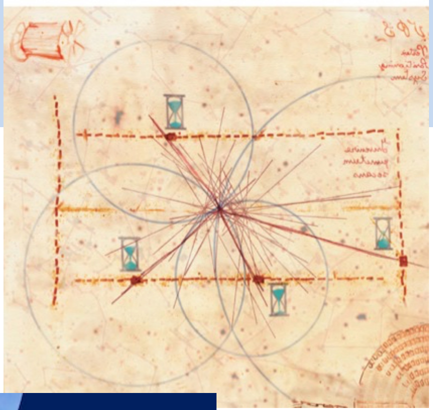
UNIVERSITA DEGLI STUDI DI TORINO

The CMS MTD Endcap Timing Layer: Precision Timing with Low Gain Avalanche Detectors



Marco Ferrero
on behalf of the CMS ETL GROUP

The 30th International Workshop on Vertex Detectors

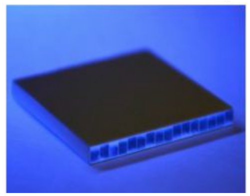
Outlook

- The CMS **MIP Timing Detector (MTD)**
- The CMS **Endcap Timing Layer (ETL)**
- ETL Sensors
    - Sensors technology and prototype
    - Laboratory measurements
    - Beam test results
- The **ETL read-out ASIC (ETROC)**
    - ETROC0 and 1, specification and beam test results

CMS MIP Timing Detector (MTD)

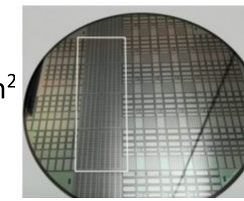
Barrel Timing Layer (BTL):

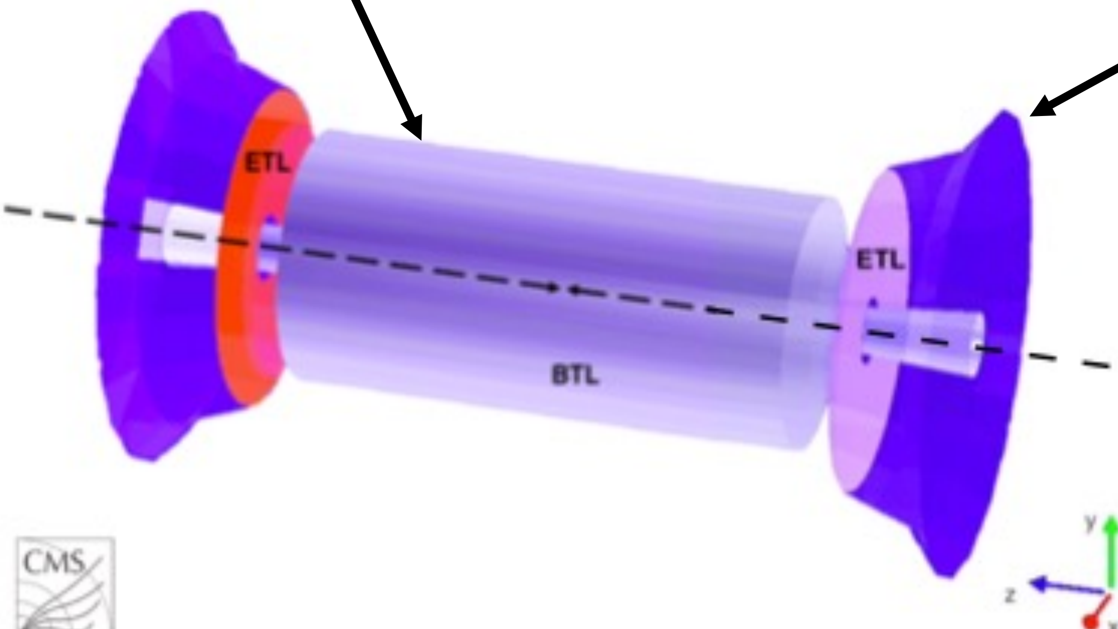
- **LYSO Crystals + SiPM read-out**
- $|\boldsymbol{\eta}| < \mathbf{1.45}$
- Total surface of $\sim$ 38 m^2
- Fluence at 3 ab^{-1}: $2\text{x}10^{14}\ n_{eq}/cm^2$



Endcap Timing Layer (ETL):

- **Low Gain Avalanche Diodes (LGADs)** with ASIC readout
- $\mathbf{1.6} < |\boldsymbol{\eta}| < \mathbf{3.0}$
- Total surface of $\sim$ 14 m^2
- Fluence at 3 ab^{-1}: up to $1.7\text{x}10^{15} n_{eq}/cm^2$



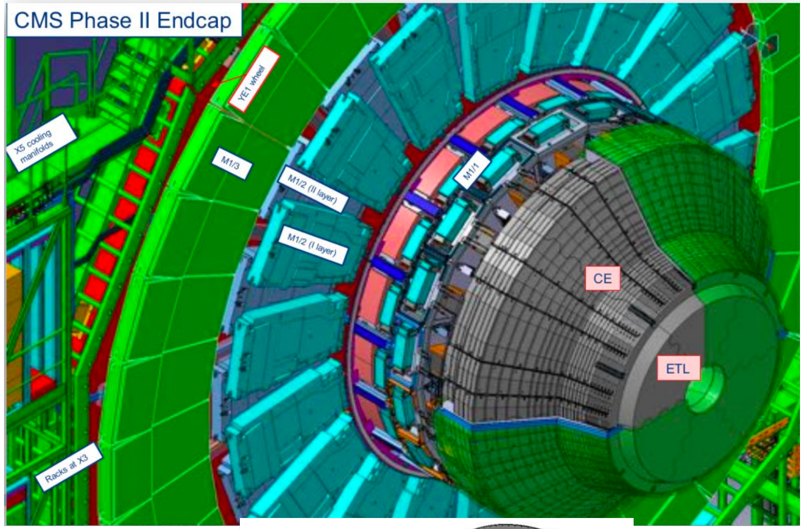


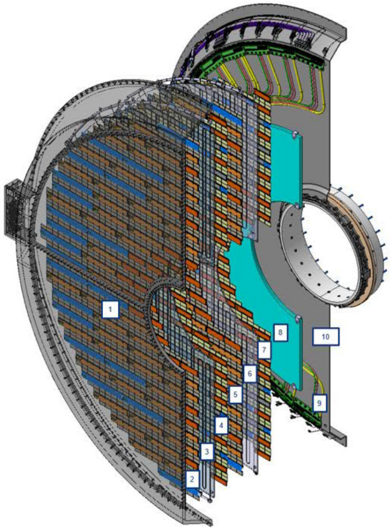
MTD will improve reconstruction by:

- Combining tracking with timing of charged particles
- Providing **a timing resolution of $\sim$ 30 – 40 ps** at the start of HL-LHC, barrel degrades to 50 – 60 ps at the end of HL-LHC

CMS Endcap Timing Layer (ETL)

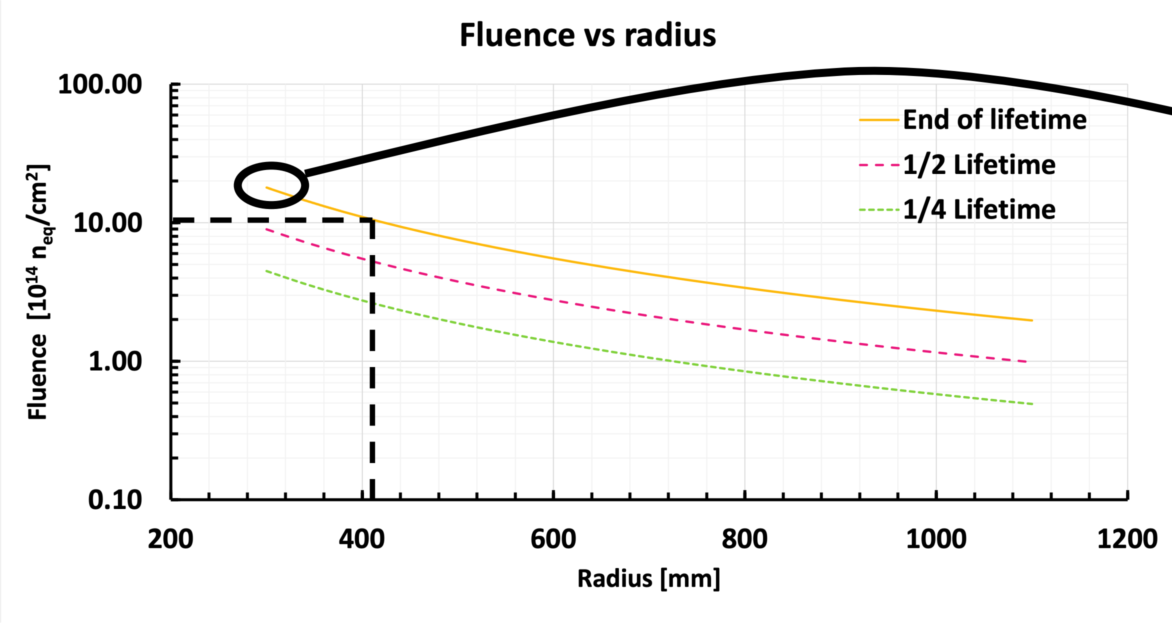
- ETL will be mounted on the HGCAL nose
- **Two double-sided disks** for each endcap
  - Large geometrical acceptance (85%/disk)
  - Ensure two hits for each track
    - → **Single hit resolution < 50 ps**
    - → **Track resolution < 35 ps**
- Coverage:
  - z = 3m from the pp interaction
  - **1.6 < $|\eta|$ < 3.0**
  - **0.31 m < Disk Radius < 1.2 m**





CMS Endcap Timing Layer - radiation environment

ETL will operate in a large range of radiation fluences
ETL must ensure unchanged performances up to the end of lifetime



In the inner region ($|\eta|$ = 3.0)

1.7×10^{15} n_{eq}/cm^2 is the expected maximum fluence at the end of HL-LHC program

2.5×10^{15} n_{eq}/cm^2 is the expected maximum fluence considering a **x1.5 safe factor**

The fluence will exceed **1×10^{15} n_{eq}/cm^2** only on a small fraction of the detector surface, after ½ lifetime

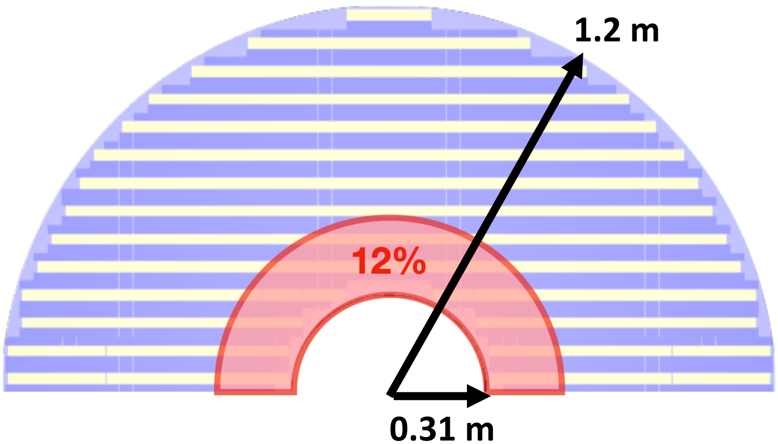
CMS Endcap Timing Layer

- **$1x10^{15}$ n_{eq}/cm^2** : turning point in term of performance degradation
  - 88% of ETL **< $1x10^{15}$ n_{eq}/cm^2** → performance degradation not an issue
  - Only 12% **> $1x10^{15}$ n_{eq}/cm^2** → optimization sensor design to achieve unchanged performances also in this region

  Operating temperature below -25°C

- **Fill-Factor** (ratio between active and total detector area) **> 95%**

- **Low occupancy** (< 0.1% at low η, 1% at highest η) to avoid double hits and ambiguous time assignment



