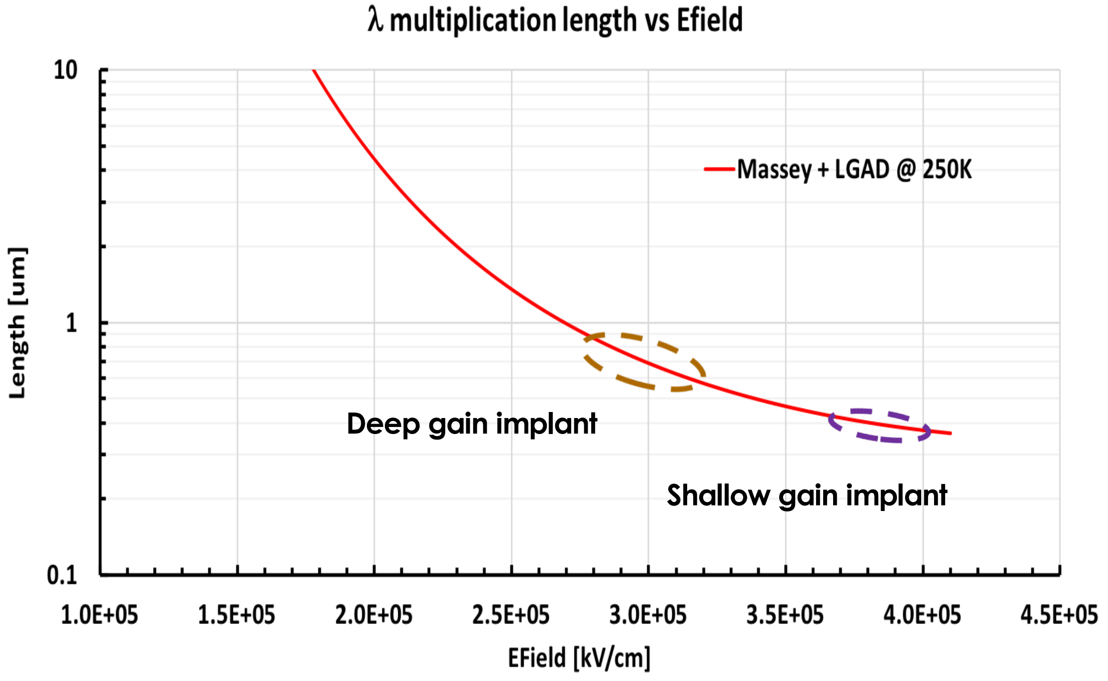
**Shallow gain layers work at higher E field.**

