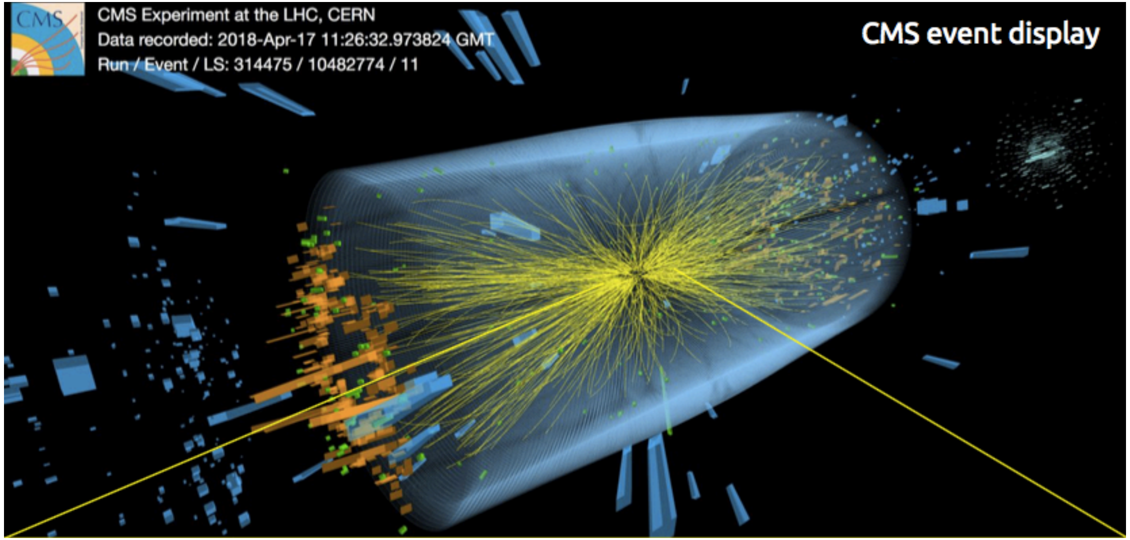
Development of large-area UFSD sensors for the CMS MIP Timing Detector

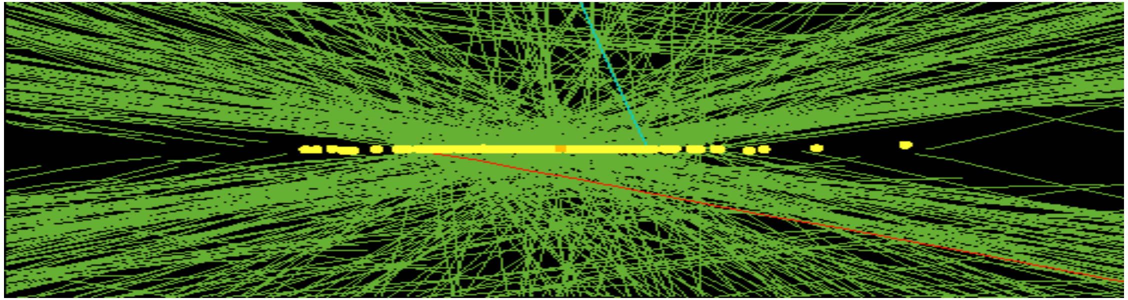
R. Arcidiacono on behalf of the ***CMS collaboration***

UPO & INFN Torino

LHC upgrade: the High Luminosity Challenge

	Inst. Lumi $(cm^{-2}s^{-1})$	Peak pileup (PU)
LHC	1.7×10^{34}	60
HL-LHC	$5\text{-}7.5 \times 10^{34}$	140-200





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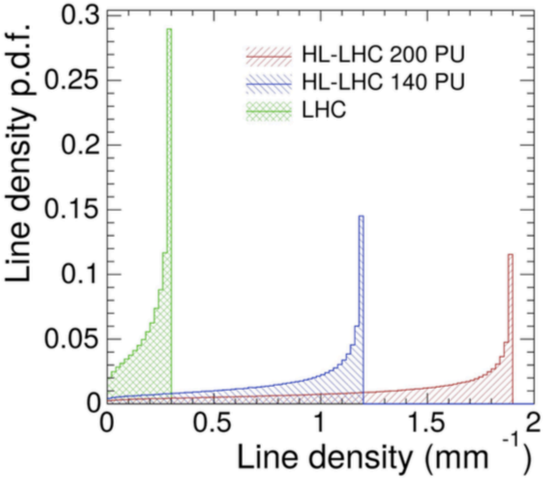
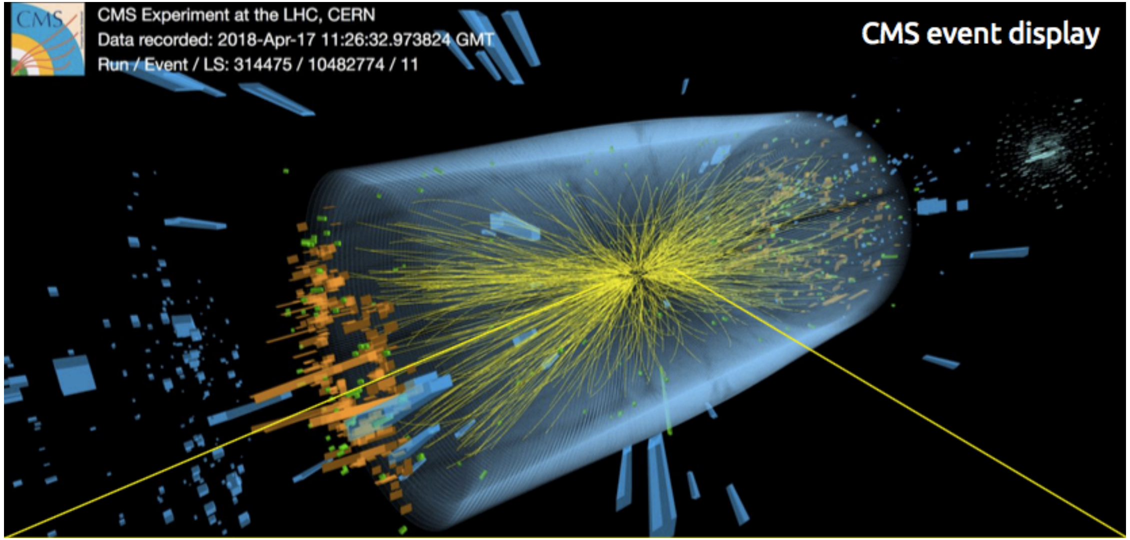
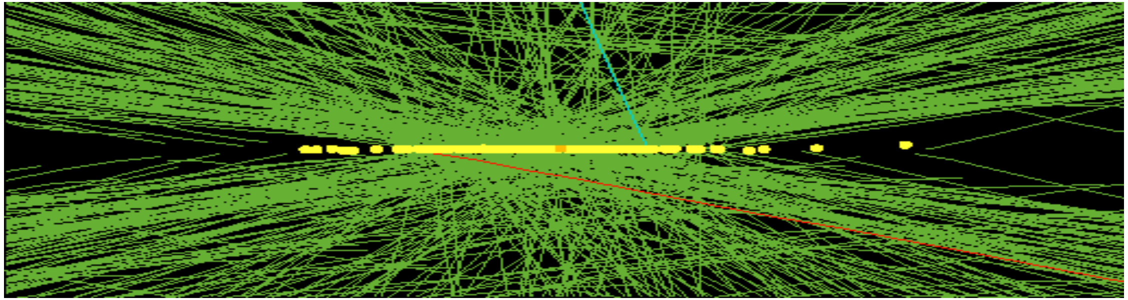
HL-LHC	5-7.5 x 10^{34}	140-200