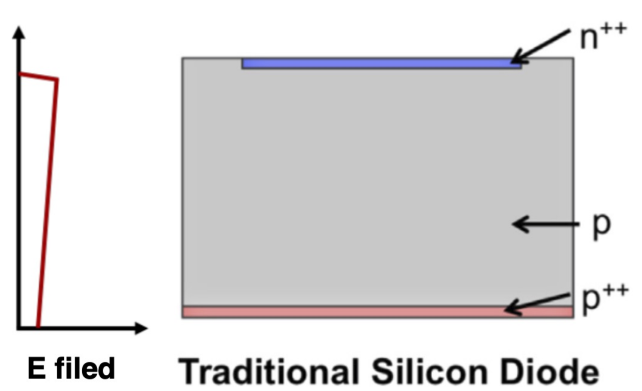
Radiation fluence expected in ETL, in red the region > **$1x10^{15}$ n_{eq}/cm^2**

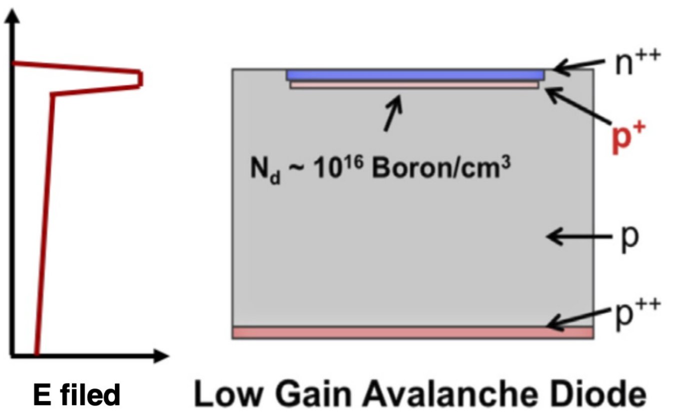
ETL sensors technology

ELT will be instrumented with Low Gain Avalanche Diodes (LGADs) optimized (50µm-thick) for timing measurements

LGAD technology:

- **p^+ gain laye**r implanted underneath n^{++} electrode
  → High located electric field (**E > 300 kV/cm**)
  → **charge multiplication**
  → **Moderate internal gain 10 – 30** to maximize signal/noise ratio





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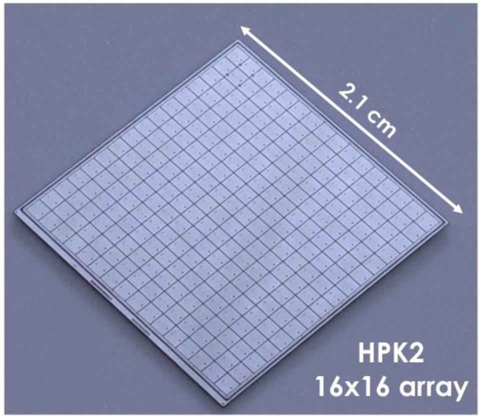
- **Sensor Requirements:**
  → Pad size of few mm^2 determined by occupancy and read-out electronics (**pad capacitance ~ 3 – 4 pF**)
  → Gain, leakage current and breakdown voltage uniformity
  → Low leakage current
  → Provide **large and uniform charge**, > 8 fC when new and > 5 fC at the highest irradiation fluence
  → **No-gain distance** between adjacent pads **< 50 µm**

- **The final sensor :**
  16x16 pad array with 1.3x1.3 mm^2 pads



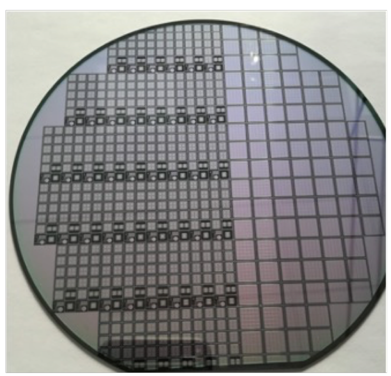
ETL sensor prototypes

Large size prototypes have been produced by FBK (Italy) and HPK (Japan)
R&D activities on ETL sensor design are on going

Latest **FBK production**:

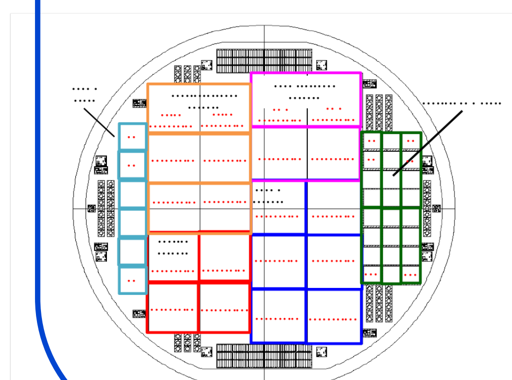
- **Gain layers** with different doses and depths of implant
- **Carbon** co-implantation into gain layer to improve the radiation resistance
- 9 **inter-pad layouts**

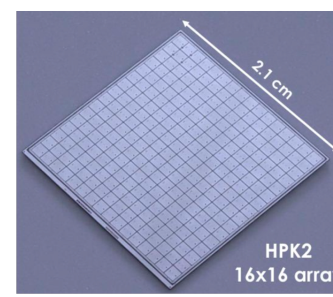
Thickness	DEPTH	Dose Pgain	Carbon	Diffusion
45	Standard	0.98	1.*A	CH-BL
45	Standard	0.98	1*A Spray	CH-BL
45	Standard	0.98	0.8*A	CH-BL
45	Standard	0.98	0.4*A	CH-BL
25	Standard	0.94	1.*A	CH-BL
35	Standard	0.94	1.*A	CH-BL
55	Standard	0.98	1.*A	CH-BL
45	deep	0.70	1.*A	CBL
55	deep	0.70	1.*A	CBL
45	deep	0.70	0.6*A	CBL
45	deep	0.70		BL
45	deep	0.74	1*A	CBL
45	deep	0.74	0.6*A	CBL
45	deep	0.74	1.*A	CBH
55	deep	0.74	1.*A	CBH
45	deep	0.74	0.6*A	CBH
45	deep	0.74		BH
45	deep	0.78	A	CBH
45	deep	0.78	0.6*A	CBH



