Precision Timing with Low-Gain Avalanche Diode Sensors with the CMS Endcap Timing Layer for HL-LHC

European Physical Society Conference on High-Energy Physics, 7.26.2021

Federico Siviero
on behalf of the CMS ETL group

Outline

- ➢ A MIP Timing Detector for the CMS experiment
  - ○ The Endcap Timing Layer
- ➢ Sensors for ETL
  - ○ Laboratory measurements
  - ○ Beam test results
- ➢ ETL ASIC (ETROC)

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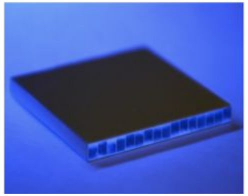
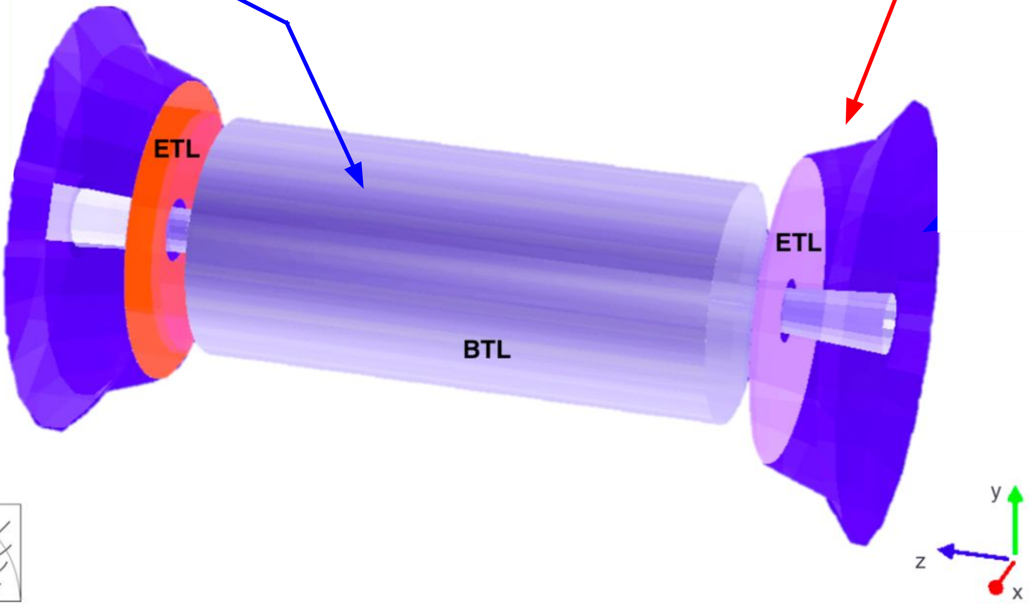
CMS Mip Timing Detector (MTD)

BTL: LYSO bars + SiPM read-out

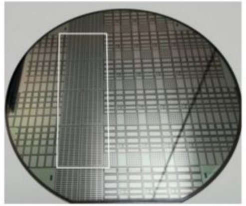
- TK/ECAL interface ~ 45 mm thick
- $|\eta|<1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels





ETL:Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; 8.5M channels



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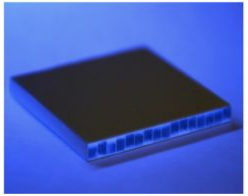

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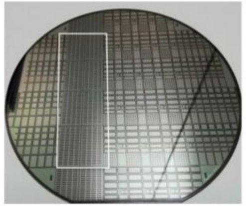

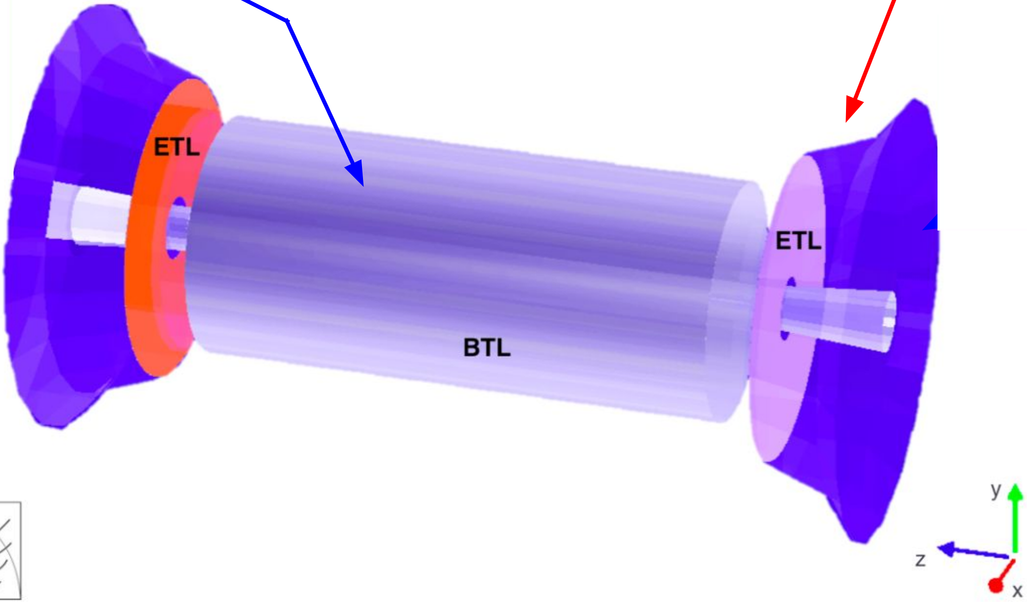

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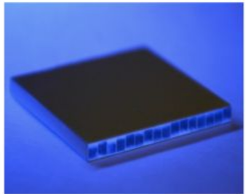

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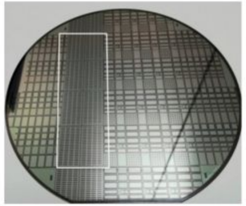
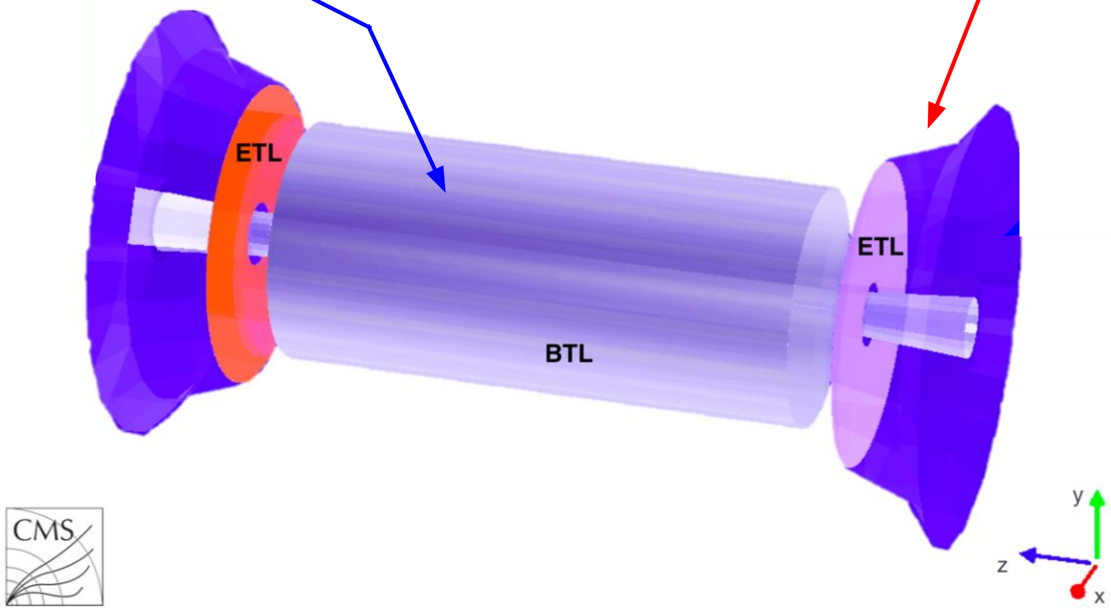
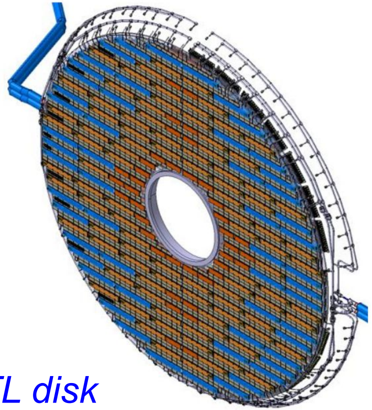


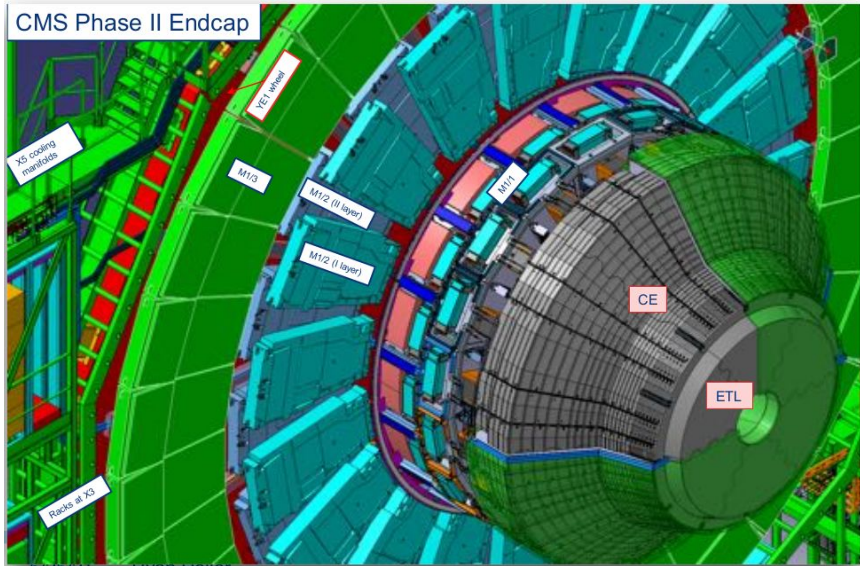


Endcap Timing Layer (ETL)

- ETL will be mounted on the nose of the CMS CE calorimeter
- Coverage:
  - z = 3 m from pp interaction
  - $1.6 < |\eta| < 3.0$
  - $0.31 \text{ m} < R < 1.2 \text{ m}$