- Up to **5x higher vertex density**
- Current track-vertex compatibility cut is @ 1mm





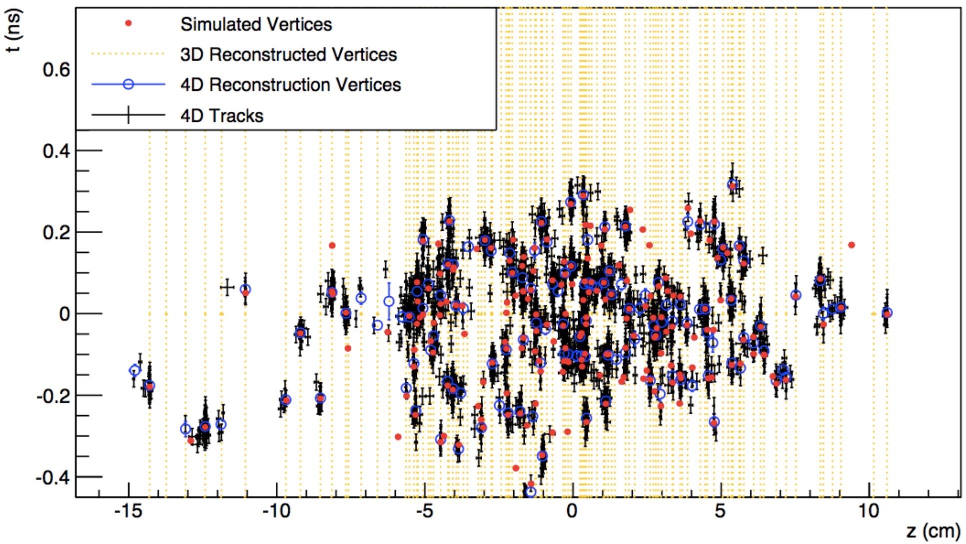


Why a MIP Timing Detector in CMS?

The MTD will provide timing information for MIPs with a 30-40 ps resolution.

Time-tagged charged tracks enable

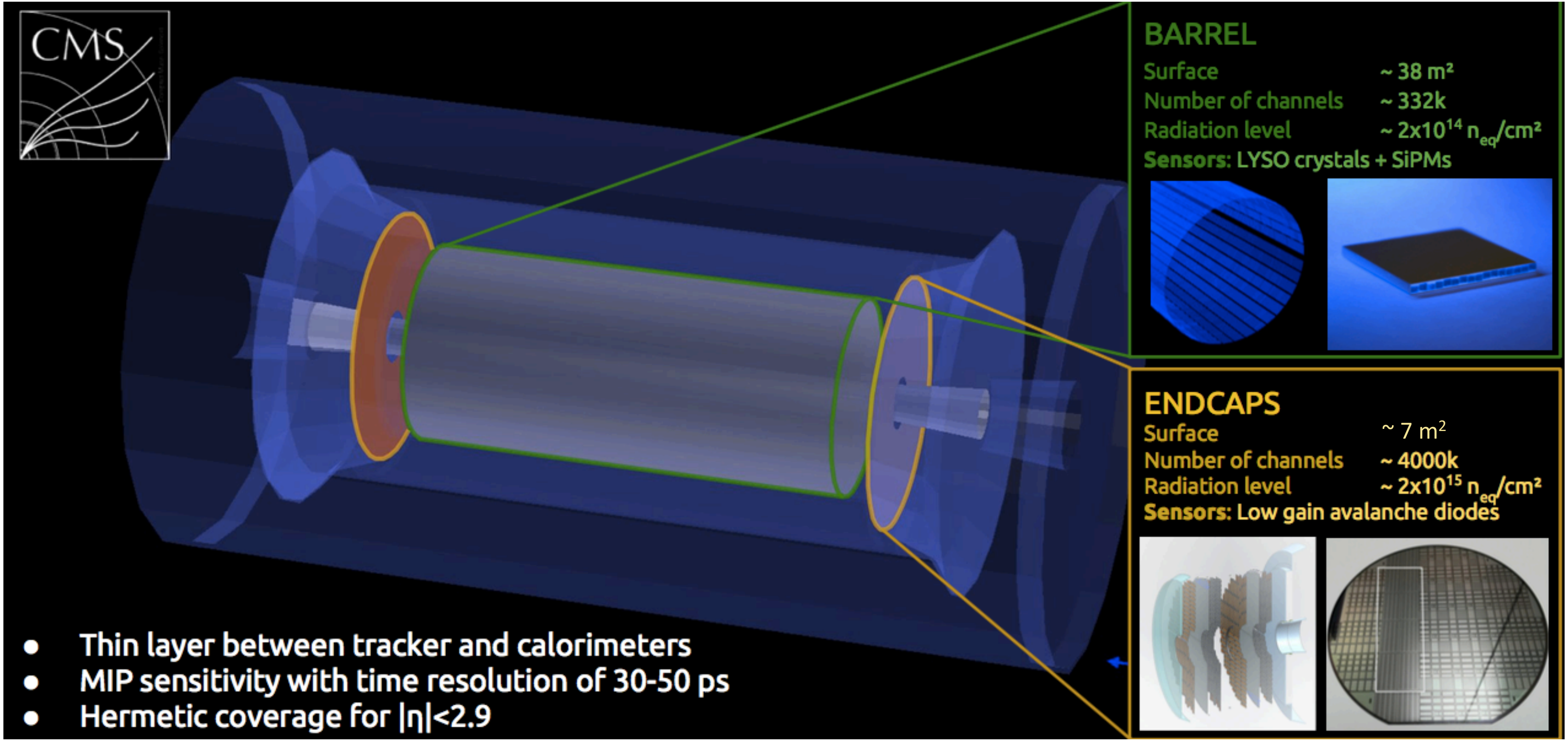
- time compatibility check for track-vertex association
- charged tracks/vertices association with photons and hadronic showers (measured by upgraded calorimeters)
- **Reduction of effective pile-up** to the level of the current CMS detector, exploiting the longitudinal extent of the beams