Latest **HPK production**:

- 4 **gain layer** doses
- **No carbon** co-implantation
- 4 **inter-pad layouts**



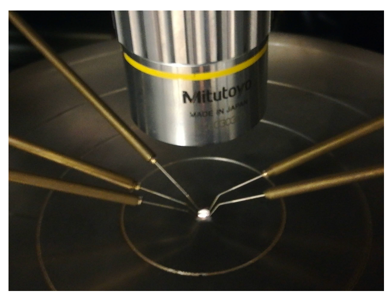


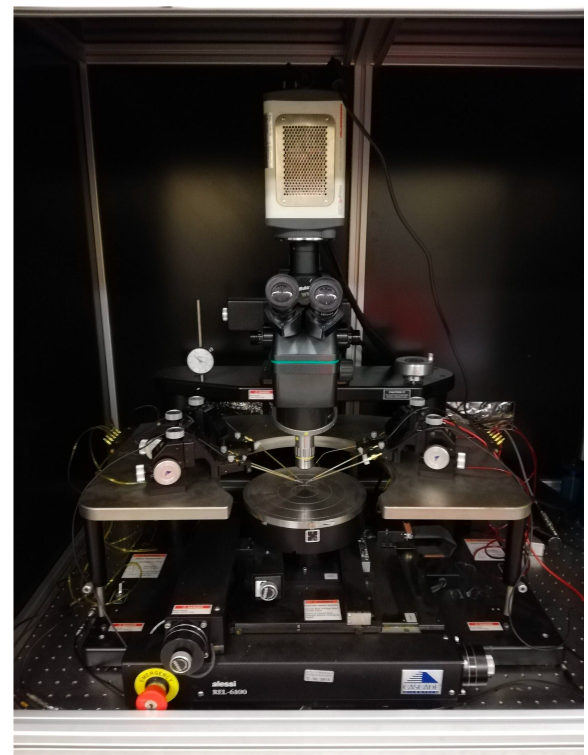
Laboratory measurements: Probe Station

LGAD sensors are tested on wafer and after dicing with probe station

Two main tests are usually performed:
- Current vs Bias Voltage (IV Curve)
- Capacitance vs Bias Voltage (CV Curve)

These measurements provide information on:
- Leakage current
- Breakdown voltage
- Production uniformity
- Evolution of the gain layer with radiation





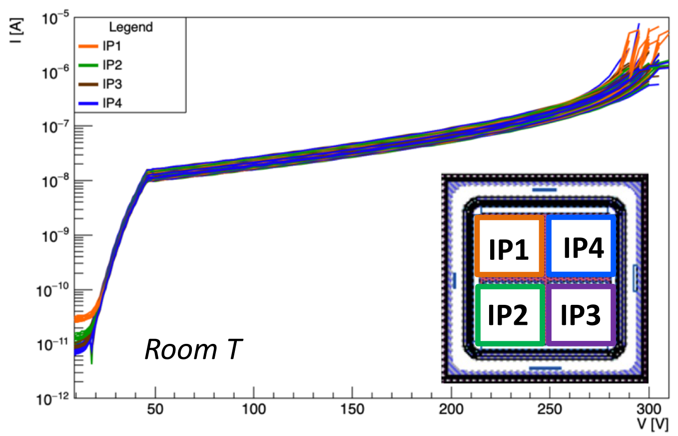
Probe station in the Torino Laboratory of Innovative Silicon Sensors

ETL sensors - Laboratory measurements: production uniformity

IV Curves

Example of 2x2 FBK-LGAD array

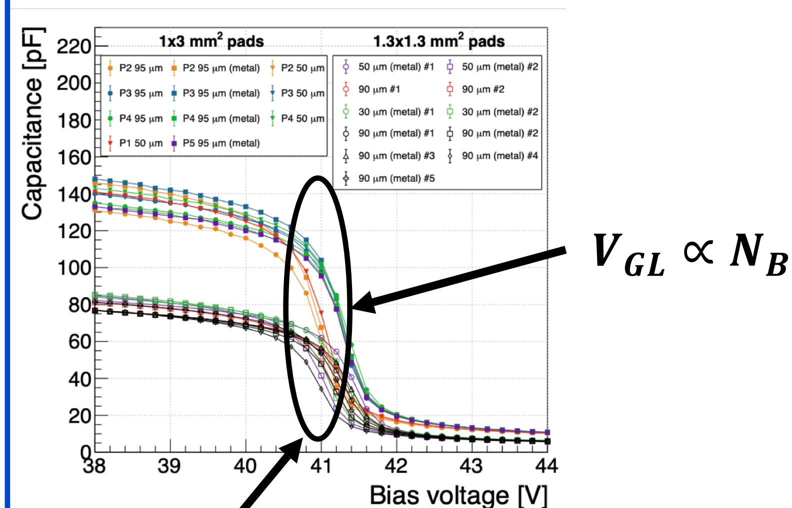
Similar measurements have been performed on all wafers