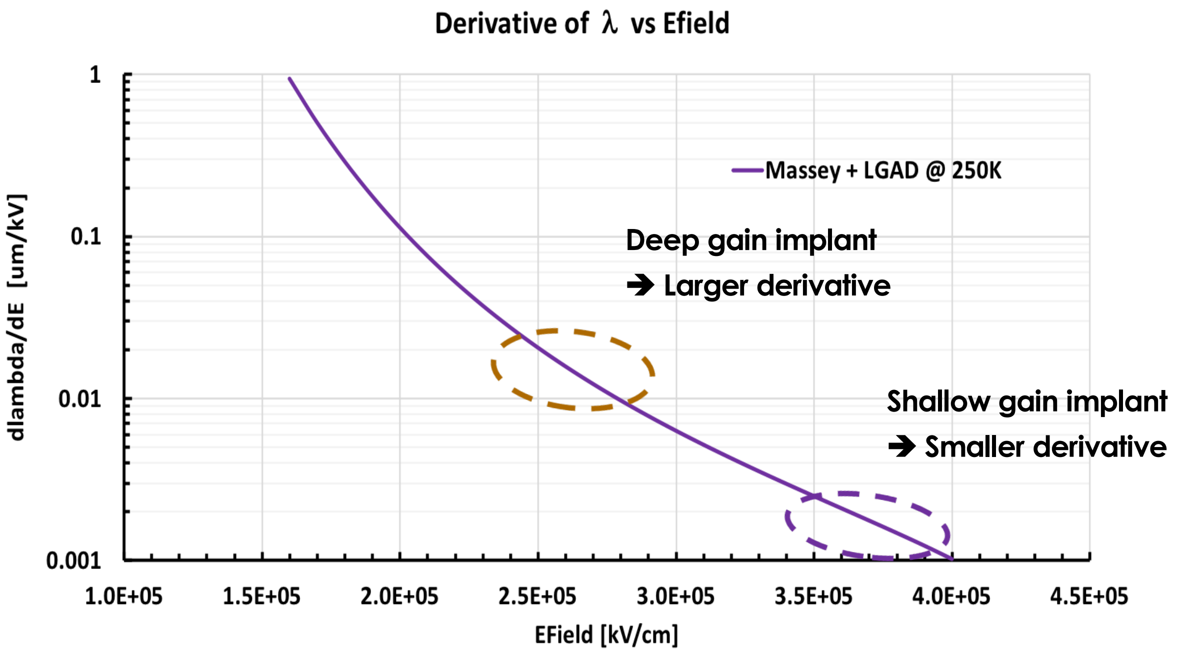



$$E_1 > E_2$$

# Multiplication length in shallow vs deep gain implants

$$G \propto e^{\alpha * d}, \alpha = \frac{1}{\lambda}$$



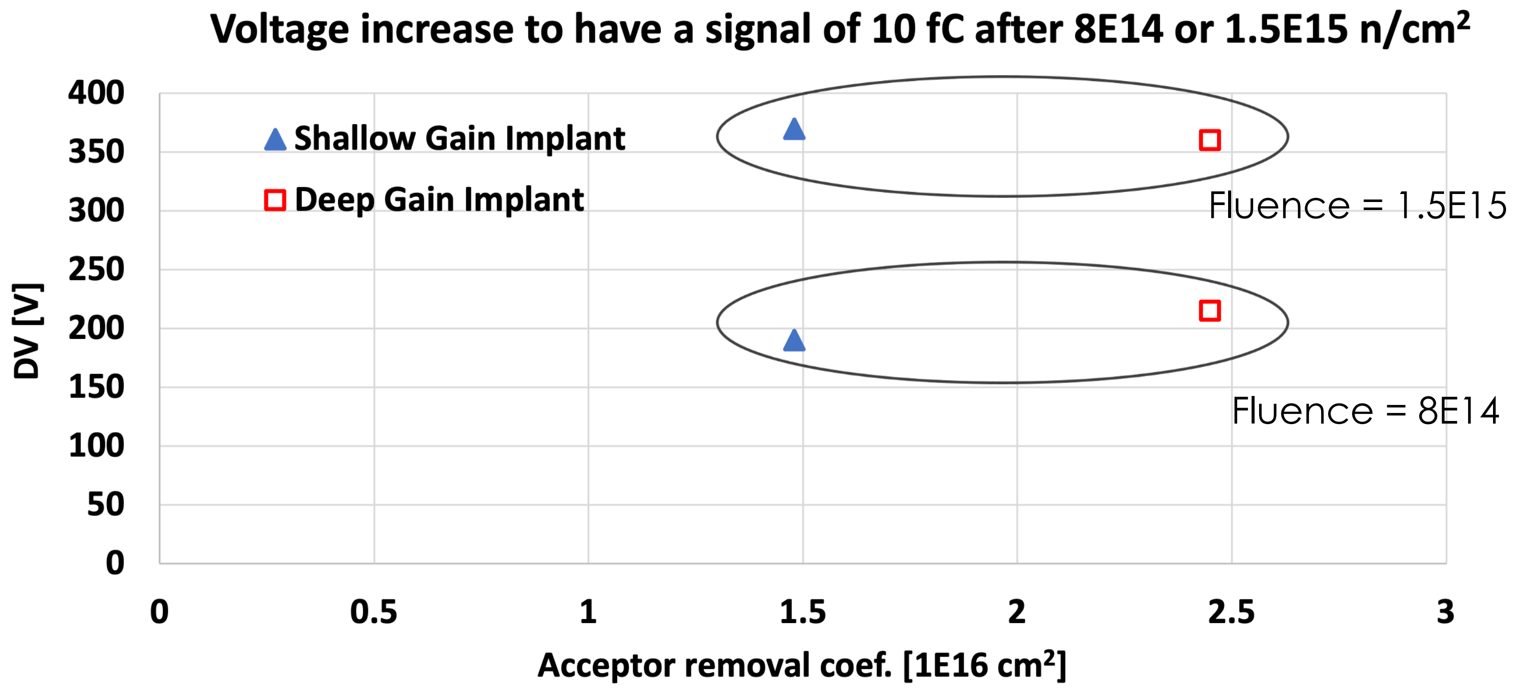

The compensation works better at lower Efield (higher λ derivative)

➔ **In deeper gain layer, Vbias has a stronger recovery capability**

# Improved radiation resistance: results

FBK UFSD32 production has sensors with gain implant at 2 different depths

| | Shallow | Deep |
|---|---|---|
| Bias recovery | Weaker (larger bias increase needed) | Stronger (smaller bias increase needed) |
| Acceptor removal | Smaller (lower "c" coef) | Larger (larger "c" coef) |




This plot shows the benefit of a deep implant: even with a higher "c", the radiation resistance is the same.