ETL disk



Endcap region of the CMS detector: ETL will be mounted on the CE nose

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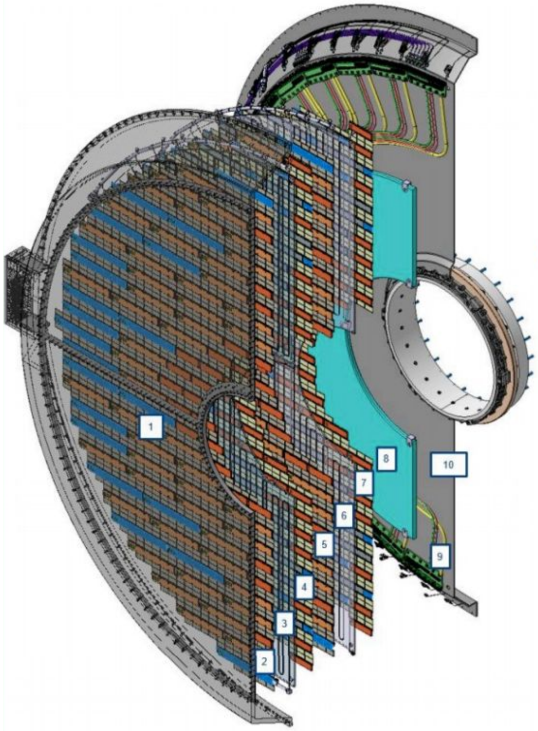
- 2 double-sided disks for each side, assembled into D's
  - double-sided disk → large geometrical acceptance (85% / disk)
  - 2 disks to achieve target resolution:
    - **Single hit resolution < 50 ps**
    - **track resolution < 35 ps**

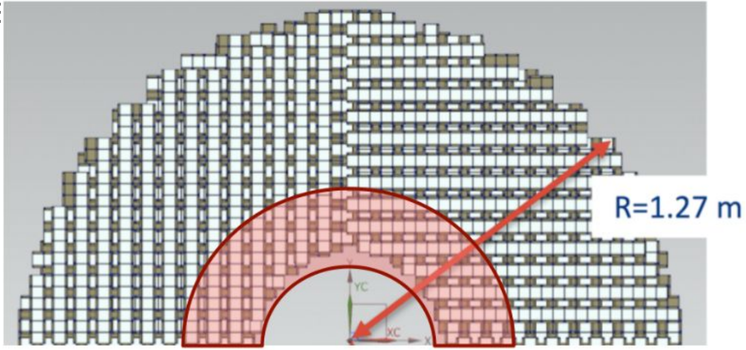


Exploded view of one of the D-modules composing the ETL disks

Endcap Timing Layer (ETL)

- ETL will operate in a large range of radiation fluences
  - Goal: unchanged performances up to the end of lifetime

- Expected fluence at the end of lifetime ranges from 1.5e n_{eq}/cm^2 to 1.6e15 n_{eq}/cm^2 at high |η| *



Radiation fluences expected at ETL, in red the region > 1e15 n_{eq}/cm^2

***1.6e15 n_{eq}/cm^2 is the nominal max fluence, it gets to 2.5e15 n_{eq}/cm^2 considering a x1.5 safety factor**

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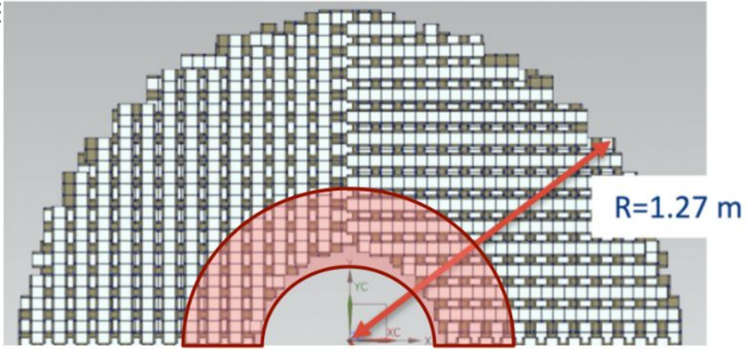

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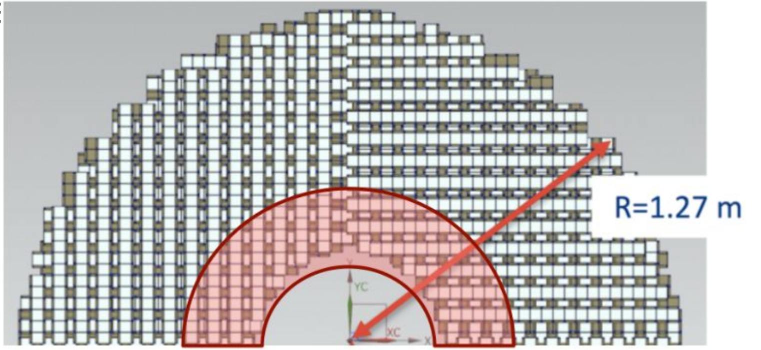
- Expected fluence at the end of lifetime ranges from 1.5e n_{eq}/cm^2 to 1.6e15 n_{eq}/cm^2 at high |η|
- **~ 1e15 n_{eq}/cm^2 : turning point in terms of performance degradation**
  - **88% of ETL < 1e15 n_{eq}/cm^2** → performance degradation not an issue
  - **only 12% > 1e15 n_{eq}/cm^2** → innovative sensor design to achieve unchanged performances also in this region



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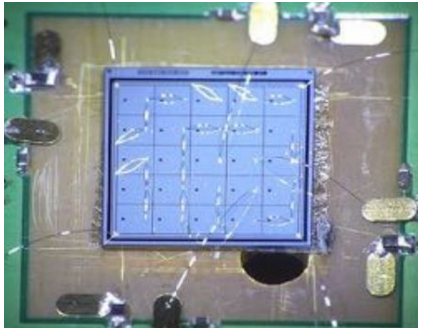
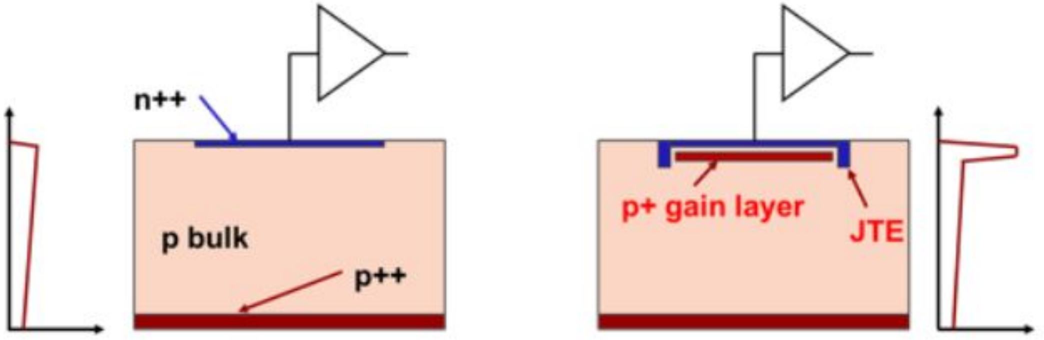
Sensors for ETL

- **50 µm-thick silicon sensors based on the Low-Gain Avalanche Diode (LGAD) technology**
    - p^+ gain layer implanted underneath n^{++} electrode
    - electron charge multiplication for $E > 300\ kV/cm$
    - moderate internal gain: 10-30

5x5 LGAD array bonded to its read-out board





E field | Traditional silicon detector | LGAD | E field

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  - electron charge multiplication for *E > 300 kV/cm*
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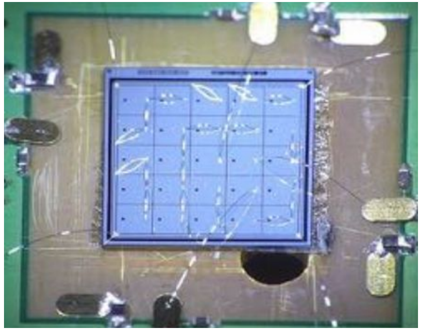
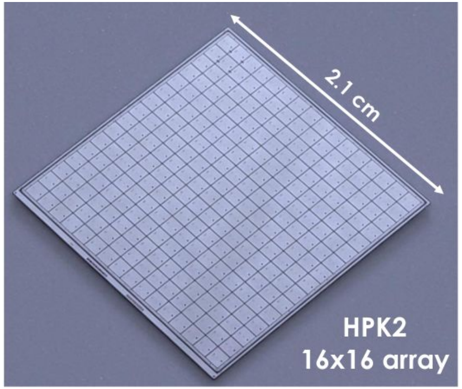
- **The final sensor will be a 16x16 pixel array, read out by the ETL ASIC** (ETROC, see next slides)
- Sensor requirements:
  - 3-4 pF capacitance → pad size: few mm^2
  - Uniform Breakdown Voltage
  - Low leakage current
  - time resolution 30-40 ps
  - No-gain distance between adjacent pads < 50 µm

5x5 LGAD array bonded to its read-out board





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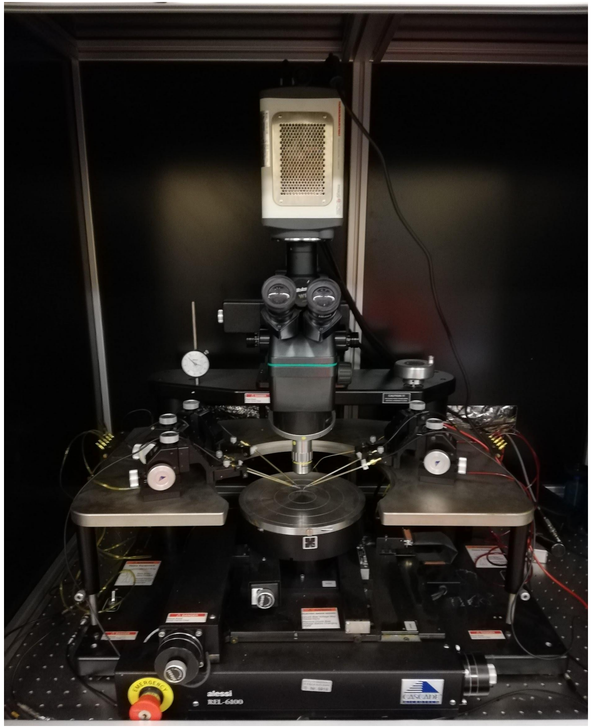
Laboratory measurements