- **Uniform breakdown** voltage
- **Leakage current < 1 μA** below breakdown

CV Curves

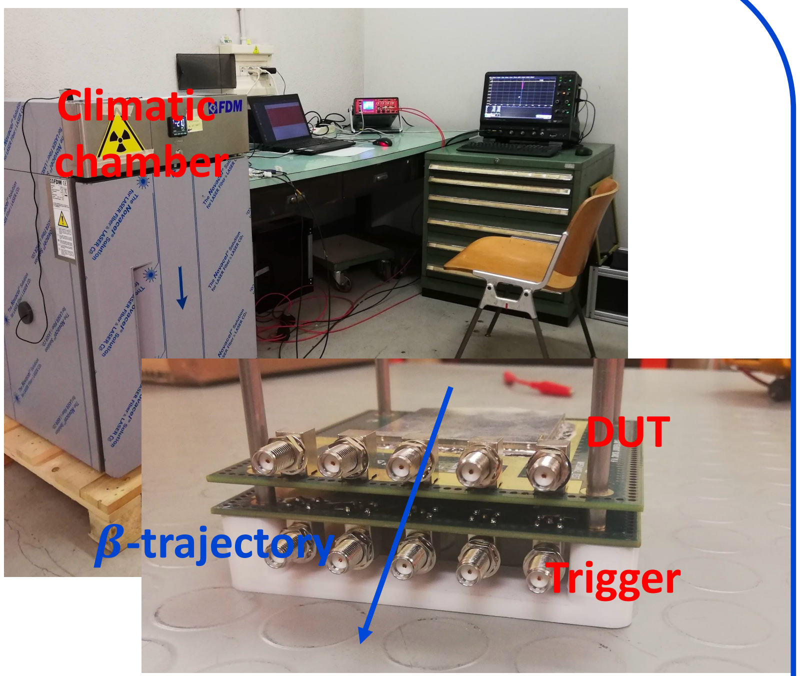
Example of HPK LGAD



- **Uniform depletion voltage**
- ~ 1% spread in gain layer depletion voltage

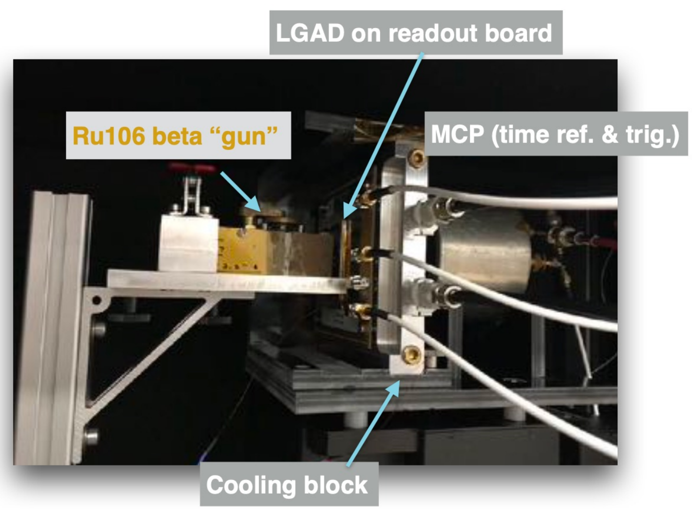
Latest FBK and HPK LGAD productions are highly uniform and with low leakage current
Well within specifications

Laboratory measurements: β-setups



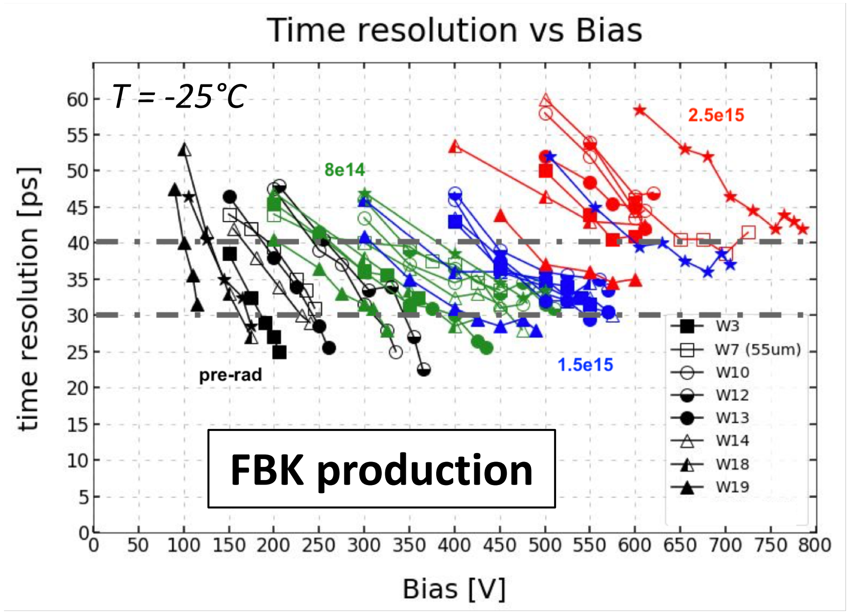
Torino:
- Sr^{90} source
- DUT + trigger in a climatic chamber
- Automated DAQ and analysis system

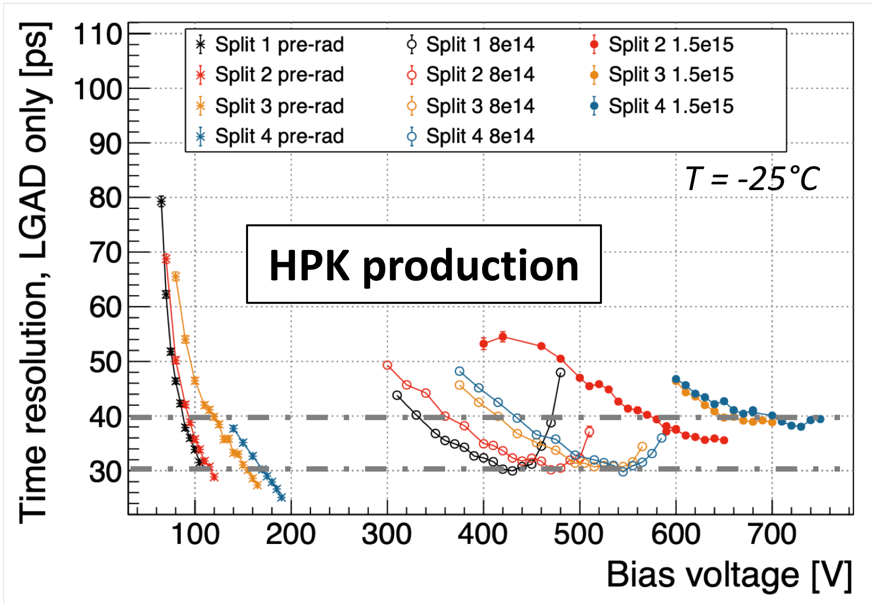
FNAL:
- In Fermilab SiDet Laboratory
- Sr^{90} source
- MCP used as time reference and trigger
- DUT mounted on a cooling block