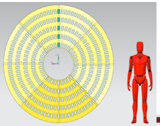


Interactions are distributed over time (and space) with an RMS of 180-200 ps

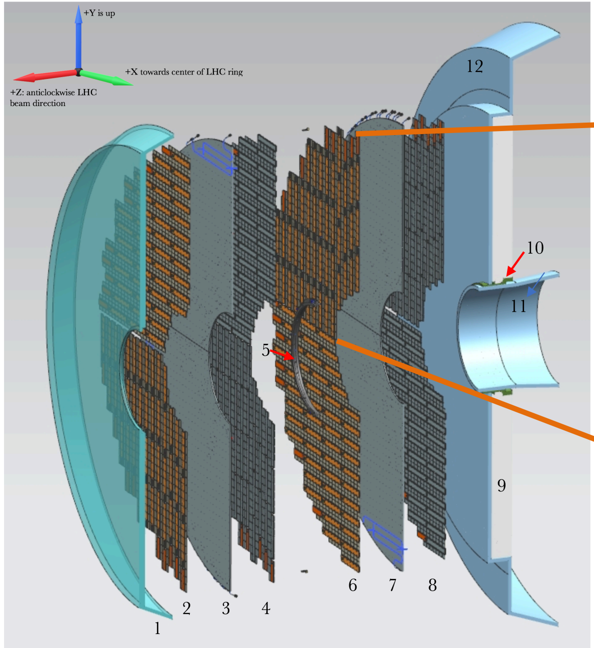
R. Arcidiacono – Tredi2019 - Trento

Design of the MTD detector



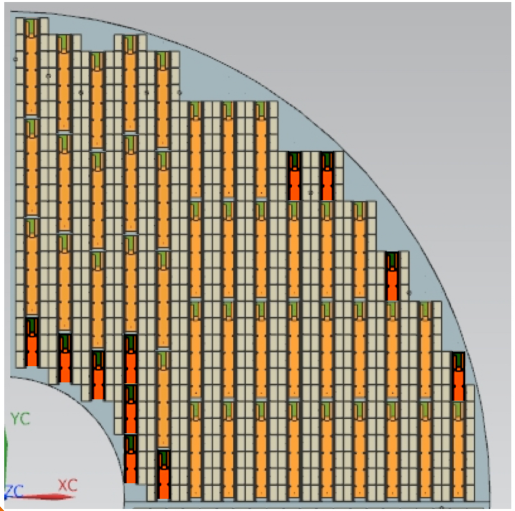


The Endcap Timing Layer (ETL) layout



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

each face made of 4 identical wedges



On each endcap side [$|\eta|$ = 1.6 to 2.9]

2 supporting disks, with **sensor modules** mounted on **all four faces of the two disks**, placed in an **x-y layout**, in a **staggered** way

(areas for readout, power, and cable infrastructure are covered by the sensors on the opposite face)

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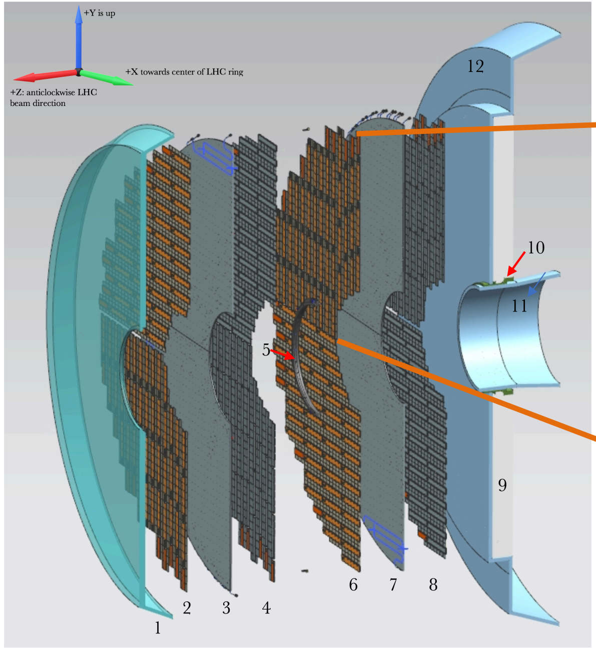

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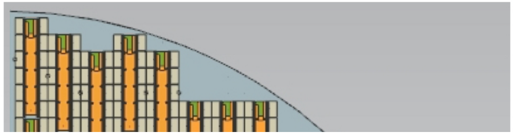
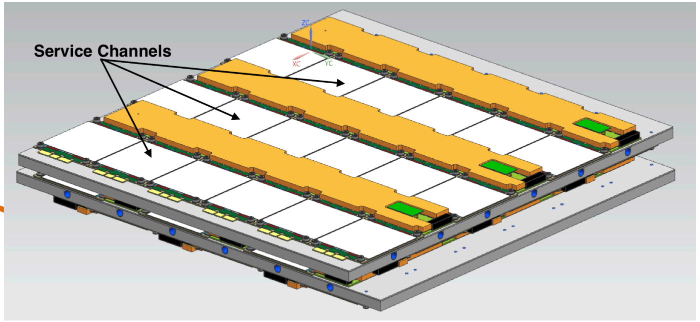
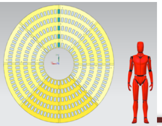


portion of supporting disk with sensors and services





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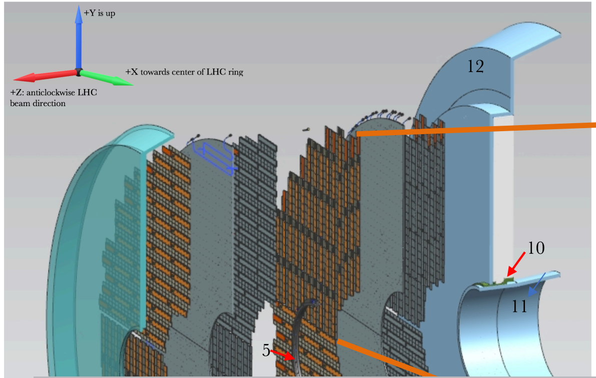

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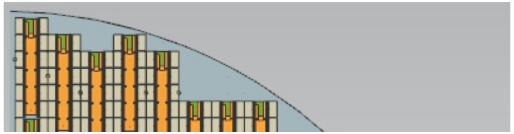

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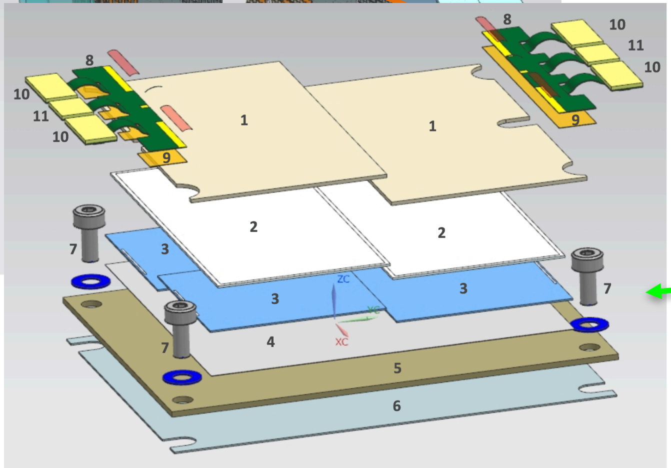
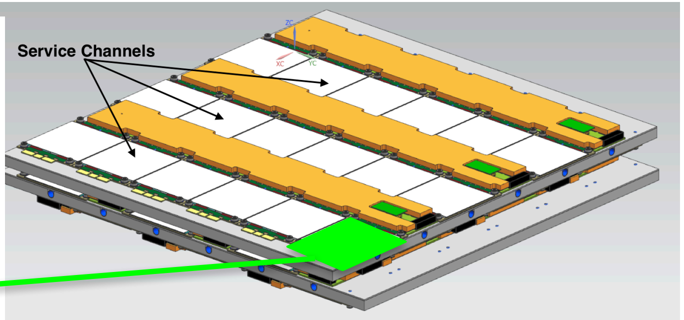
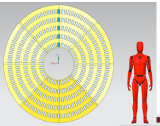


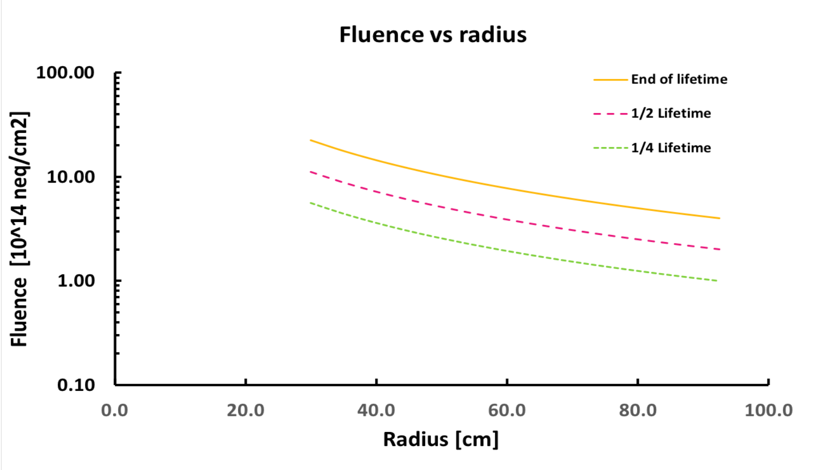
1: AlN module cover
2: LGAD sensor
3: ETL ASIC
4: Mounting film
5: AlN carrier
6: Mounting film
7: Mounting screw
8: Front-end hybrid
9: Adhesive film
10: Readout connector
11: High voltage connector