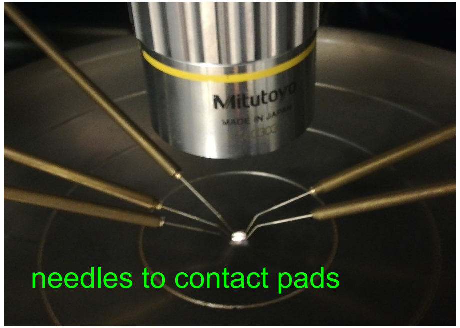
- LGAD sensors are always tested in the laboratory with a probe station
- Two main tests are usually performed:
  - Current vs bias voltage (IV curve)
  - Capacitance vs bias voltage (CV curve)
- Such key measurements provide information about:
  - leakage current
  - breakdown voltage
  - evolution of the gain layer with radiation
  - production uniformity

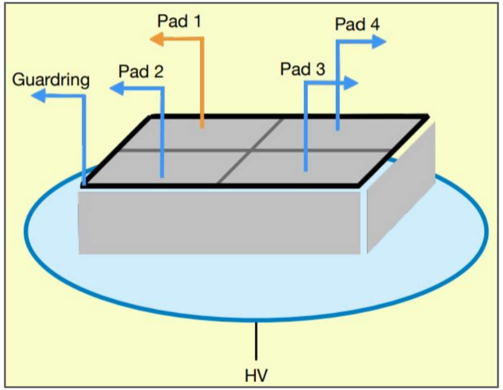


probe station in the Torino Laboratory of Innovative Silicon Detectors

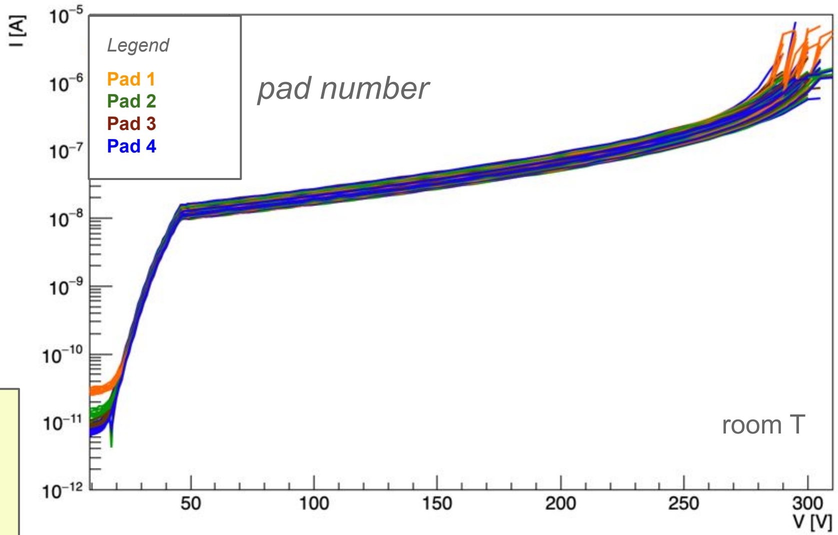
Laboratory measurements

- IV curves of 25 2x2 arrays from a wafer of the latest LGAD production *
- All 4 pads of each sensor are tested
- Similar measurements are performed on all wafers, to test production uniformity
- Biasing scheme is shown below





2x2 ETL LGAD array



*example of FBK sensors are shown here

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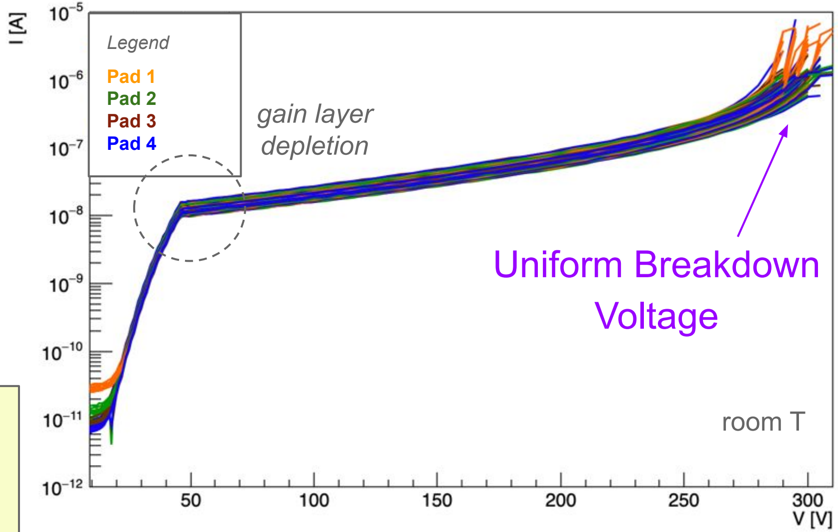

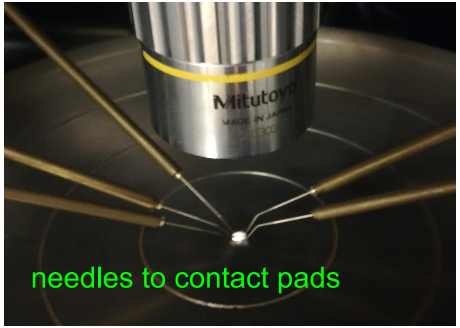

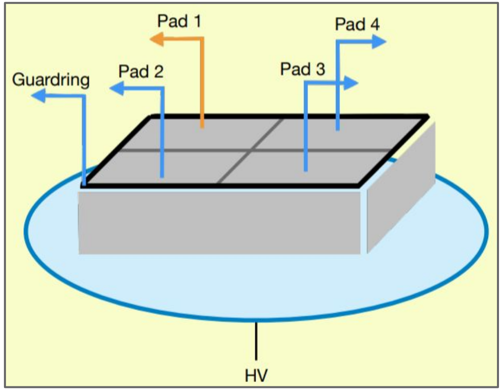

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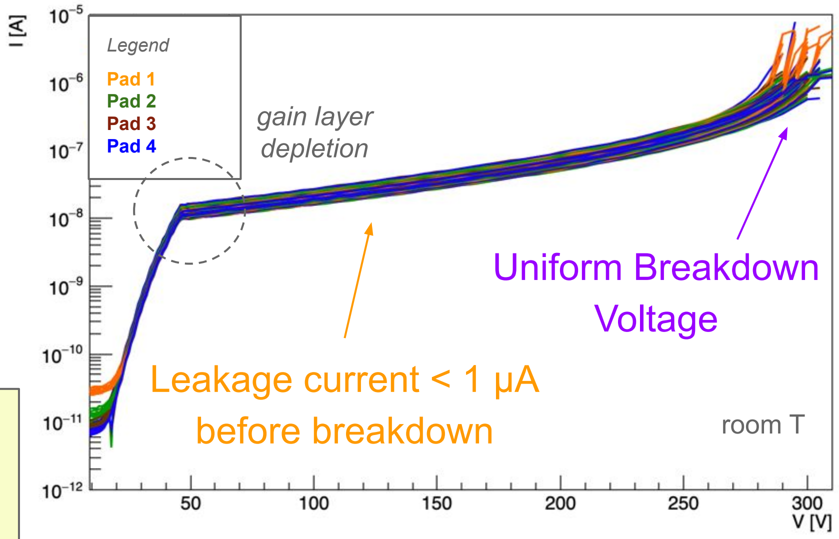

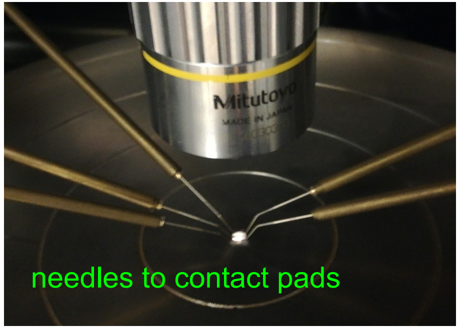

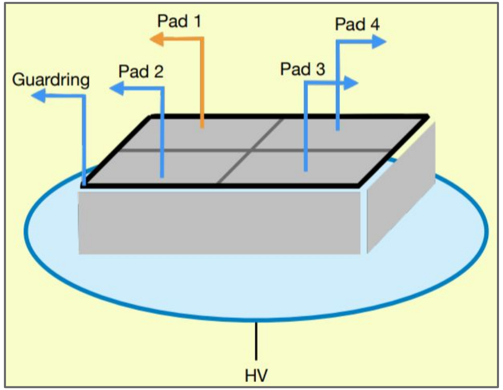

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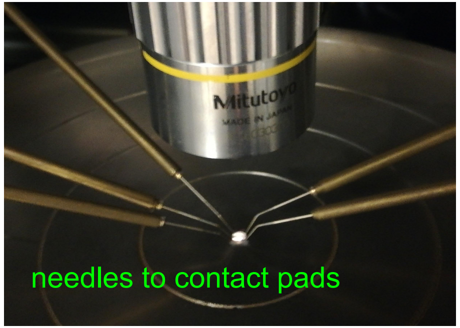