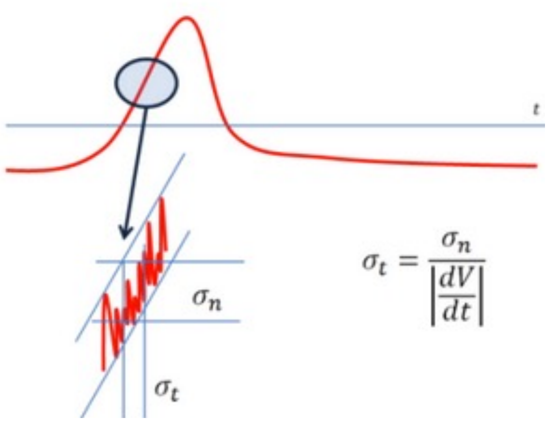
**Need to find the optimal depth**

# 3) Improved temporal resolution

$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2$$

Usual **"Jitter"** term

Here enters everything that is "Noise" and the steepness of the signal




**Need large dV/dt**

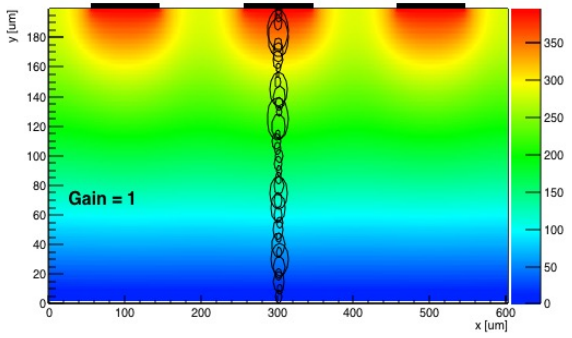
**➔ Need internal gain**

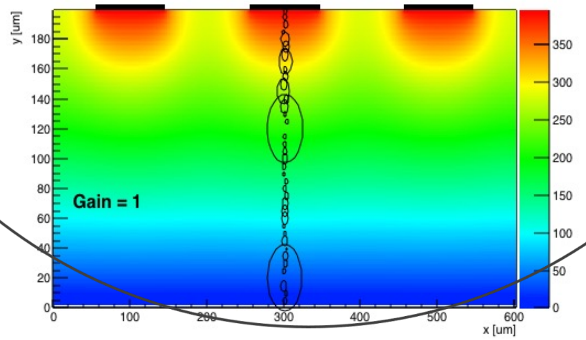
**Amplitude variation:**

variation in the total charge

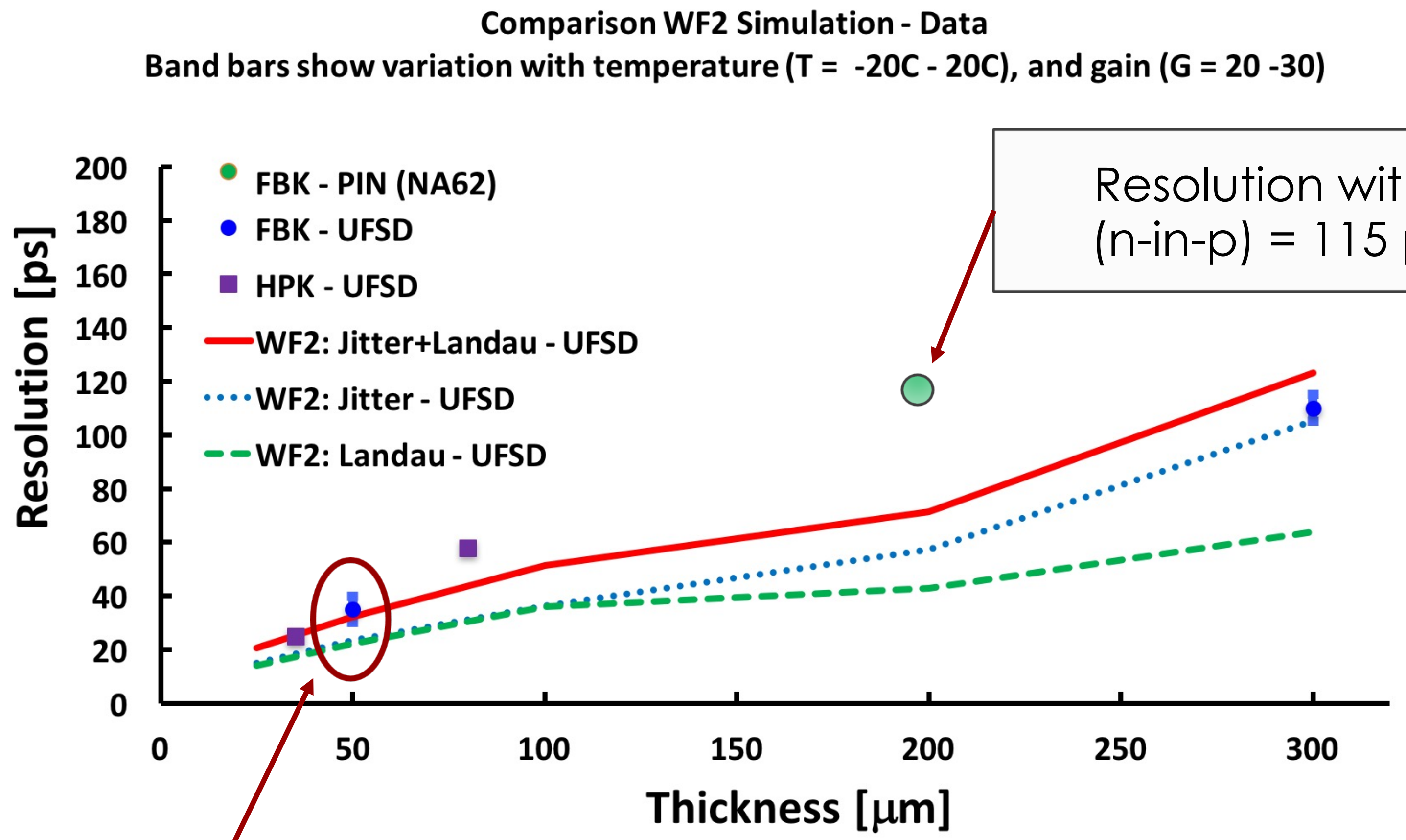
**Shape distortion**:

non homogeneous energy deposition



# Summary of UFSD temporal resolution




Resolution without gain (n-in-p) = 115 ps at 250V

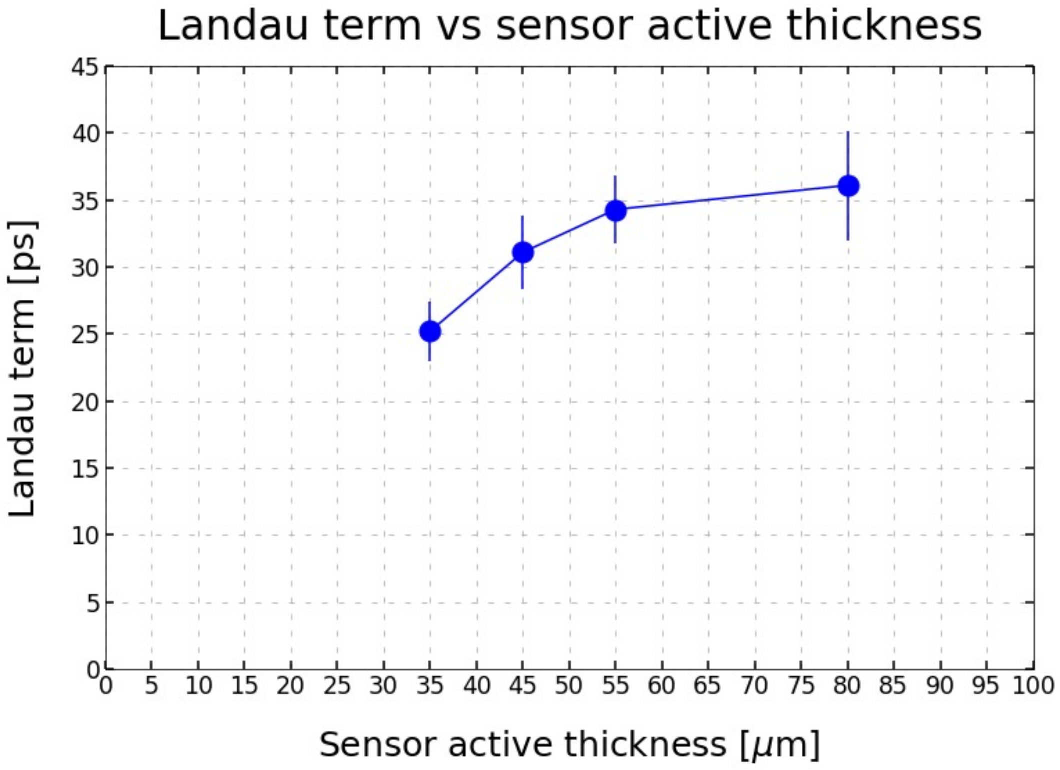
**There are now hundreds of measurements on 45-55 μm-thick UFSDs**

**➔ Current sensor choice for the ATLAS and CMS timing layers**

# Improved temporal resolution: results

The FBK Exflu0 production (PI V. Sola) has manufactured

**sensors with 25 and 35 microns active thickness**




The trend expected from simulation is confirmed

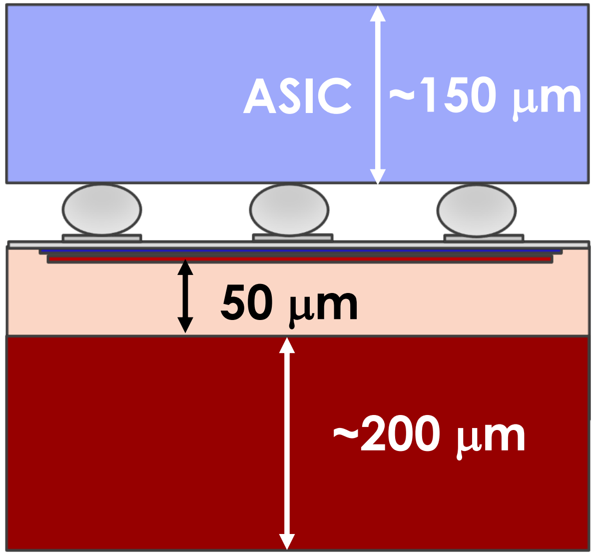
==> **15 – 20 ps resolution looks achievable with thinner sensors**

# 4) Reduced material budget

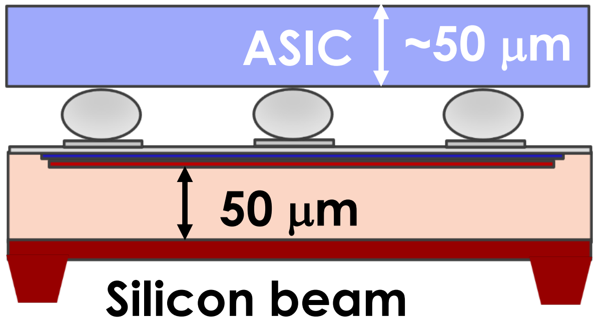
The active thickness of UFSD sensor is rather small ~ 50 um.

In the present prototypes, the active part is attached to a thick "handle wafer"

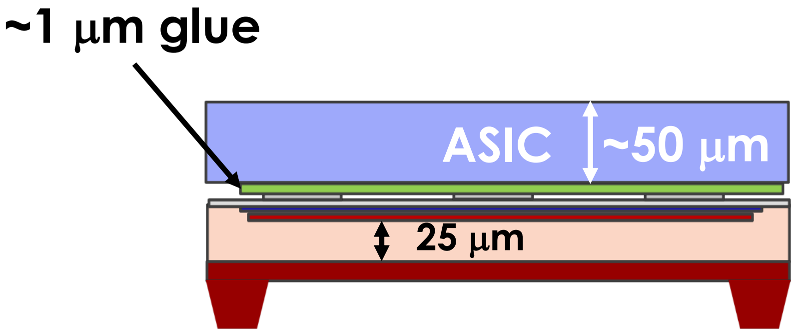
**There is a clear path leading to < 100 μm material:**