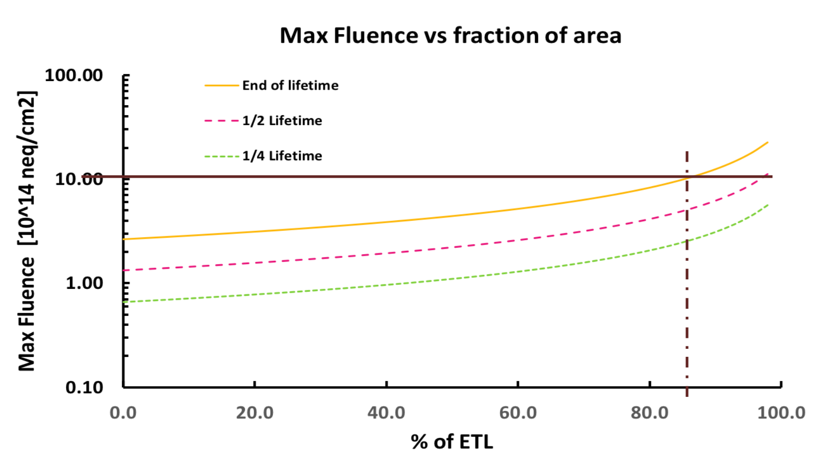


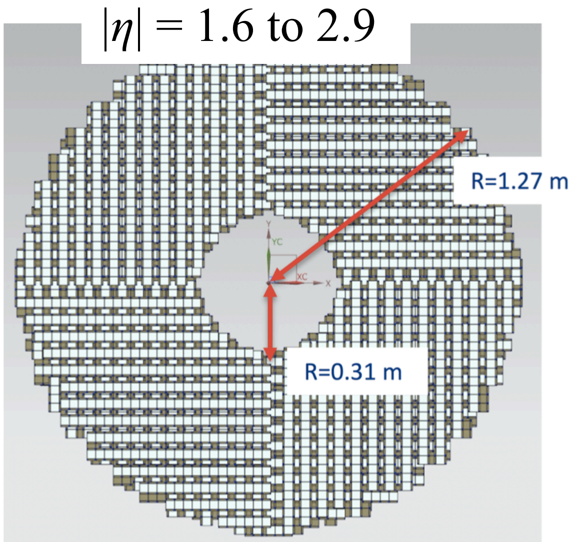
One ETL sensor module, with 2 LGAD sensors read out by **4 ETL ASICs**



Expected Irradiation Conditions of ETL







End of lifetime irradiation level (for $\mathcal{L}$ = 4000 fb^{-1})

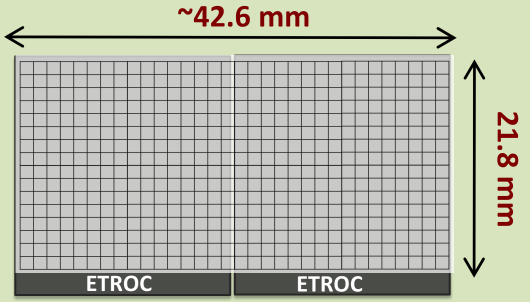
ETL exposure: 42% < 4E14 n/cm^2

80% < 8E14 n/cm^2

14% > 1E15 n/cm^2

The LGAD sensor production/R&D

ETL sensor design



matrix of 32x16 pads

pad size: 1.3 x 1.3 mm^2 (C=3.4 pF)

UFSD 50 microns thick

Total area to cover:

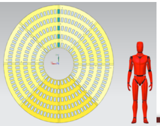
7 m^2 x 2

Number of sensors: ~18500

3 VENDORS (FBK, HPK, CNM) engaged in the R&D towards large area UFSDs production (2018) for CMS/ATLAS upgrades, focusing on

- Large Area sensor feasibility
- Optimization of gain layer radiation hardness, inter-pad dead spaces, sensor edges, gain uniformity
- Long term stability
- Evaluate the 35-micron option

Common R&D project with ATLAS
Development work done also in collaboration with RD50



ETL sensor specifications

For radiation damage mitigation, the sensors will be operated at -30℃

Considering the present ETL read-out chip simulation, a time resolution better than ~40 ps is achieved for charges larger than 5 fC (min Gain = 10)

→ **sensor needs to provide enough charge**, without increasing the noise contribution, **till the end of HL-LHC lifetime**

When new:

- sensor gain between 10 and 20 in a bias interval between 125V - 175V, with BD > 220 V
- less than 2 μA leakage current per mm^2
- Sensor edge < 500 microns, interpad (no-gain) distance < 50 microns
- Gain uniformity within a sensor better than 20%

Low noise, stable operation, and gain above 10 after a fluence of

- 5E14 *neq*/cm^2 for 50% of the total sensors
- 1E15 *neq*/cm^2 for 30% of the total sensors
- 2E15 *neq*/cm^2 for 20% of the total sensors.

2018 R&D SENSOR PRODUCTIONS

FBK, HPK and CNM have delivered their first CMS/ATLAS dedicated R&D productions:

Lot's of results collected so far… some still not final.

Given their R&D nature, there were unforeseen problems for all the vendors (either related to the optimizations undertaken, or not …)

FBK: structures with early breakdown and/or "pop-corn" noise (p-stop design, inter-pad design?)

HPK: the 35microns sensor design suffers very early breakdown (too low bulk resistivity, too high gain layer doping)

CNM: high leakage current/ large variations (inter-pad design ?)

All vendors are "offering" engineering internal productions to address the problems. These productions will be extremely useful for the definition of the characteristics of the next prototyping production this year.

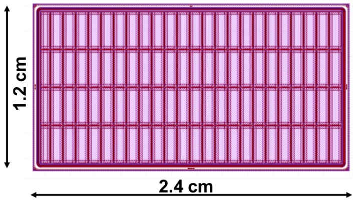
Final Production expected to start in Q1 2023

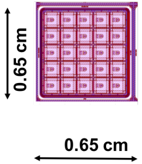
Wafer uniformity and sensor yield

Overall, a very good uniformity and yield from HPK and FBK.

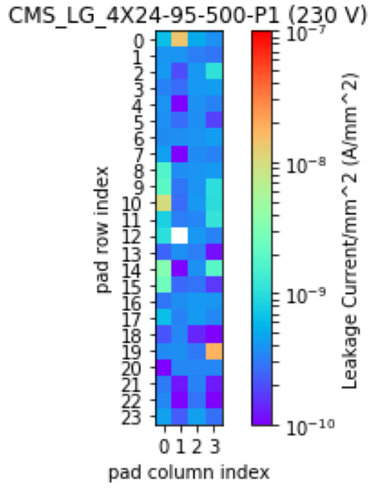
Table 3.4: Summary of the uniformity studies on the latest sensor productions.