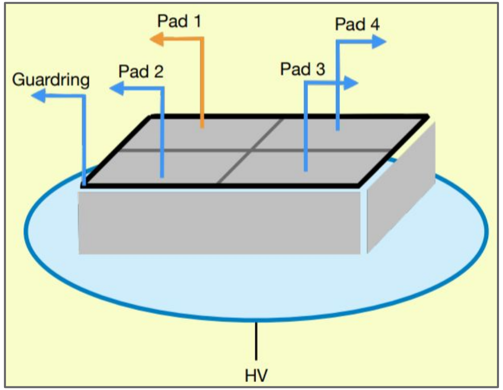

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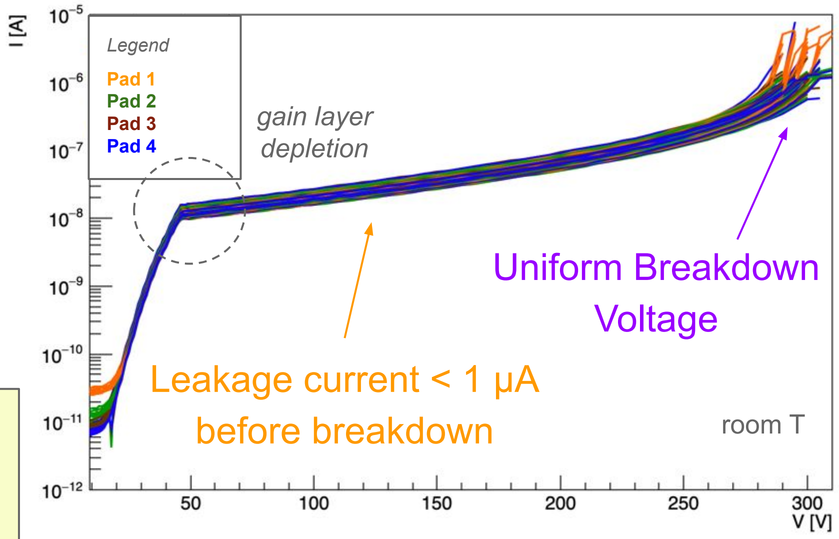
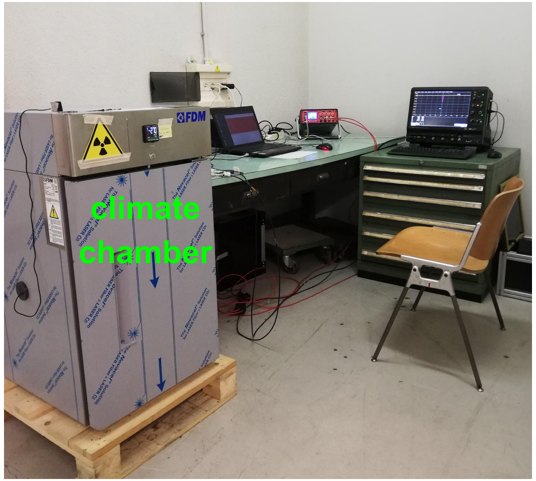
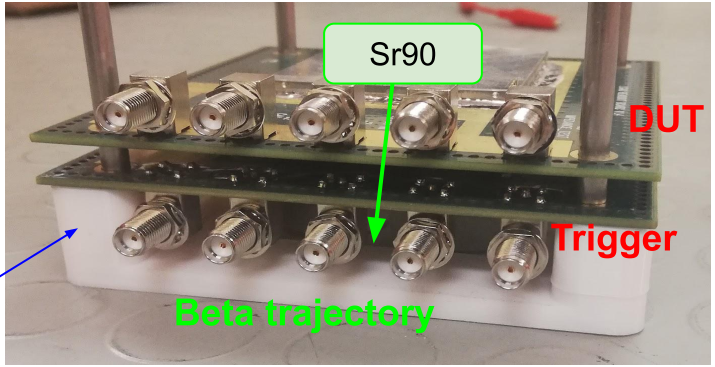


Latest LGAD production highly uniform and with low leakage current → well within specifications

Time resolution: β-source setup

- Laboratory setup based on a Sr90 β-source
- Test a large number of sensors and measure fundamental quantities such as time resolution and gain

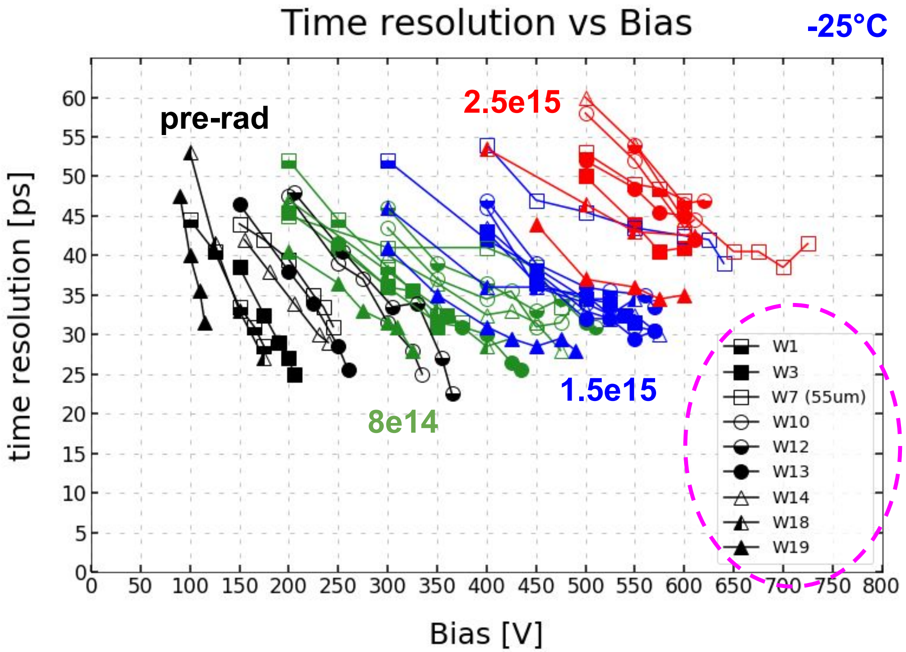




DUT + trigger Telescope, placed inside a specific structure (3d-printed) for alignment

Time resolution: β-source setup

- All tested sensors come from the latest ETL LGAD productions
  - Innovative design that enhances radiation hardness
- Wafer number indicates sensors with different gain implants
- 4 different radiation levels: from pre-irradiation to 2.5e15 n_{eq}/cm^2



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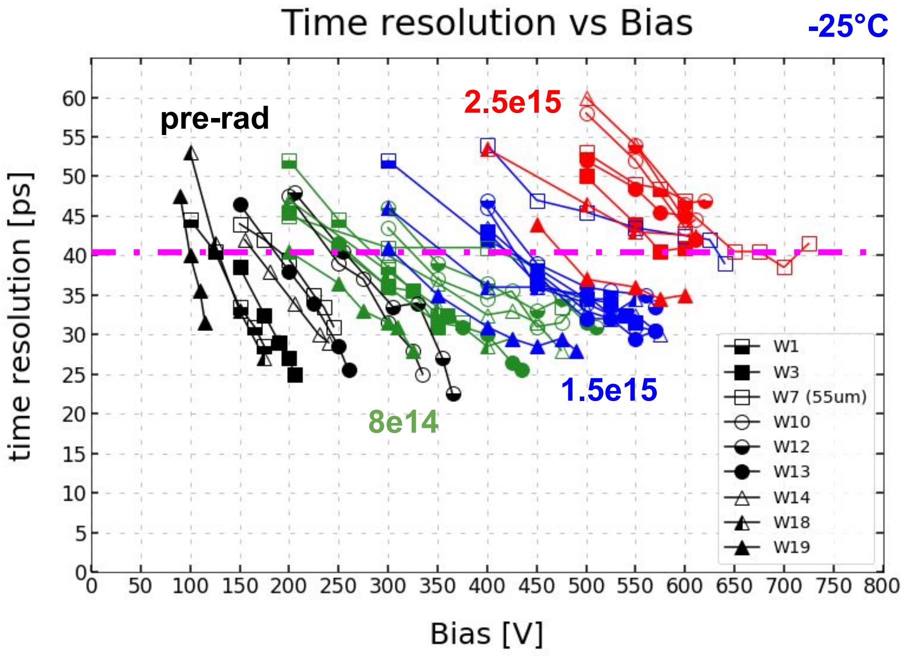
- **All sensors** are able to reach a time **resolution ≲ 40 ps up to 2.5e15** $\mathbf{n_{eq}/cm^2}$ *



**maximum fluence expected in the innermost part of ETL considering a x1.5 safety factor*

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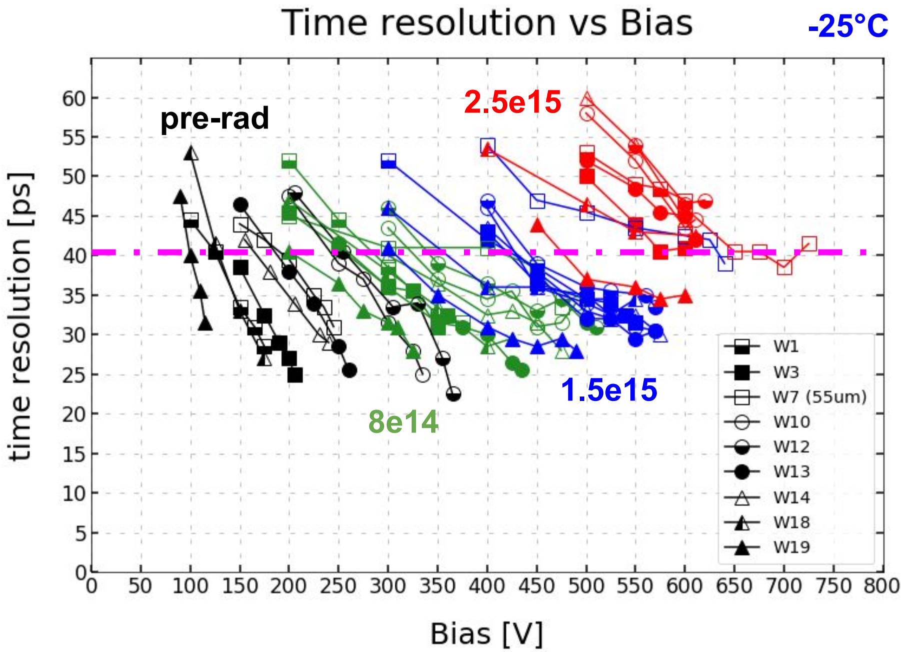
- 4 different radiation levels: from pre-irradiation to 2.5e15 n_{eq}/cm^2
- **All sensors** are able to reach a time **resolution $\lesssim$ 40 ps up to 2.5e15 n_{eq}/cm^2 ***
- With the latest LGAD designs, **ETL able to avoid performance degradation even in its most irradiated region**



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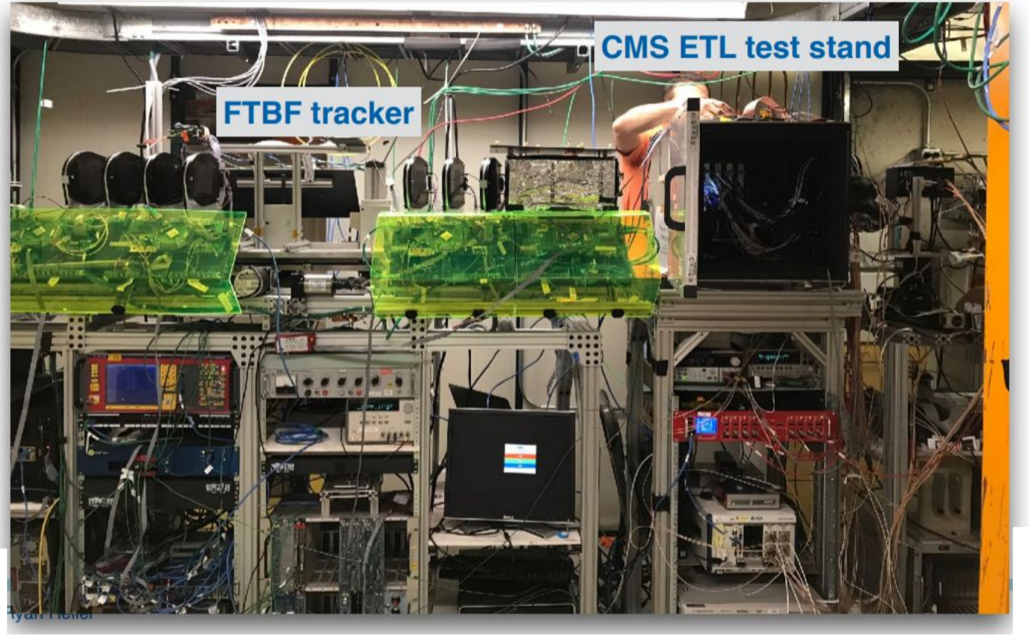
Beam Test