Present design: no material budget optimization




- Thinned handle wafer:
  500 um ➔ 10-20 um

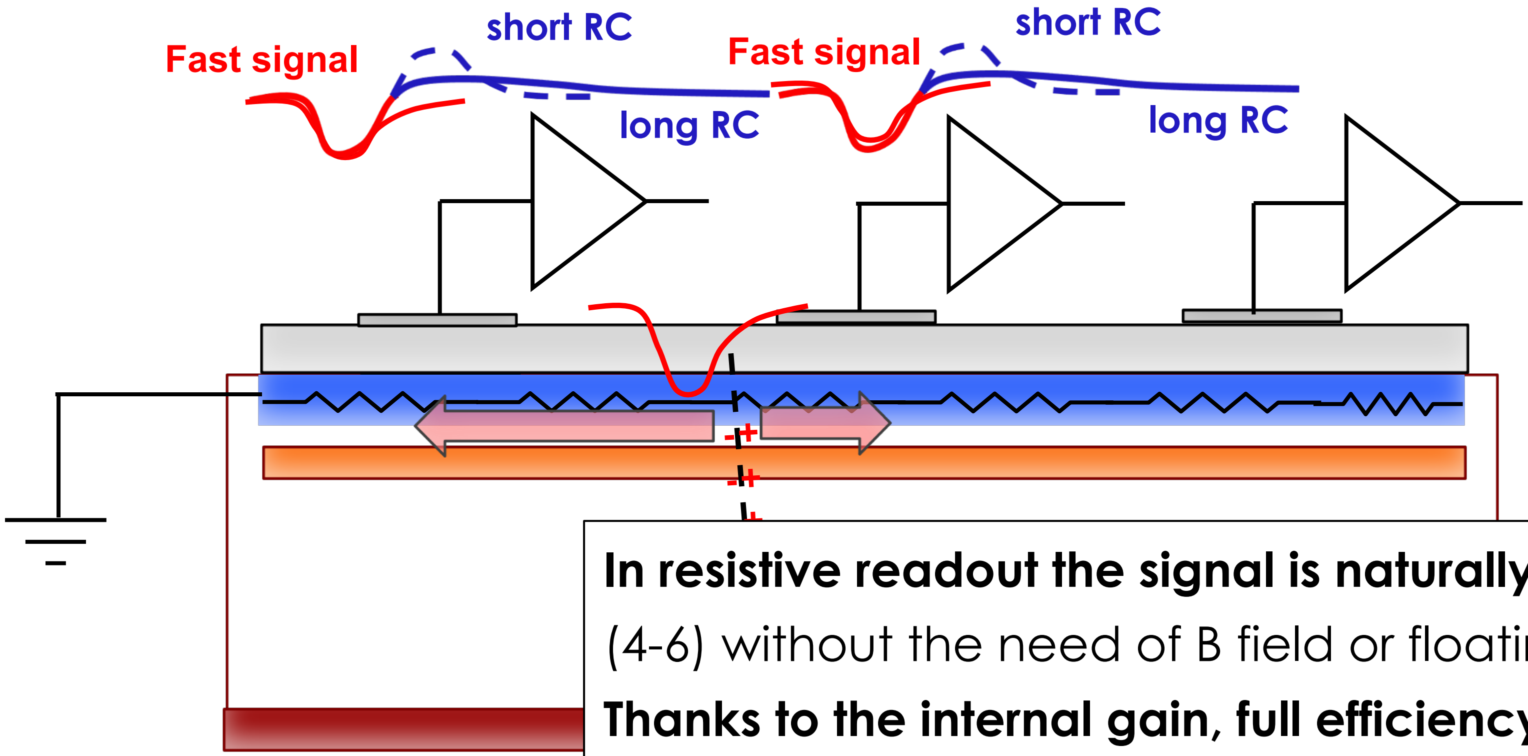



- Thinned handle wafer:
  500 um ➔ 10-20 um
- Thinned active area:
  50 um ➔ 25 um
  50 ps ➔ 25 ps