Foundries	Sensor type	# Sensor tested	# Warm pads	# Hot pads	Comments
FBK	4x24 pads	152	14 (0.1%)	0	bias = 100V
FBK	5x5 pads	23	4 (0.7%)	0	bias = 300V
HPK	4x24	15	20 (1.3%)	0	bias = 250V

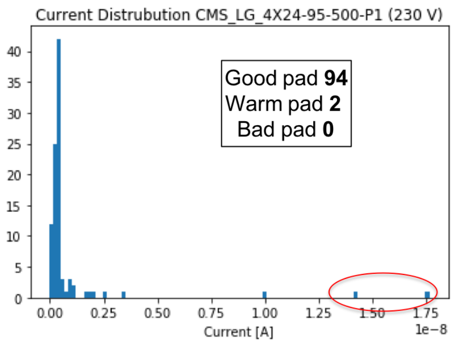




The largest device present in the 2018 prods, 3.5 times smaller than the final one



BD Voltage ~ 240/250 V

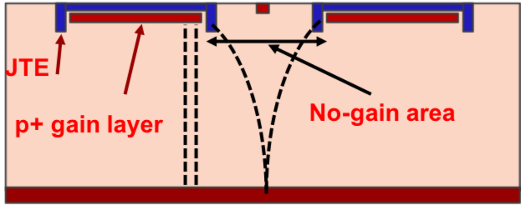


See also V.Sola/G. Paternoster talks

Status of interpad no-gain area

Foundries	No-gain distance [μm]	Comments
CNM	100	The latest production with smaller distances has very high leakage current and cannot be used. A new production is expected in August 2019
FBK	40, 70	In the latest production much smaller distances were attempted but the sensors go into early breakdown. A dedicated new production is expected in April 2019.
HPK	75, 90, 135	Even the shortest separation works well, most likely HPK can obtain even smaller distances.

See also V.Sola/G. Paternoster talks



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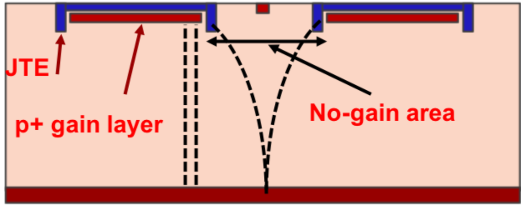
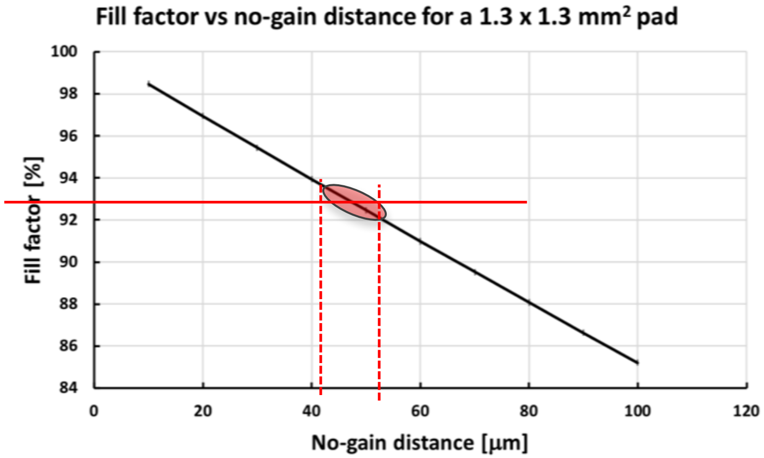
Our goal is to have a fill factor of 85% per layer, for a final average 1.8 hits per track

- 5% comes from the sensors placement
- 2-3 % dead area comes from the butting of sensors in the module
- 7-8% comes from the no-gain area

…Not yet achieved

See also V.Sola/G. Paternoster talks

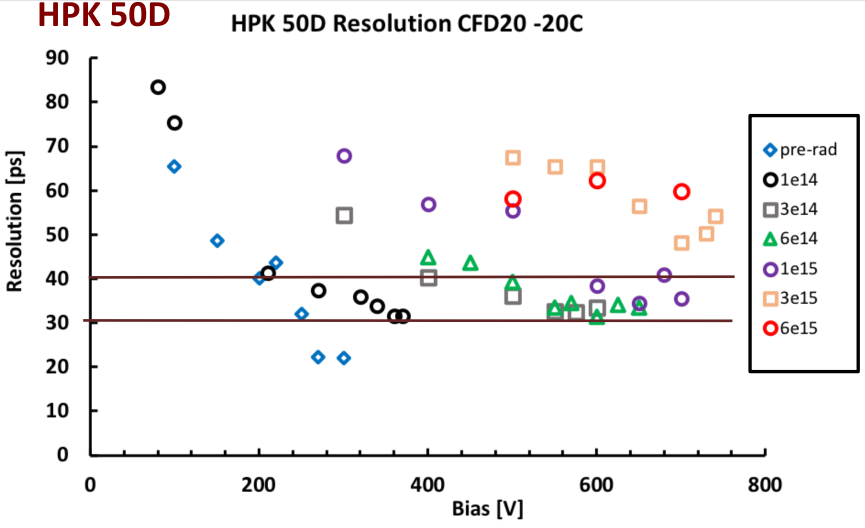


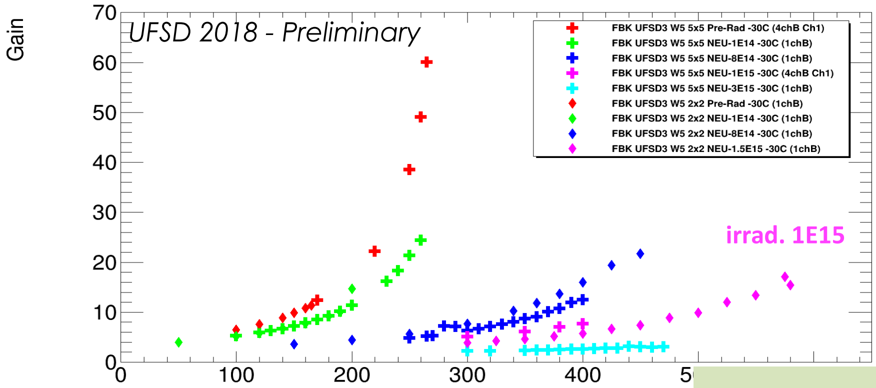


Time Resolution (beta source lab tests)

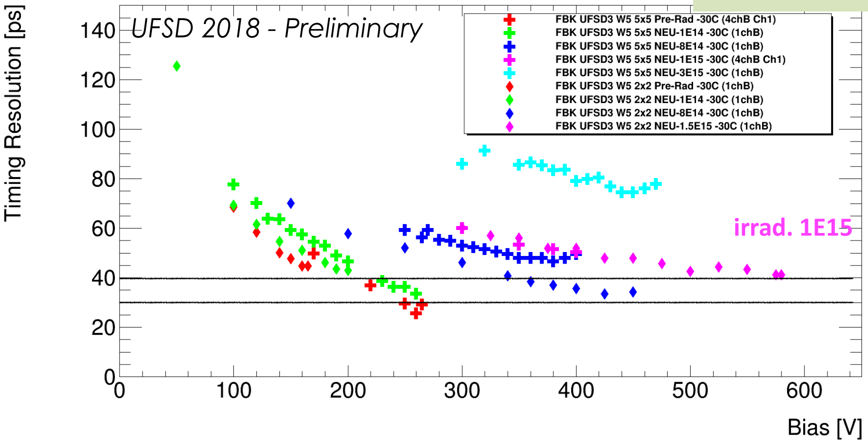
See Stefan Guindon talk for time resolution performances of CNM and preliminary results on HPK Type3.1