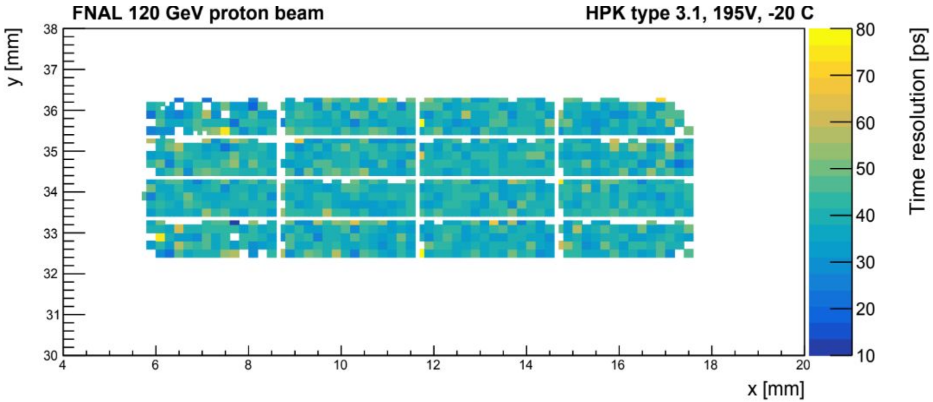
- Following laboratory tests, LGAD sensors are measured at beam tests
- Fermilab Test Beam Facility with 120 GeV protons
  - Precise tracking → detailed information on the hit position
  - Cold box
  - High-speed MCP provides reference timestamp with 10 ps resolution

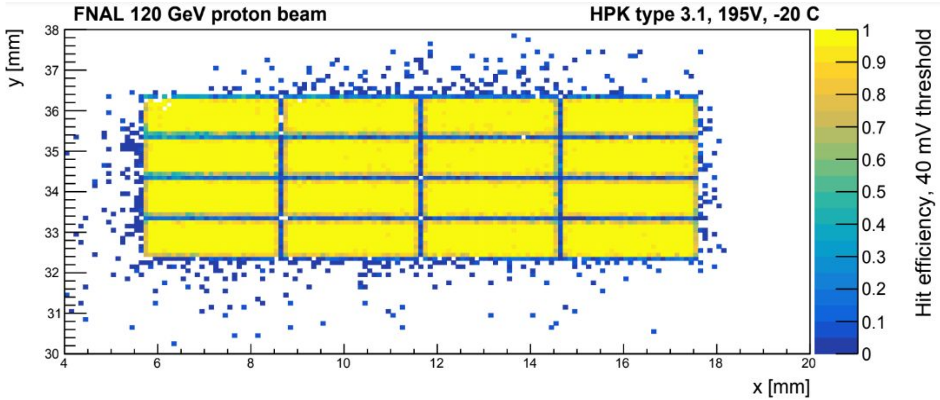
→ study a limited number of sensors with high precision



Beam Test

- Two results regarding a 4x4 LGAD array





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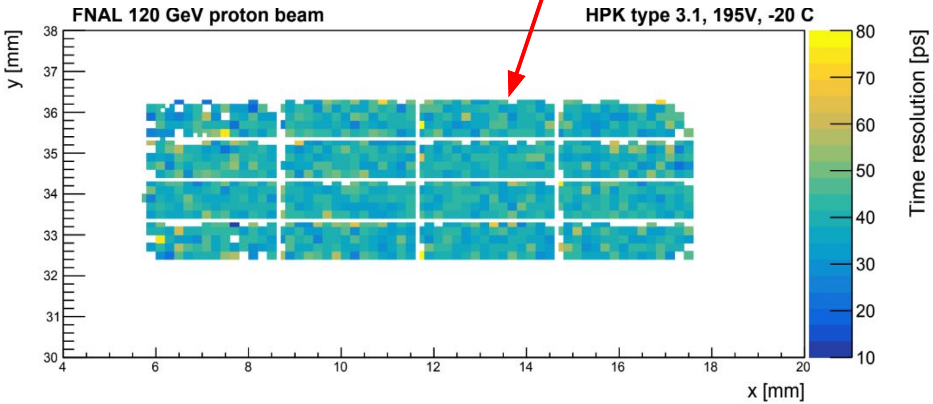
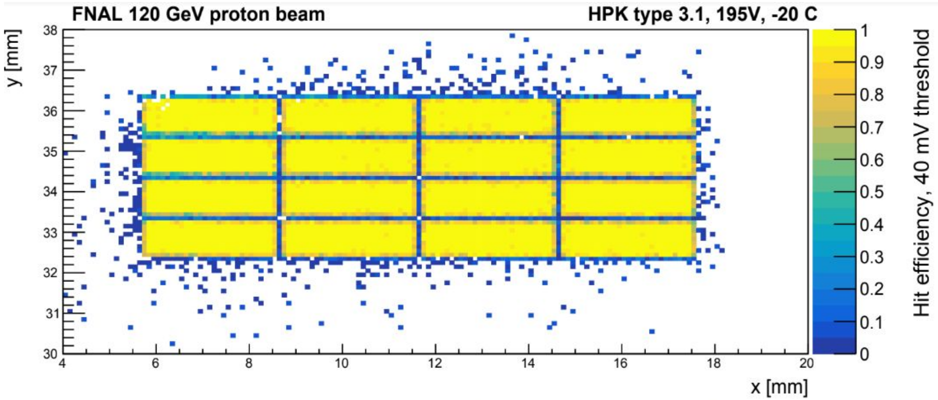
- Two results regarding a 4x4 LGAD array
- 2D-map with time resolution uniformity: 40 ps achieved all across the sensor active area





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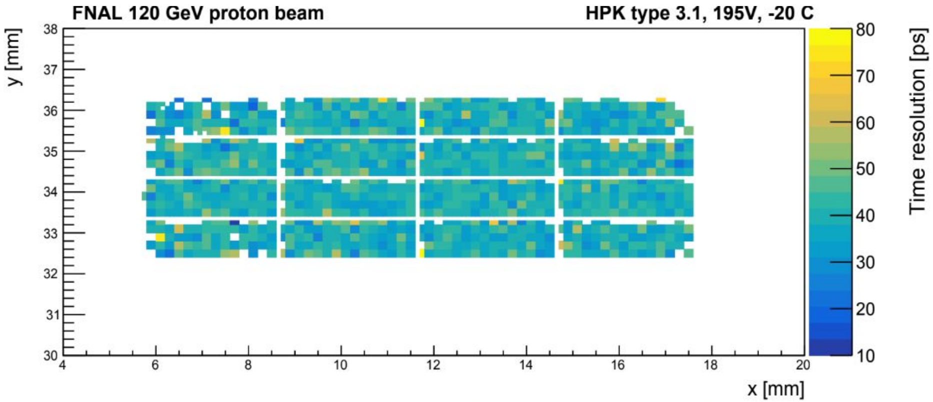
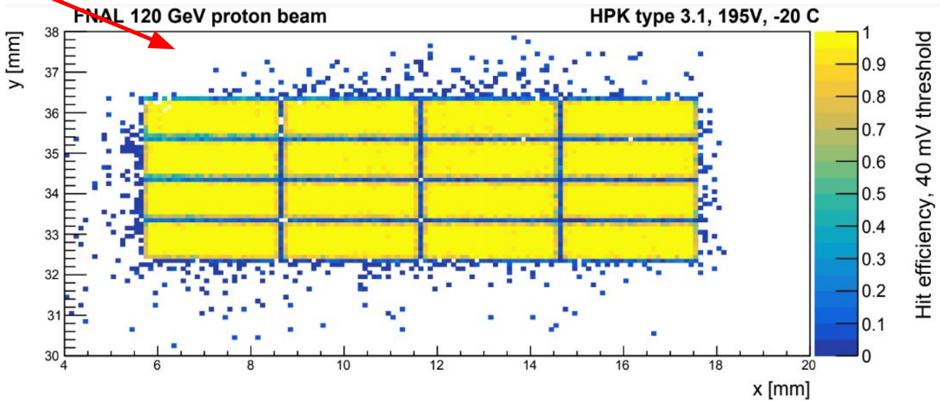
- Hit efficiency uniform and ~ 100%





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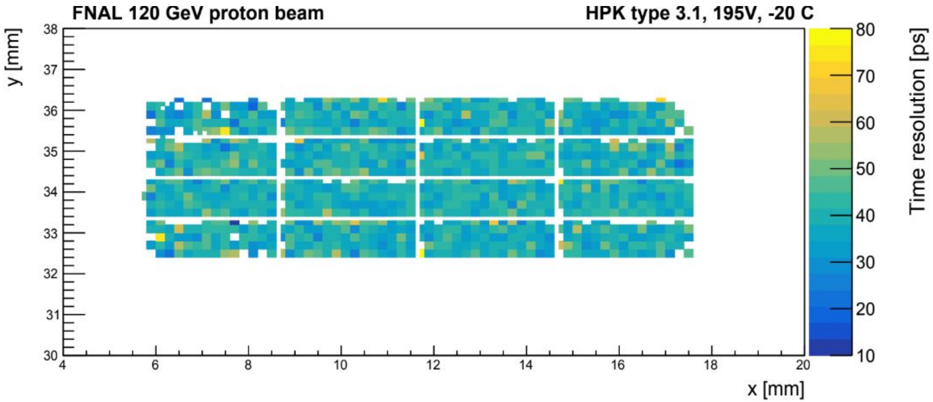