# 5) Improved Position precision

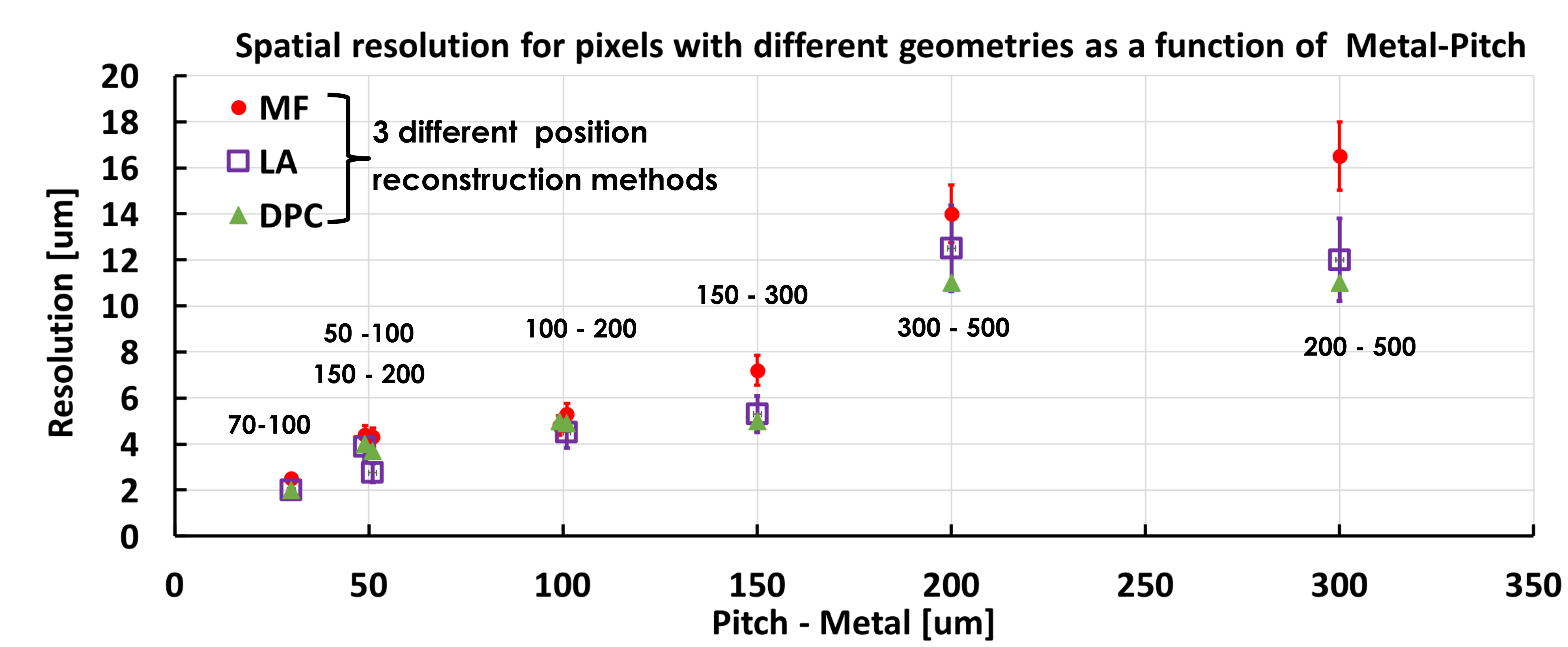
**Innovative design: resistive read-out   (AC-LGAD)**

- **The signal is formed on the n+ electrode ==> no signal on the AC pads**
- **The AC pads offer the smallest impedance to ground for the  fast signal**
- **The signal discharges to ground**




**In resistive readout the signal is naturally shared among pads**
(4-6) without the need of B field or floating pads
**Thanks to the internal gain, full efficiency even with sharing**
**Results presented here are from the FBK RSD1 production**

# Laser study: position resolution as a function of pixel geometry




**RSDs reach a spatial resolution that is about 5% of the inter-pad distance**

**➔ ~ 5 μm resolution with 150 μm pitch**

**RSDs have the “usual” UFSD temporal resolution of 30-40 ps**

# Wrap-up

1) **Very small no-gain distance** ==> real 4D tracking

   **TI-LGAD (**and also **AC-LGAD) seems to be able to solve the problem**

2) **Improved radiation resistance** ==> inner layer of HL-LHC and behyond

   *This is a long R&D plan, **presently small incremental steps***

3) **Improved temporal resolution**

   **Thin sensors deliver**, as predicted by simulation, **better precision**

4) **Reduced material budget** ==> future ee $\mu\mu$ experiment

   *In the process of **thinning the handle wafers***

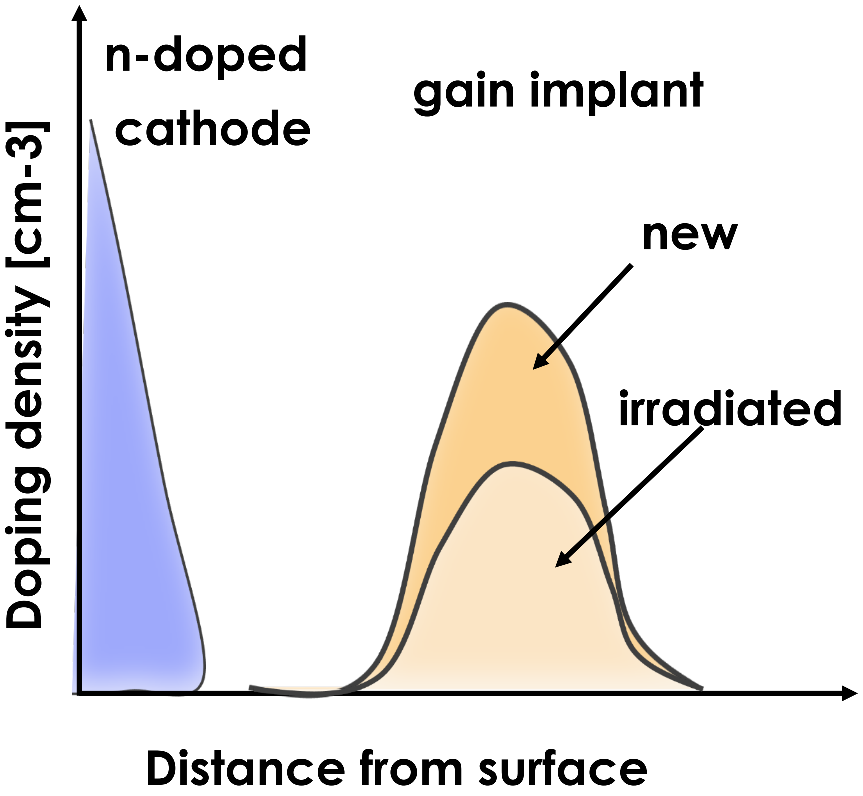
5) **Improved position resolution** ==> 4D tracking