HPK 50D



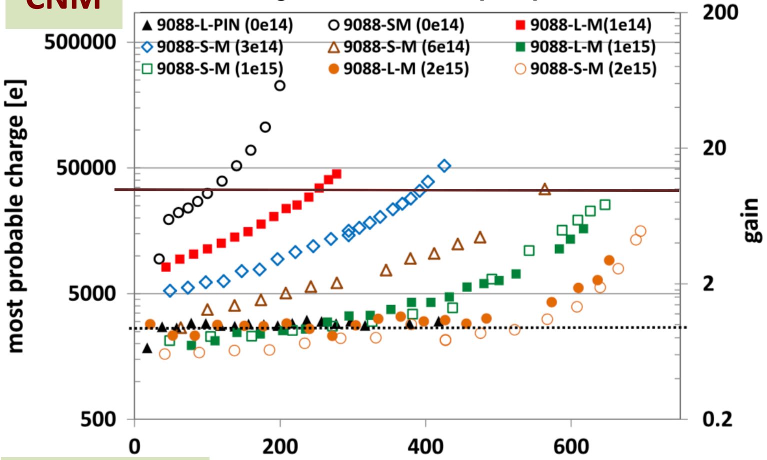


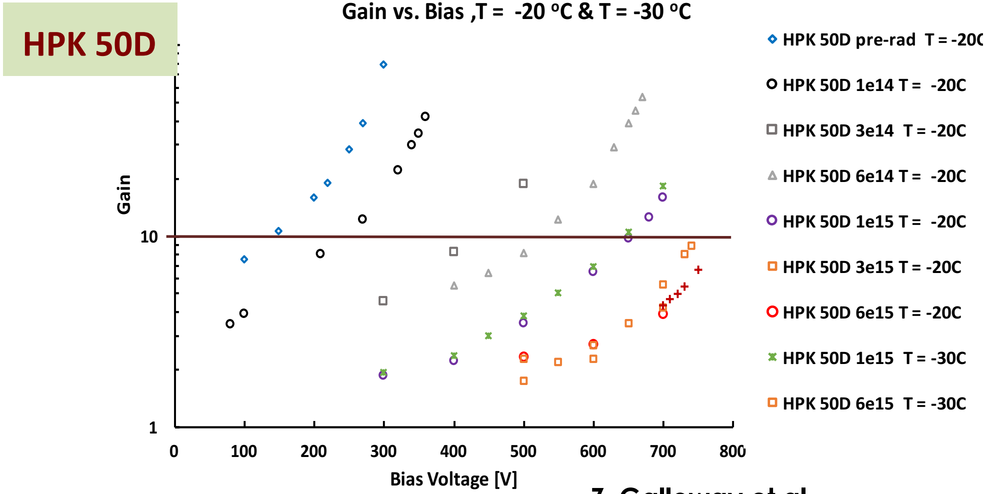
FBK UFSD3



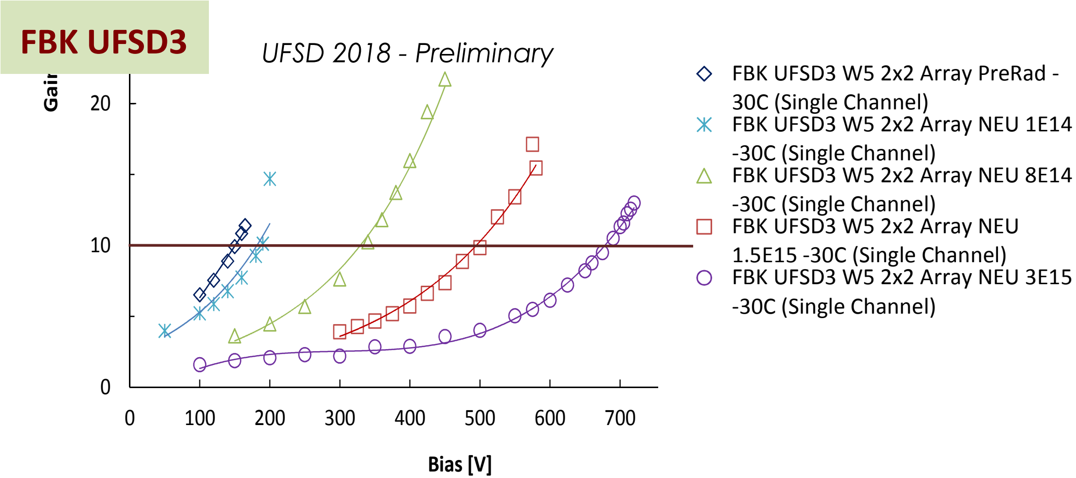
On radiation hardness…

G. Kramberger et al, NIMA 891 (2018) 68–77



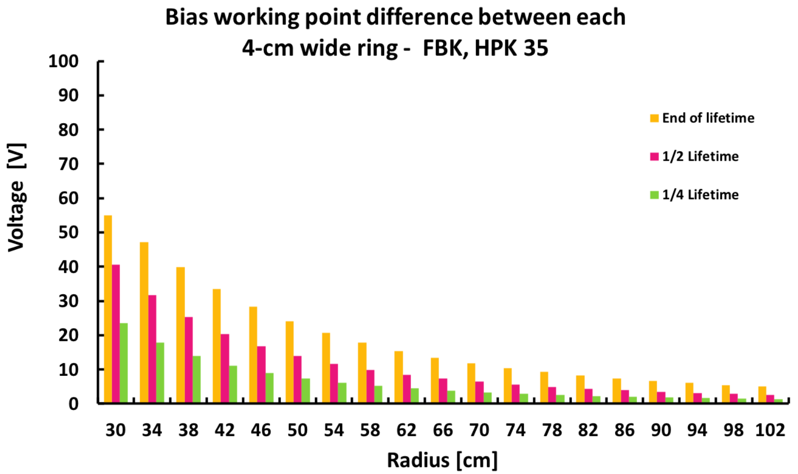


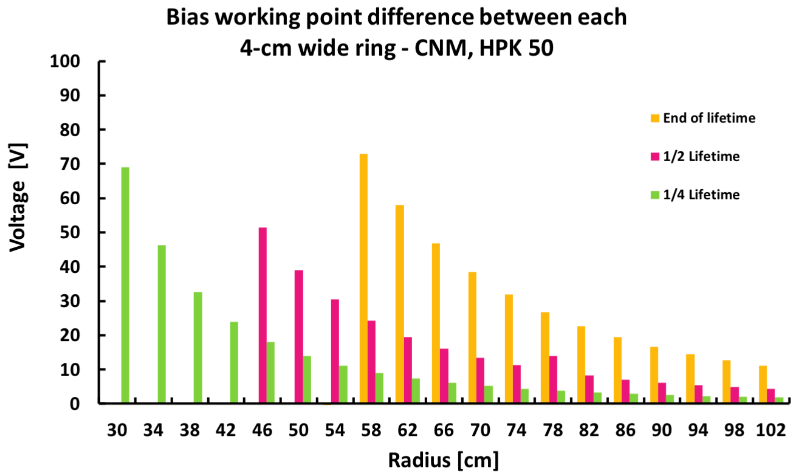
Z. Galloway et al.,
https://arxiv.org/abs/1707.04961



On the detector sensor biasing schema

Comparison between the best devices of the three vendors so far:

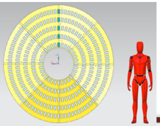




Difference in sensor biasing voltage for G=10 over a 4-cm sensor,

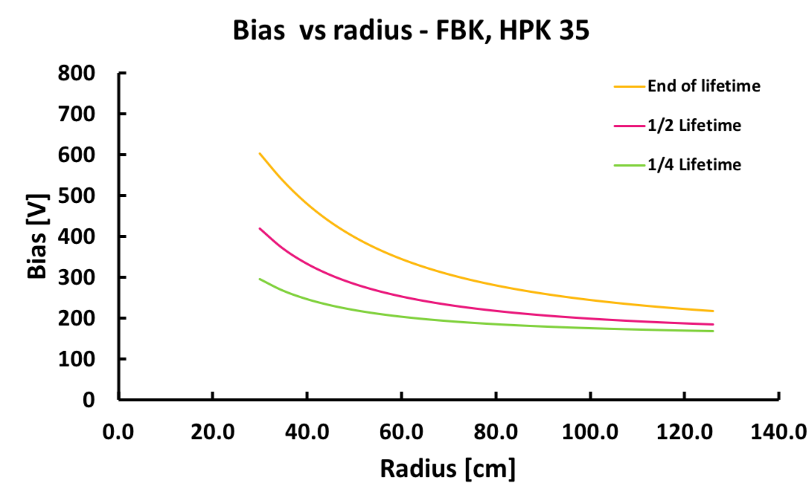
as a function of ETL radius, for three different moment in CMS lifetime.