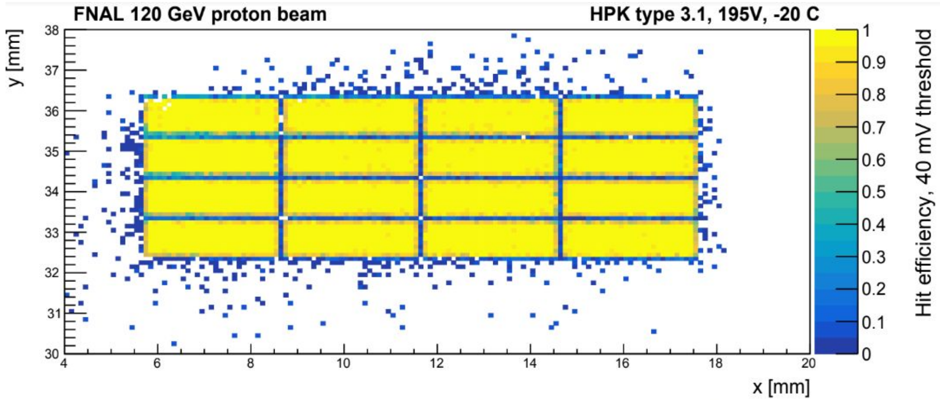

Beam test results show that LGAD sensors are highly uniform and efficient, able to achieve the target resolution even on large multi-pad arrays

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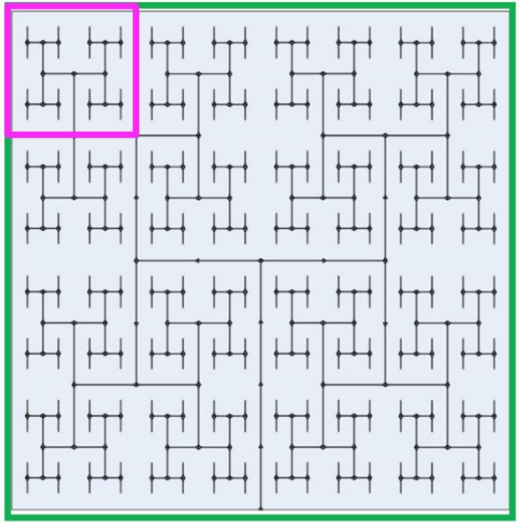
ETROC

- **ETROC is the ETL read-out ASIC**
- **To achieve time resolution < 50 ps per single hit:**
  - low noise + fast rise time
  - power budget: 1 W/chip, 3 mW/channel
- **3 prototype versions before getting to the final, full-size chip**
  - ETROC0 and ETROC1 produced and tested
  - ETROC2 is being designed



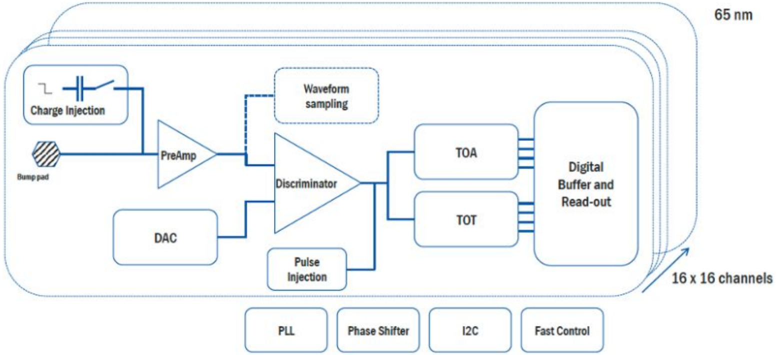
✔ ETROC0: single analog channel

✔ ETROC1: with TDC and 4x4 clock tree

◉ ETROC2: full functionality + full size

◉ ETROC3: 16x16 full size chip

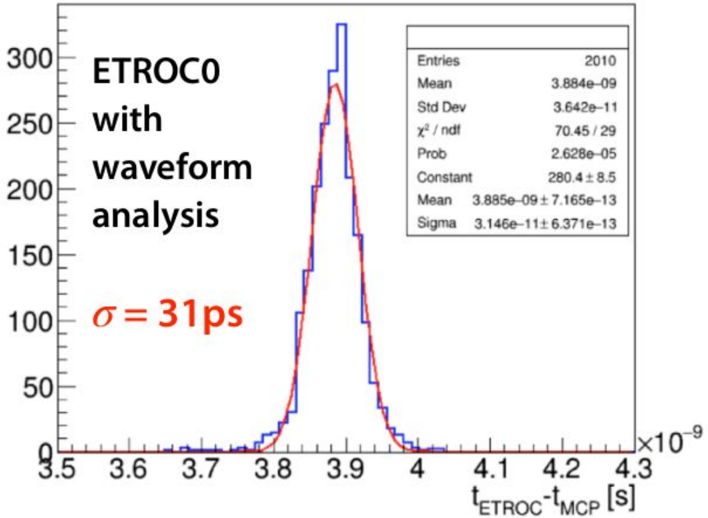
ETROC diagram



ETROC0

- **Goal: measure core front-end analog performance**
- Jitter measurements agree with chip post-layout simulation
- Power consumption for preamp and discriminator consistent with expectation

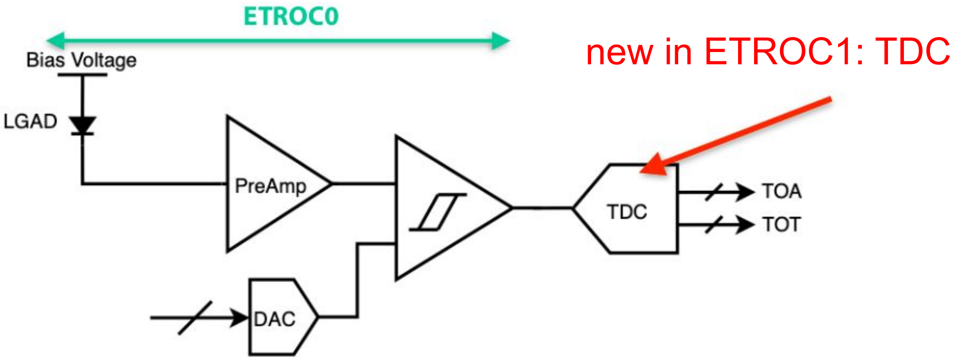
Time resolution measured at FNAL beam test, using a fast MCP as reference



ETROC1

- ETROC1 is the 2nd prototype version: 4x4 pixels + TDC
- ETROC TDC design optimized for low power
- Low power achieved using simple delay cells with self-calibration

ETROC1 diagram



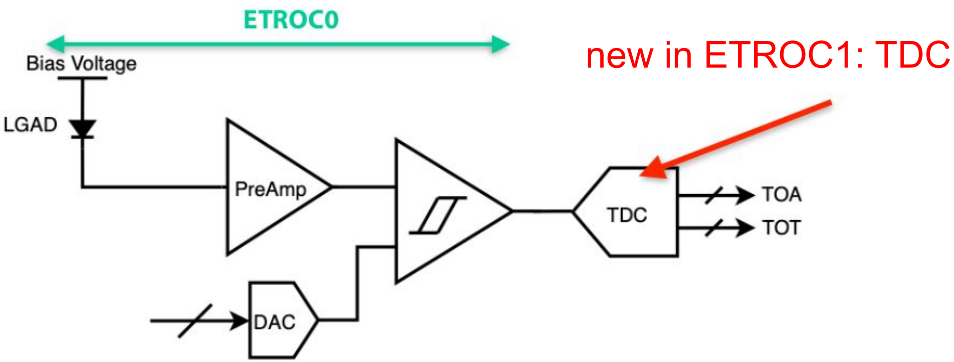
Submitted in Aug. 2019, Received in Dec. 2019

ETROC1

- **ETROC1 is the 2nd prototype version: 4x4 pixels + TDC**
- **ETROC TDC design optimized for low power**
- **Low power achieved using simple delay cells with self-calibration**

> - **40 MHz noise** observed on bumb-bonded ETROC1 + LGAD
> - Coupled through the sensor due to 40MHz clock activity in the circular buffer memory
> - Can be **suppressed by setting the discriminator threshold to ~8 fC**

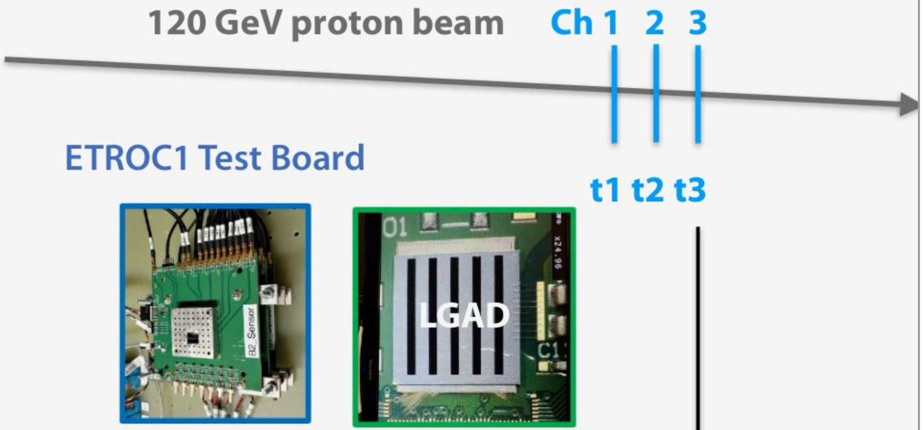
ETROC1 diagram

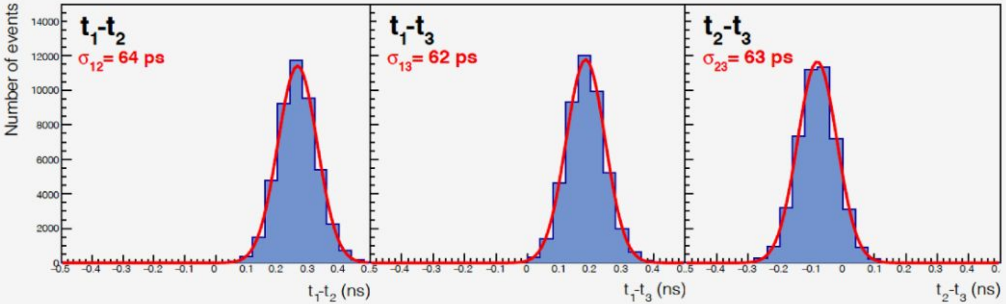


Submitted in Aug. 2019, Received in Dec. 2019

ETROC1 - Beam Test

Feb-May 2021





- Beam test at FNAL MTest
- $\sigma_i = \sqrt{(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)/2}$ = 42 - 46 ps

  (Time resolution of single LGAD+ETROC1)

Summary

- The CMS Endcap Timing Layer will provide time measurements of charged particles with single-hit time resolution < 50 ps, helping the CMS detector to maintain its excellent performances in the very challenging environment of the HL-LHC

- ETL will be equipped with thin Low-Gain Avalanche Diodes (LGADs) and read out by ETROC ASIC