   **AC-LGAD (RSD): resolution** about 5% of the pitch, can be **as low as few microns**

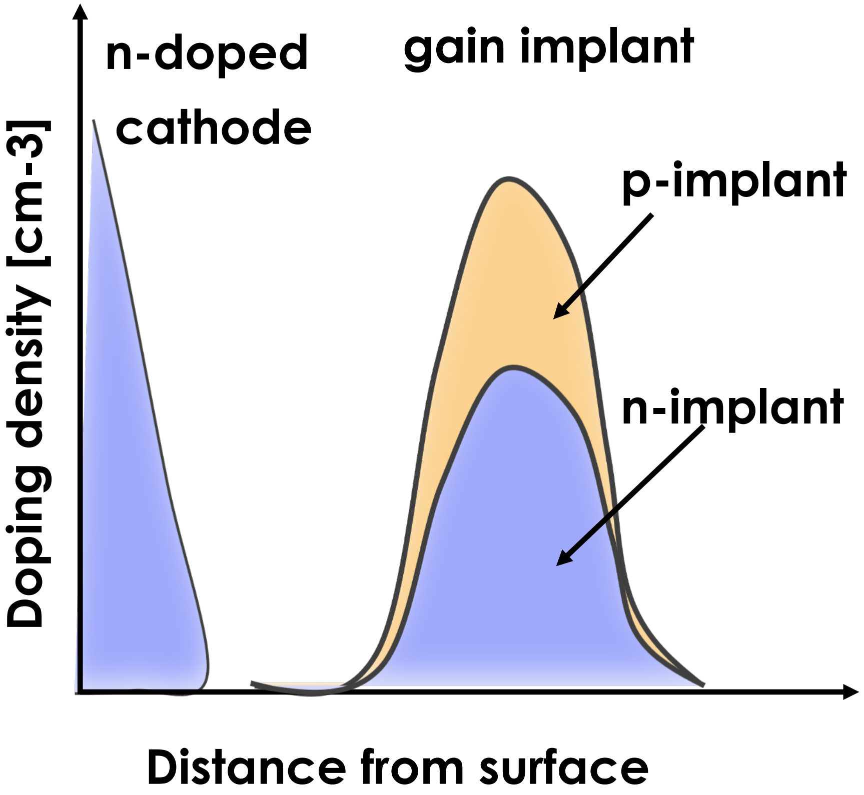
# Acknowledgement

We kindly acknowledge the following funding agencies, collaborations:

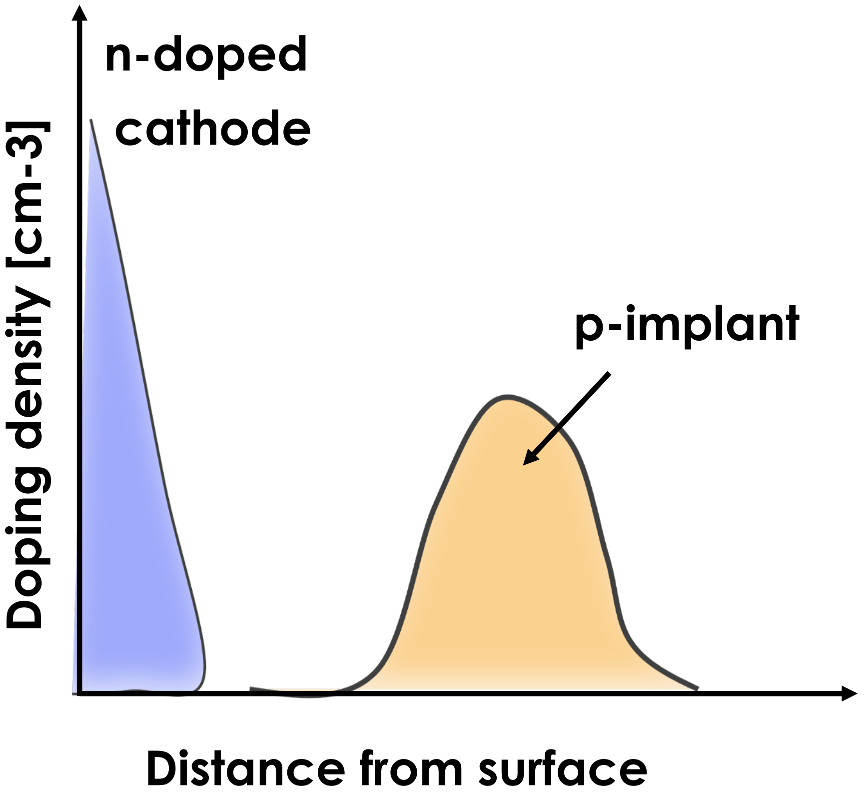
- RD50 collaboration
- INFN - Gruppo V, UFSD and RSD projects
- INFN – FBK agreement on sensor production (convenzione INFN-FBK)
- Horizon 2020, grant UFSD669529
- U.S. Department of Energy grant number DE-SC0010107
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare



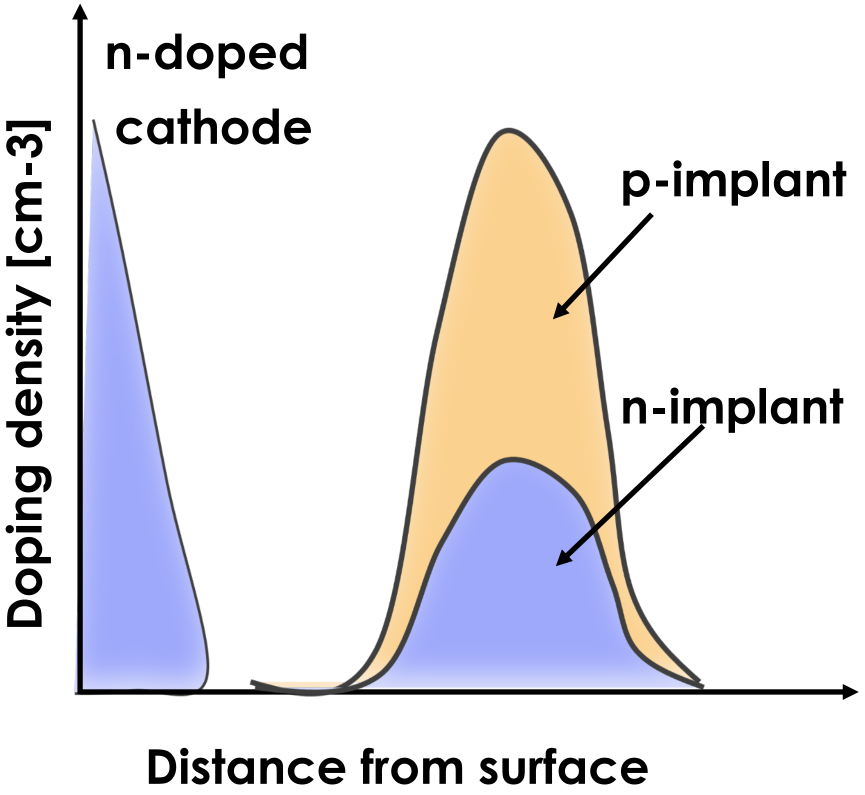

## Present LGAD design




## Compensated LGAD design




Present LGAD design




Compensated LGAD design

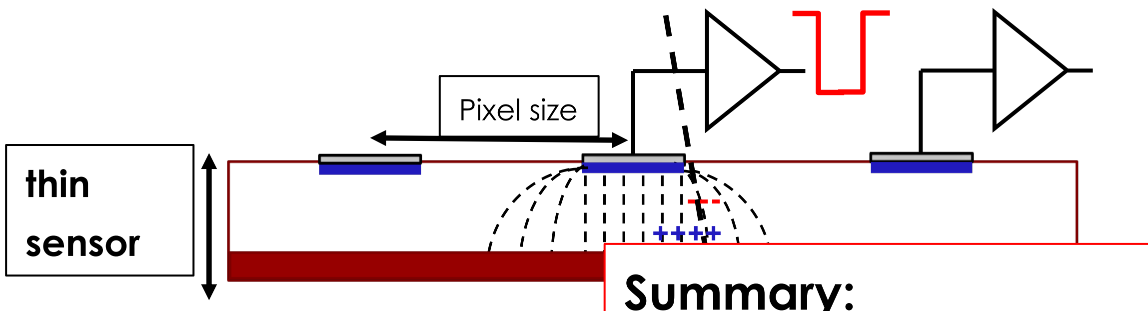
# Binary and analog read-out

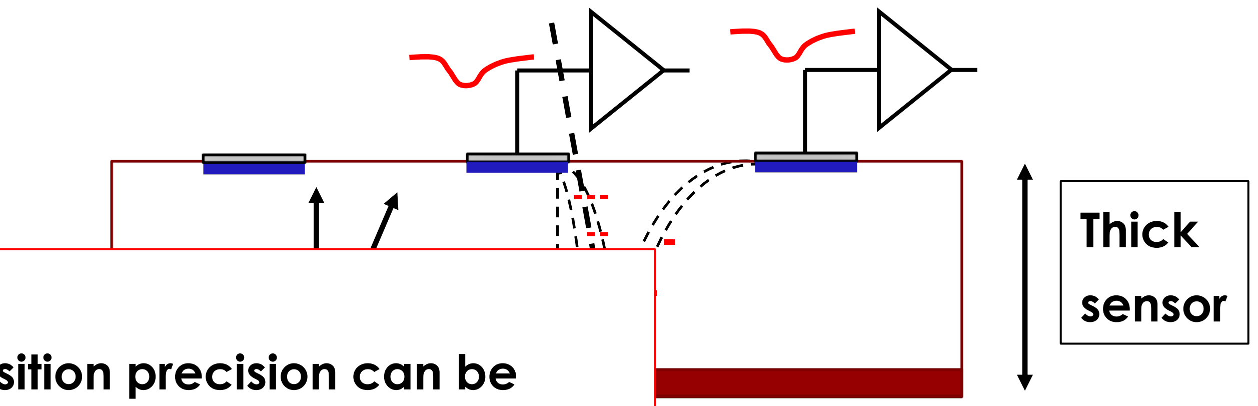
**Binary readout**

where the only information is hit/miss (0,1)

**Analog readout**

where the amplitude of the signal is recorded




**Summary:**

**Presently, very good position precision can be obtained with:**

(1) Digital readout && very small pixels

(2) Analog readout && charge sharing

$\sigma_x = k \frac{pi}{\sqrt{}}$ …

… $x_i$ / … $A_l x_l$

- $\sigma_x$ depend on th… pixel = 100 …
- $\sigma_{MS}$ small : sensors might be thin

… to maintain efficiency

- Need B field (or floating electrodes)