ETL sensors - Laboratory measurements: timing resolution

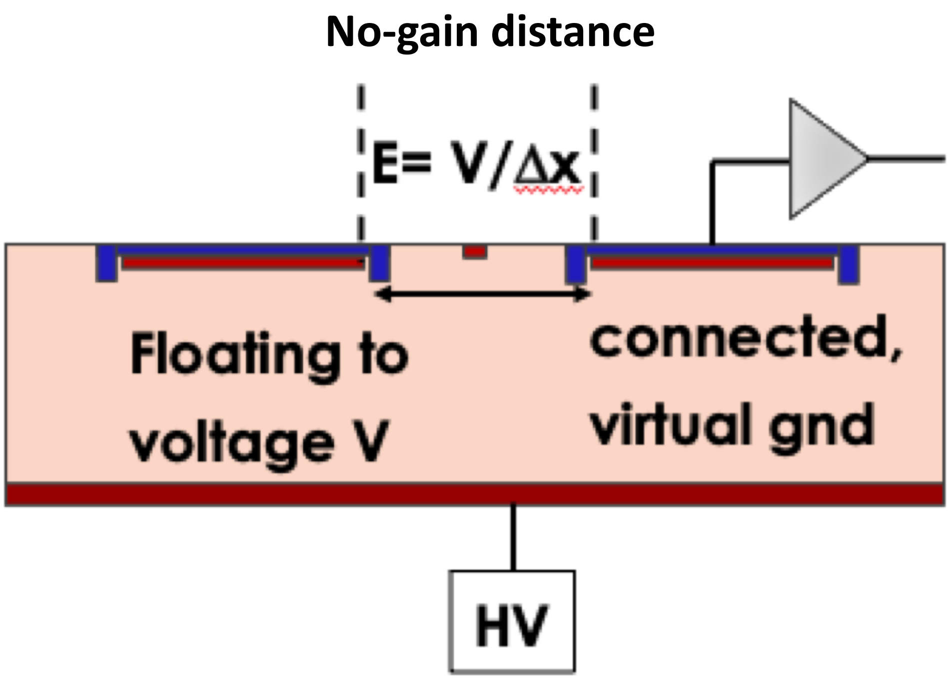
- Laboratory setups in Torino and Fermilab based on a **Sr^{90} β-source**
- Sensor performances are benchmarked using very fast **low noise electronics**
- Both FBK and HPK sensors achieve a **time resolution < 40 ps** up to **2.5×10^{15} n_{eq}/cm^2**
  → With both the latest FBK and HPK production, ETL able to avoid performance degradation even in its innermost part
  → Results might change with ELT ASIC. Additional resolution contribution from ASIC, discussed later





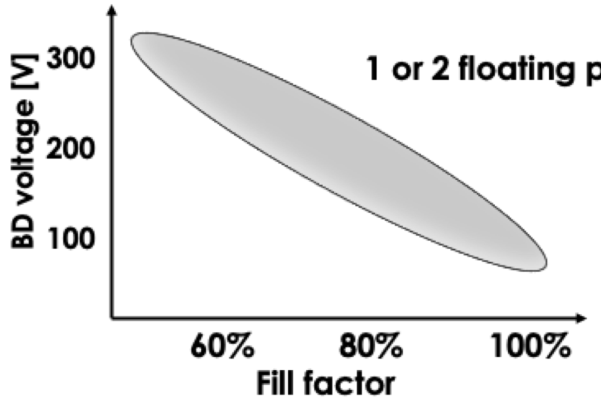
ETL sensors - no-gain distance and floating pad resiliency

Too narrow no-gain distance causes early breakdown as the floating pad resiliency get worse



No-gain distance compromise:

- Narrow enough to allow ETL reaching **95% of fill factor**
- Large enough to increase **floating pad resiliency**

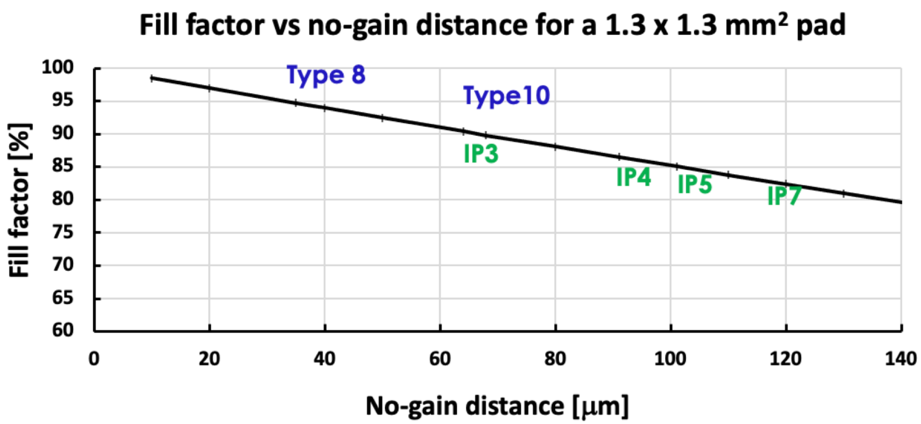


ETL sensors - Laboratory measurements: no-gain distance

No-gain distance between adjacent pads is performed with Particulars Transient Current Technique setup

		Inter-pad Type	Bias [V]	No-gain distance [µm]	Fill-Factor
FBK	UFSD3.2	T4	230	35	94.6%
FBK	UFSD3.2	T8	230	40.5	93.9%
FBK	UFSD3.2	T10	200	68	89.8%
HPK	HPK2	IP3	220	64.2	90.4%
HPK	HPK2	IP4	220	91.1	86.5%
HPK	HPK2	IP5	220	101.8	85%
HPK	HPK2	IP7	220	124.4	82.4%

No-Gain area width and corresponding fill-factor from latest FBK and HPK production