- The latest LGAD production has been measured both in the laboratory and during beam tests, to ensure they meet all the specifications:
    - Leakage currents and Breakdown Voltage highly uniform
    - Time resolution < 40 ps up to 2.5e15 n_{eq}/cm^2
    - Beam test results showed 100% efficiency and uniform time resolution across the whole active area of large LGAD arrays

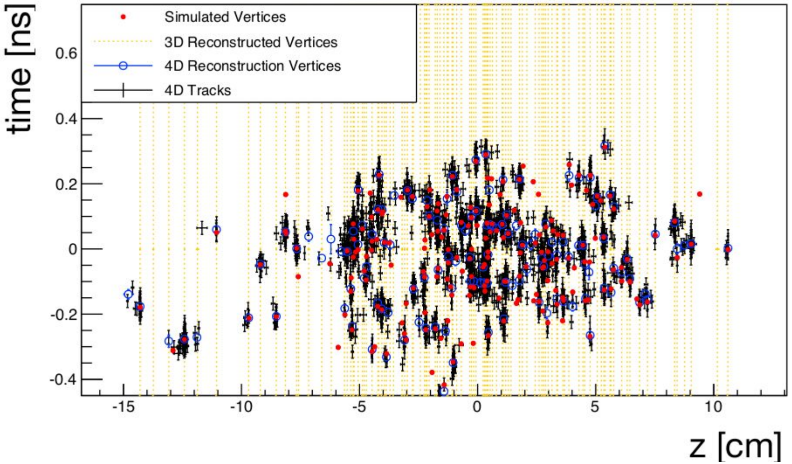
- ETROC is the ETL ASIC, required to consume low power while providing excellent timing performances
    - ETROC1 is the second prototype version: 4x4 pixels + low-power TDC :
        - 40 MHz noise observed → can be suppressed by setting discriminator thr at 8 fC
        - 42-46 ps time resolution, as measured during FNAL beam test
    - ETROC2 is being designed (submission in 2022)

Thank You!

BACKUP

Towards HL-LHC

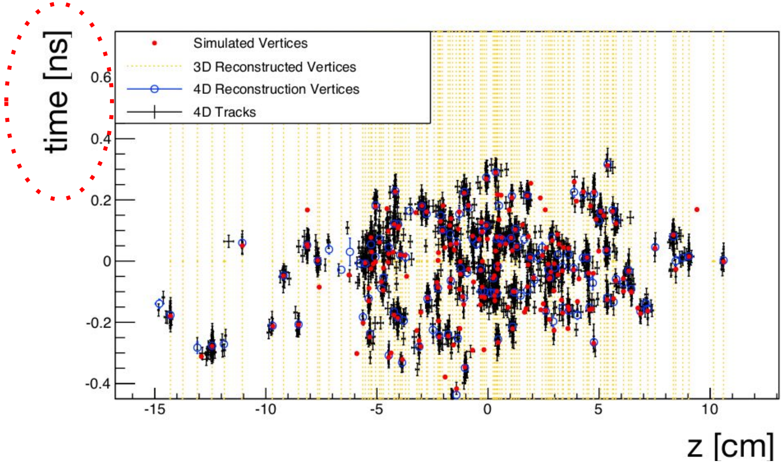
- **Unprecedented instantaneous and integrated luminosity at the HL-LHC:**
  - precision measurements of Standard Model processes involving the Higgs boson
  - searches for Beyond Standard Model processes and particles
- However, **up to 200 pile-up (PU) interactions** per bunch-crossing:
  - degradation of identification and reconstruction of the hard interaction, because of the spatial overlap of tracks

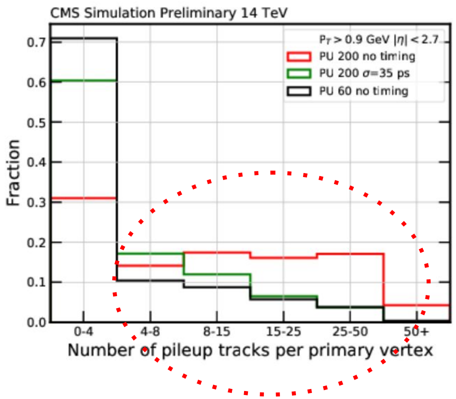


Towards HL-LHC

- **Precision timing will help recovering the present performance of the CMS detector** → add time domain and disentangle vertices overlapping in space, but not in time

- Given the ~ 180 ps time spread of the interactions, a timing detector with **30-40 ps resolution** would slice the beam crossing in ~ 5 consecutive time exposures:
  - number of **collisions per exposure drops to ~ 40, as in present LHC conditions**





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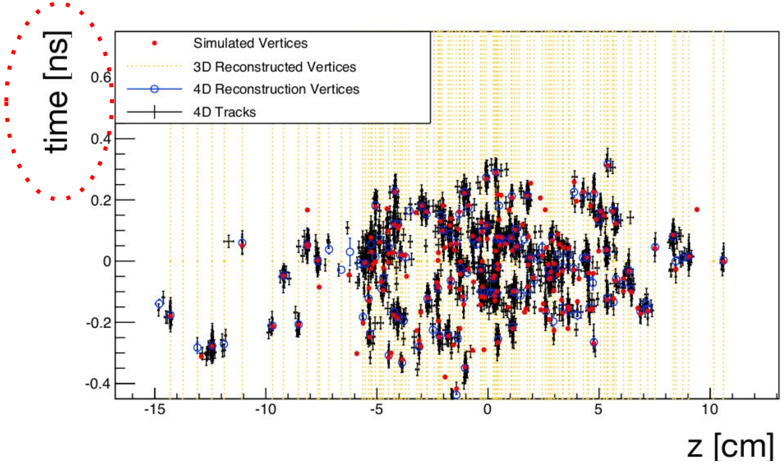
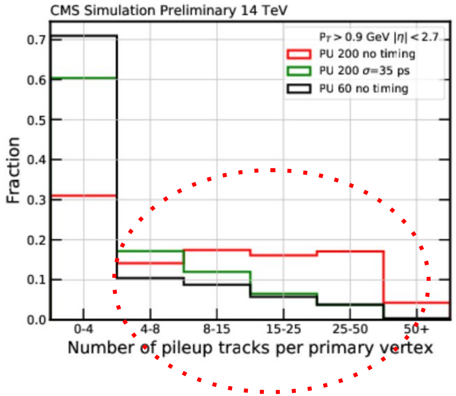
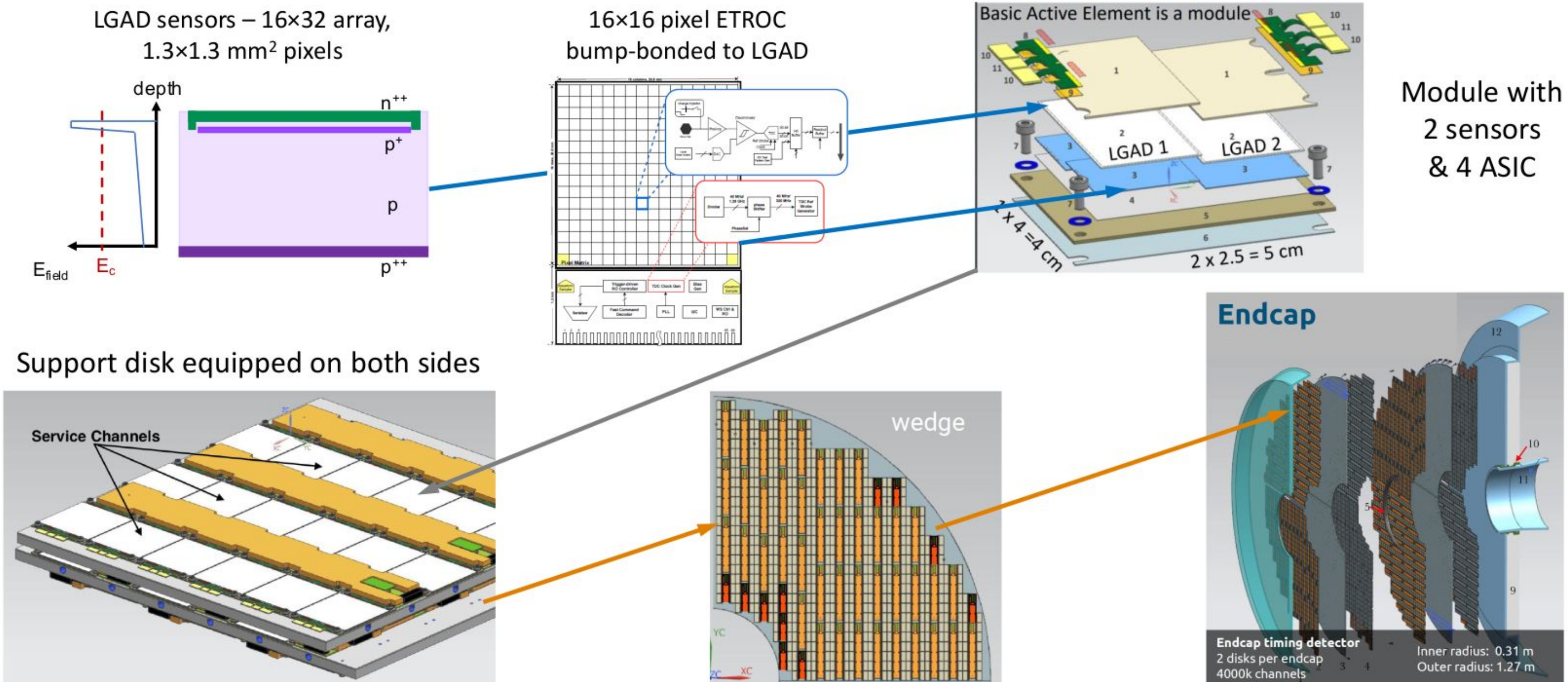




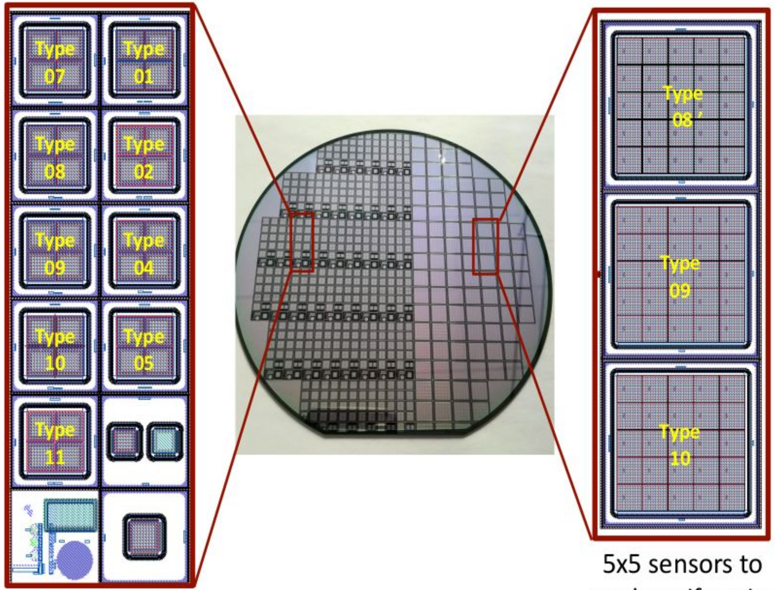
→ the CMS Mip Timing Detector (MTD) has been designed to accomplish this task