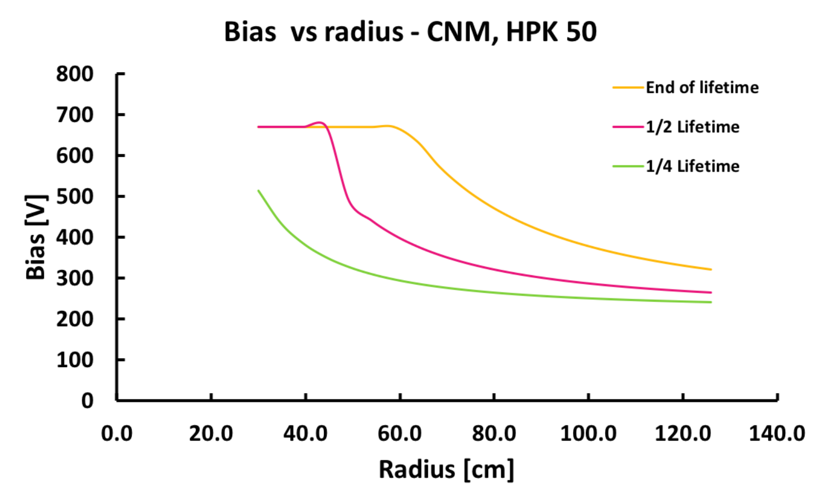
The sensor edge at higher rapidity would require higher bias, so it will be under-biased to prevent breakdown at the sensor edge at lower rapidity.



On the detector sensor biasing schema

Bias point for a Gain=10 sensor as a function of ETL radius





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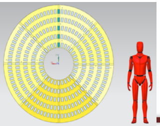


Conclusions

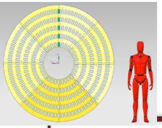
Both CMS and ATLAS need to build large area timing detectors using UFSD sensors of ~8-9 cm^2 . Common R&D project!

CNM, FBK and HPK are engaged in this R&D, and it is progressing well:

- The yield for large area sensors (measured now in FBK, HPK) is very high
- The radiation hardness has improved: latest FBK can reach good gain above 1.5E15 n_{eq}/cm^2.
- The sensors tested in lab can reach a time resolution better than 40 ps

Stay tuned! a new round of prototyping production will be available in 2019.

NB: writing the MTD TDR, to be submitted to LHCC by the end of March.

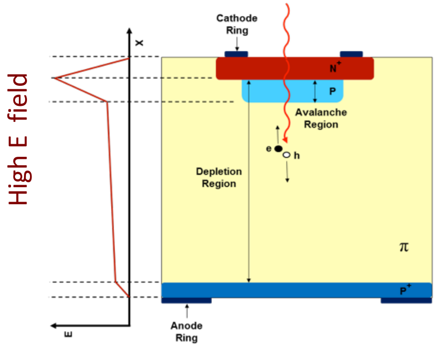


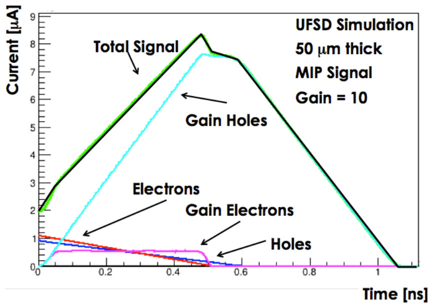
BACKUP

Ultra Fast Silicon Detectors

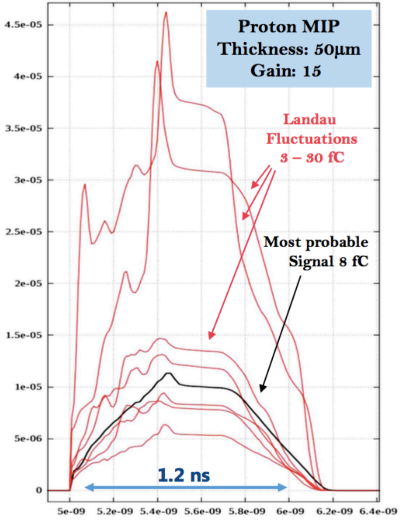
LGAD (Low Gain Avalanche Diodes) technology sensors optimized for timing measurements

The idea: add a thin layer of doping to produce low controlled multiplication (the gain layer)





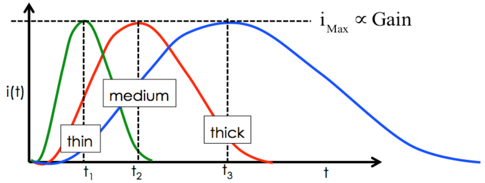
The main contribution to the signal comes from gain holes.
The signal shape depends on the sensor thickness and gain



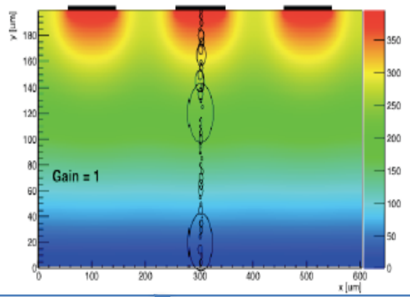
How do we measure the time

$\sigma_{Jitter} \approx N/(dV/dt) \approx t_{rise}/(S/N)$

- need **gain** to increase S
- need **thin detector** to decrease t_{rise}



Non uniform charge deposition
Decreases with detector thickness



$$\sigma^2_t = \sigma^2_{Jitter} + \sigma^2_{Time\ Walk} + \sigma^2_{Landau\ Noise} + \sigma^2_{Distortion} + \sigma^2_{TDC}$$