Smaller inter-pad allows better fill-factor

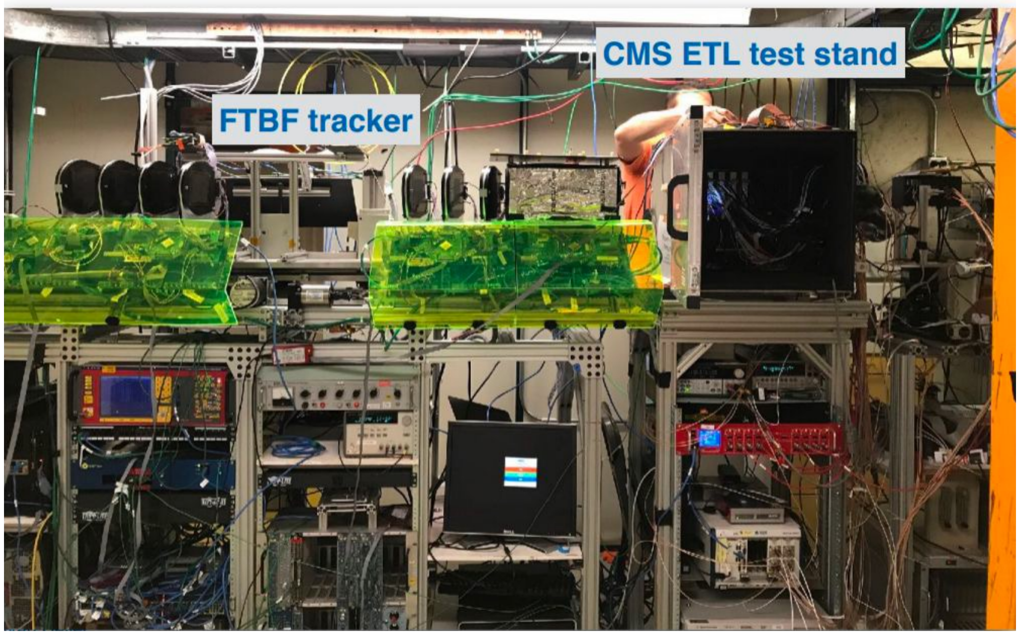
→ Study after irradiation needs to be performed

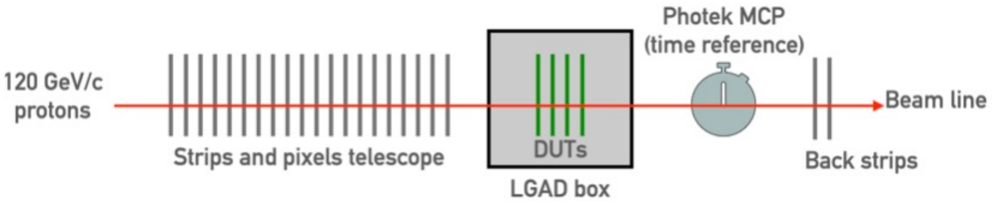
ETL sensors – Beam Test

Fermilab beam test facility:

- **120 GeV/c proton beam**
- An independent **scintillator** provides trigger
- Precise tracking performed with **pixels** and **strips telescope**
- **Cold box**
- **High-speed Photek Micro-Channel Plate** provides reference timestamp with **10 ps resolution**

→ Study of a limited number of sensors with high precision

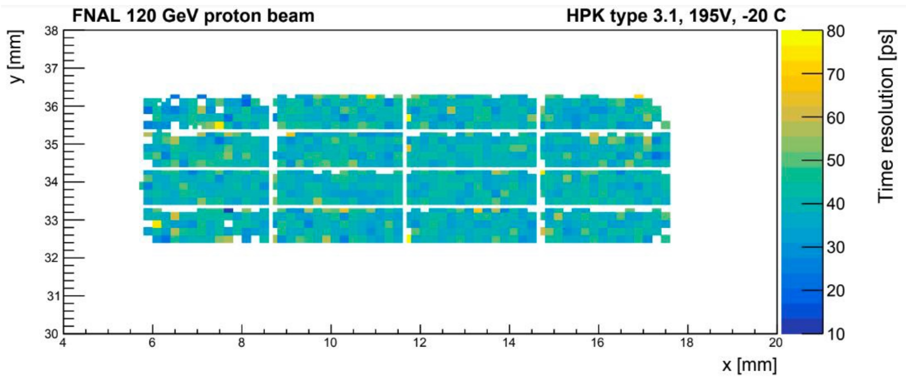




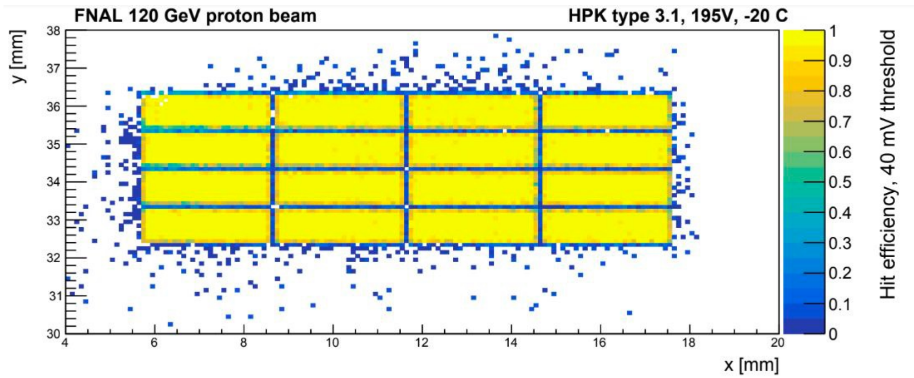
ETL sensors – Beam Test

Two results regarding a 4x4 LGAD array

Time resolution uniformity,
$\boldsymbol{\sigma_t} \sim$ **40 ps** all across the sensor active area