The ETL design



Latest LGAD productions for ETL

FBK UFSD3.2

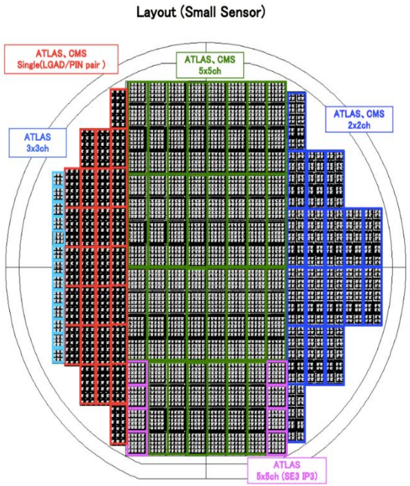


sensors to investigate different inter-pad strategies

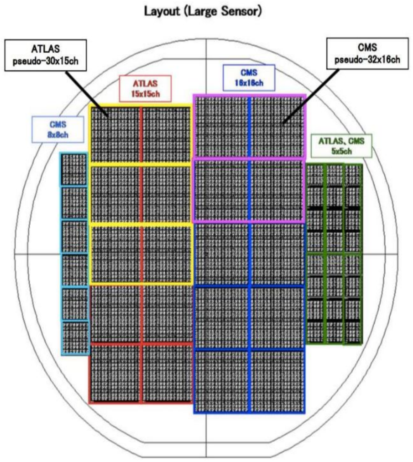
5x5 sensors to study uniformity

- 4 doses of gain layer doping
- 4 carbon implantation doses
- shallow and deep gain implants

HPK2



Small sensors to study inter-pad design, edge termination, and radiation resistance

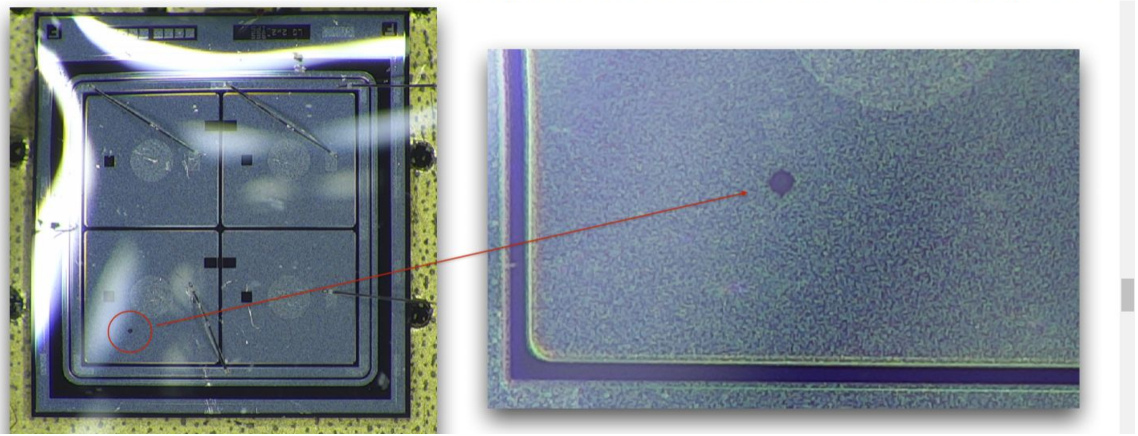


Large sensors, to study uniformity

- 4 doses of gain layer doping
- no carbon implantation
- deep gain implants only

LGAD mortality

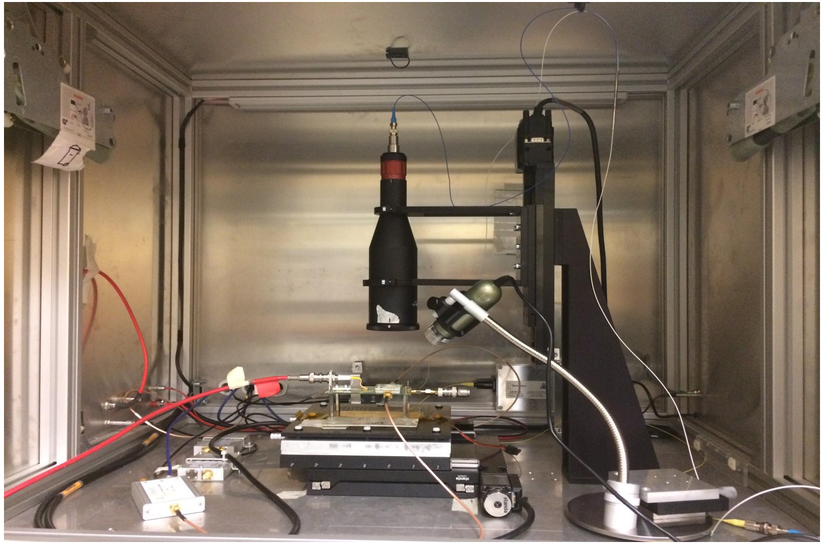
- Anecdotal evidence in past years for death of highly irradiated LGADs at test beams
  - not clear if caused by environmental/mishandling issue, or intrinsic sensor failure mode
- Mortality happens only at very high voltages: > 550-600 V
- LGAD at ETL will operate < 550V even in the most irradiated regions
- LGAD mortality interesting aspect to study, but not an issue for ETL



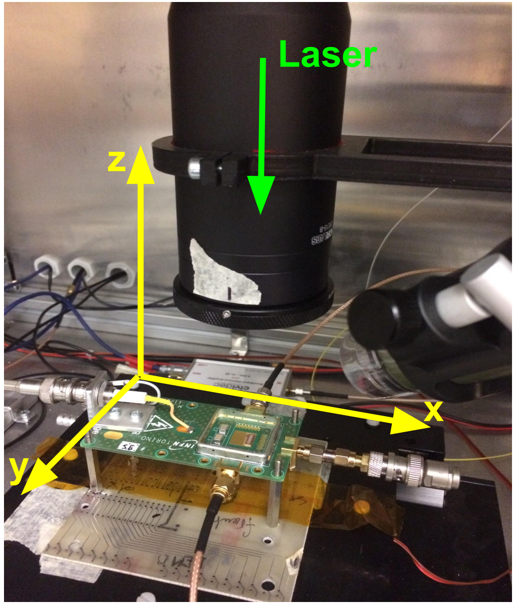
- Proton track clearly points to crater in fatal events

Laboratory measurements - TCT

- Another usual bench test is performed with a precise laser setup (TCT setup by Particulars)
    - Laser spot of only 10 μm + xy-stage (sub-μm precision) → very precise mapping of the DUT



Particulars TCT Setup



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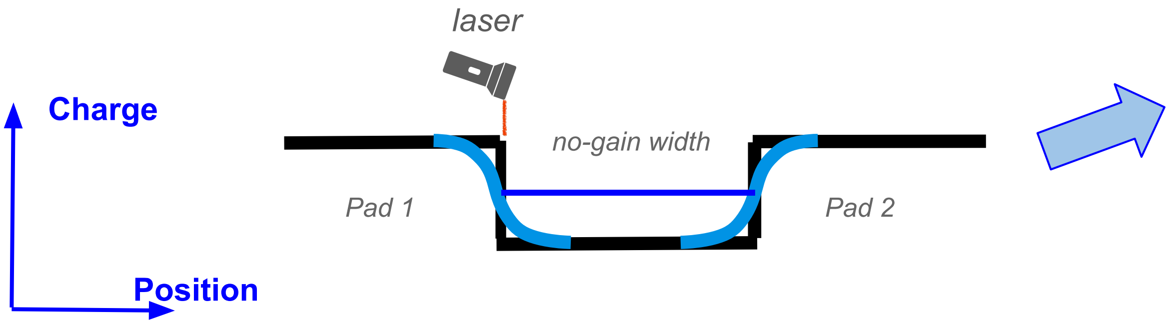
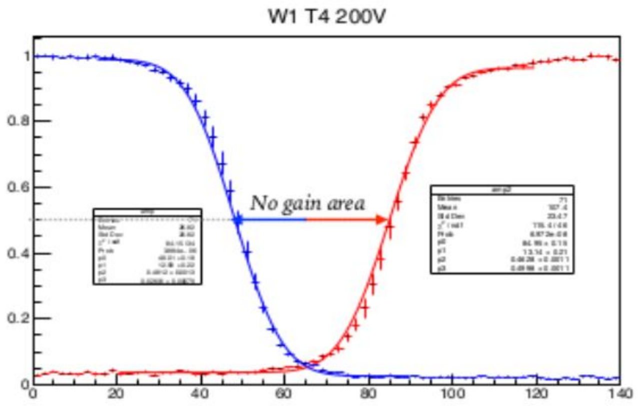
  - Obtained by scanning two nearby pads and plotting the collected charge as a function of the position





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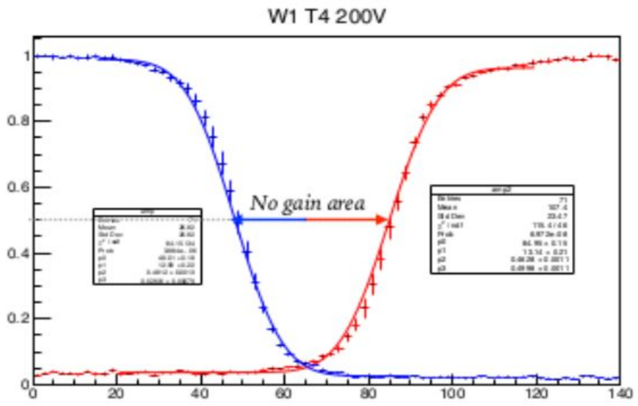
specs requirement:
width < 120 μm

sensor type	Measured width [μm]
4	35
8	41
10	68



Sensors with different no-gain regions have been measured
→ they all are within the maximum width allowed by specifications