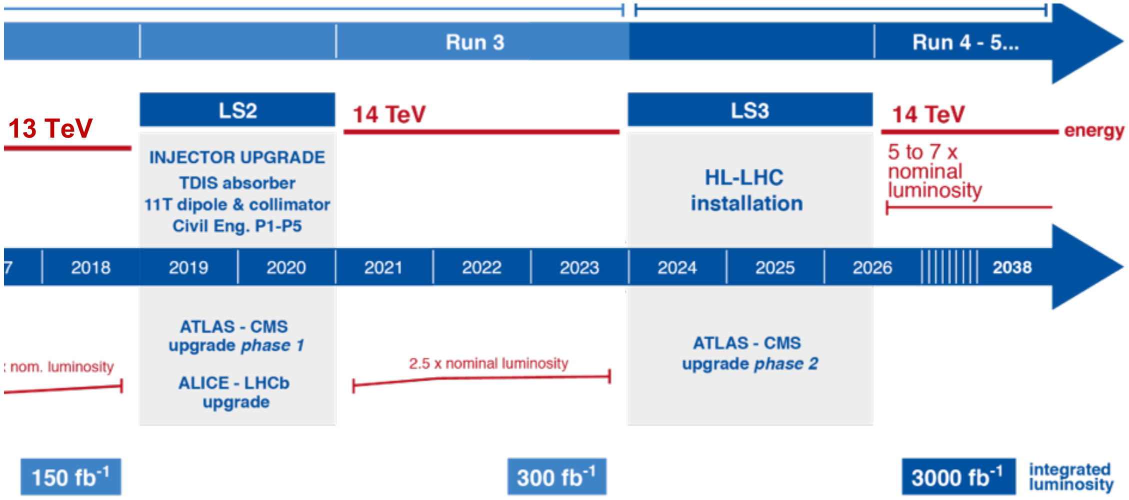
Minimized by correction techniques

Minimized by optimized RO electronics

$I_{Ramo} \approx q\, v_{drift}\, E_w$

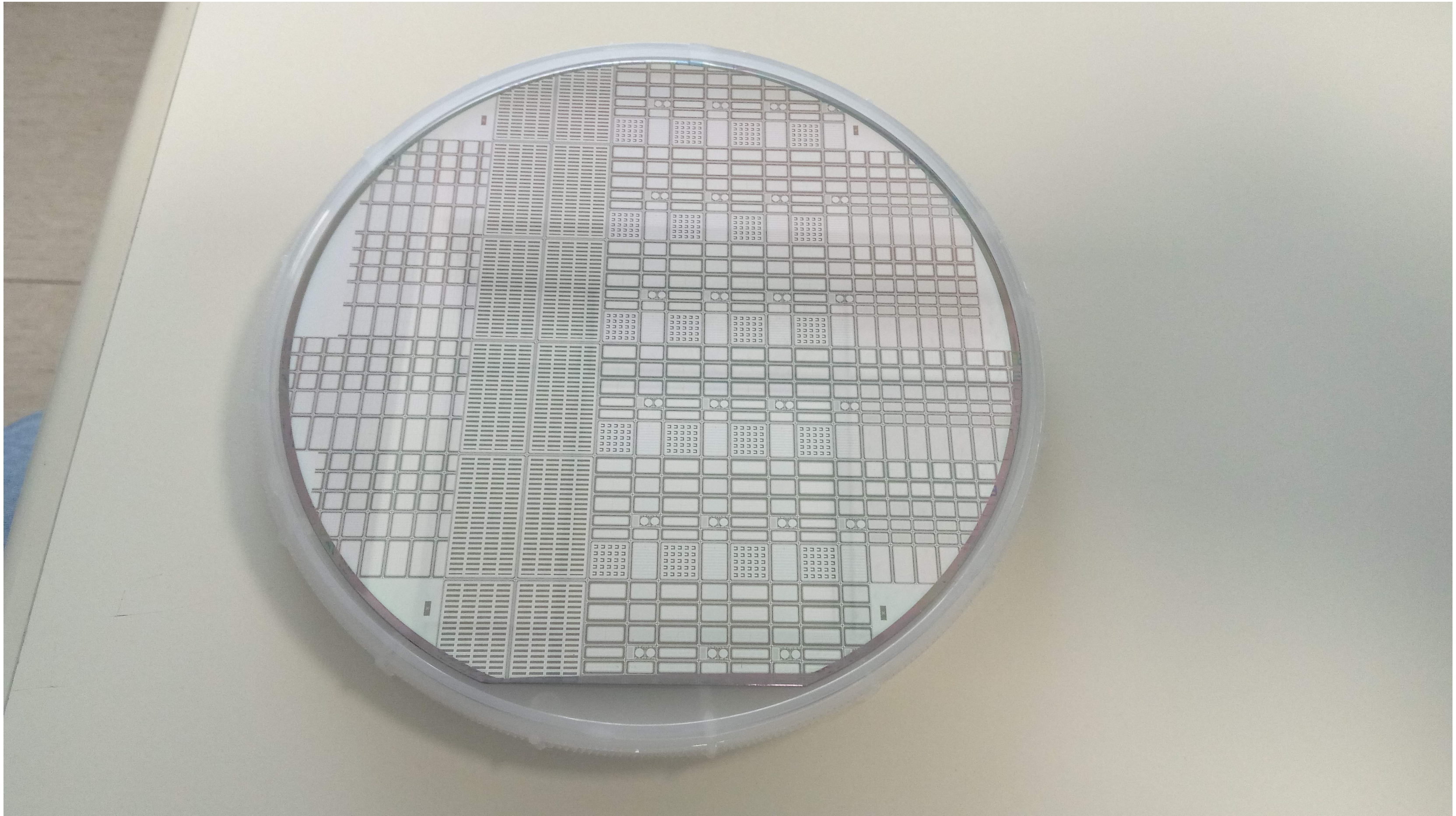
Requires **uniform v_{drift} and E_w**

LHC upgrade: the High Luminosity Challenge

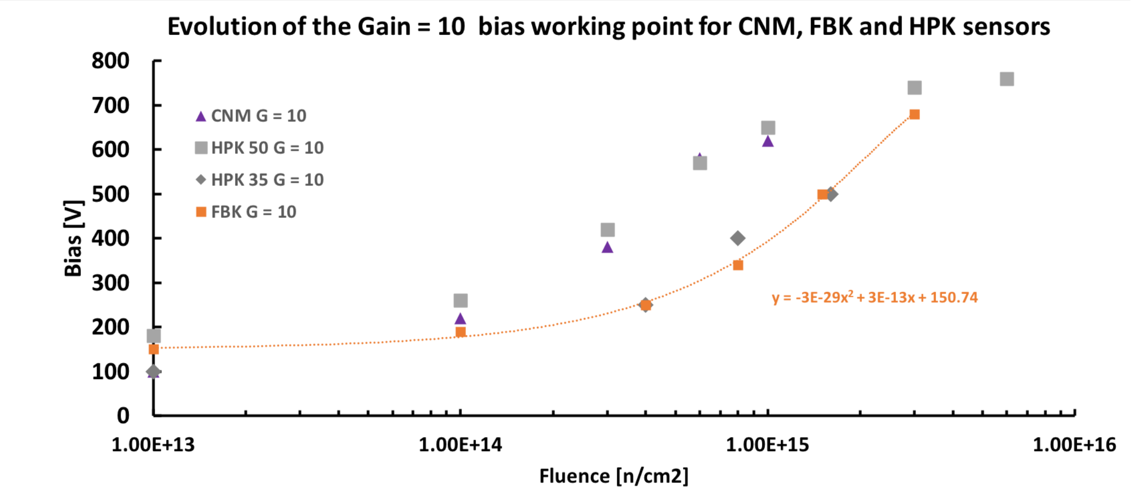


	Inst. Lumi ($cm^{-2}s^{-1}$)	Peak pileup (PU)	Int. Lumi (fb^{-1}/y)	Hadron fluence (particles/cm^2)
LHC	1.7×10^{34}	60	40-50	12E11 $\|\eta\|=1$; 3E13 $\|\eta\|=2.6$
HL-LHC	$5\text{-}7.5 \times 10^{34}$	140-200	250-320	7.6E12 $\|\eta\|=1$; 2E14 $\|\eta\|=2.6$

UFSD3 wafer layout



Bias for Gain = 10 vs fluence



- Carbon reduces the HV values needed at a given fluence
- The **"voltage reach"** of the detectors: sensors should hold high bias since it **extends the possibility to go to higher fluences.**