Hit efficiency uniformity $\sim$ **100%**



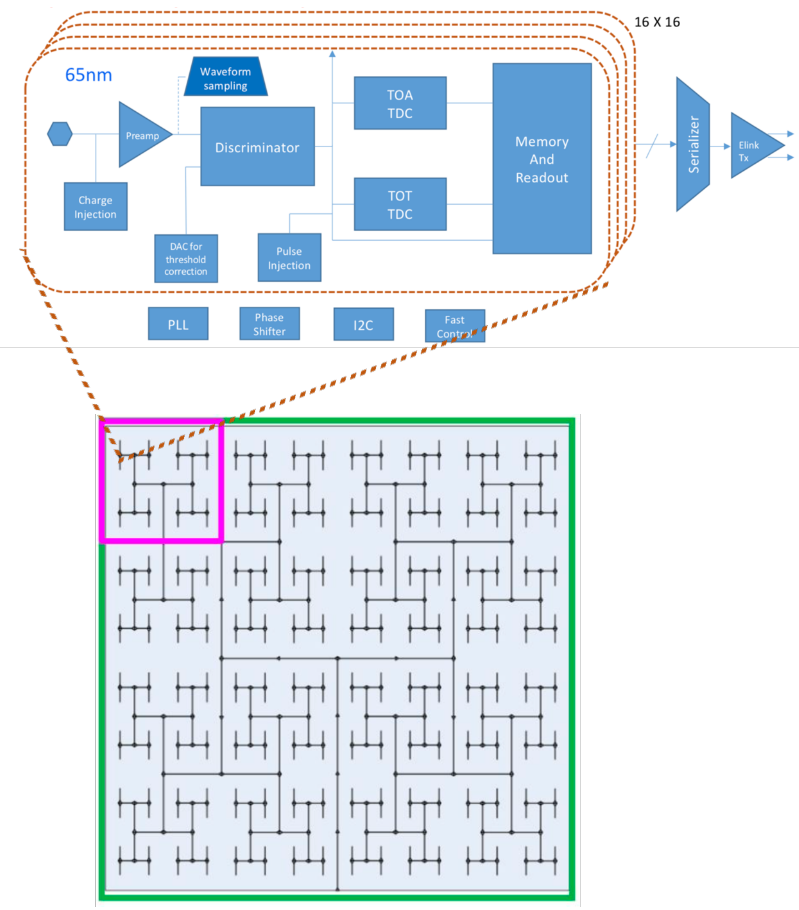
LGAD sensors are highly uniform and efficient, able to achieve the target resolution even on large multi-pad arrays

ETL ASIC – ETROC prototypes

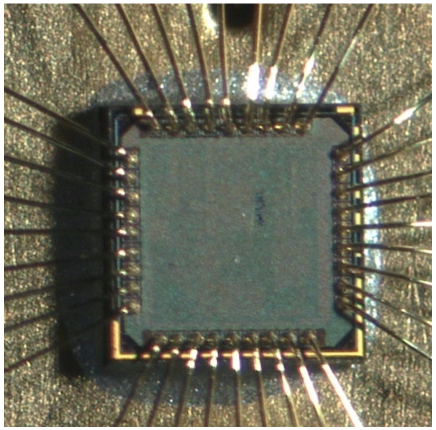
Endcap Timing Layer Read-Out Chip (ETROC) is the ETL read-out ASIC

To achieve **time resolution < 50 ps** per single hit:
- Low noise and fast rise time
- Power budget: 1W/chip, 3mW/channel

Three prototype version before the full-size 16x16 chip:
- **ETROC0** and **ETROC1** produced and tested
  - ✓ **ETROC0**: single analog channel
  - ✓ **ETROC1**: full front-end with TDC and 4x4 clock tree
- **ETROC2** design in progress: full functionality + full size



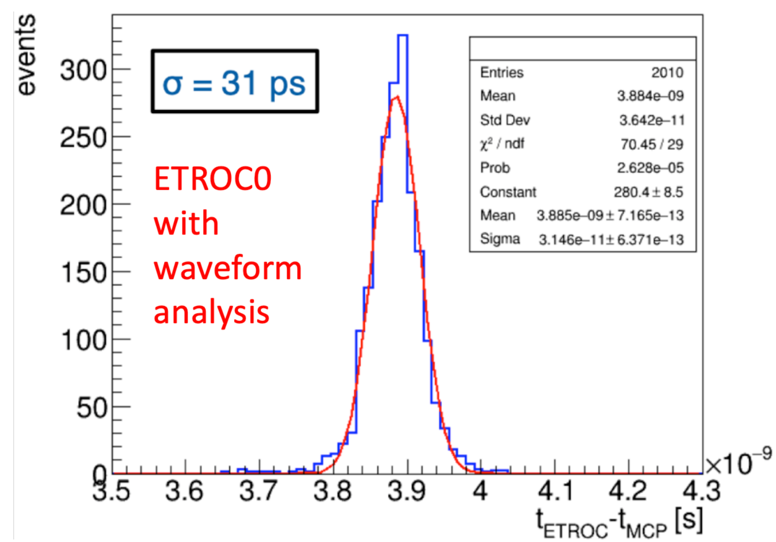
ETROC0



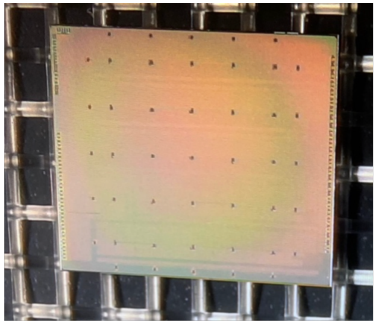
Goal: measure core front-end analog performance

- Jitter measurements agree with post layout simulation
- Power consumption for preamp and discriminator consistent with expectation
- **31 ps timing resolution** achieved at FNAL test beam with ETROC0+LGAD

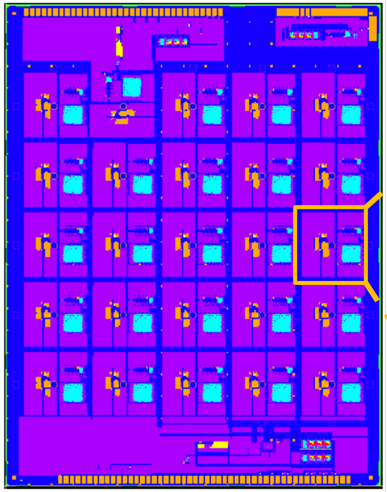
Time resolution measured at FNAL beam test, using a fast MCP as reference

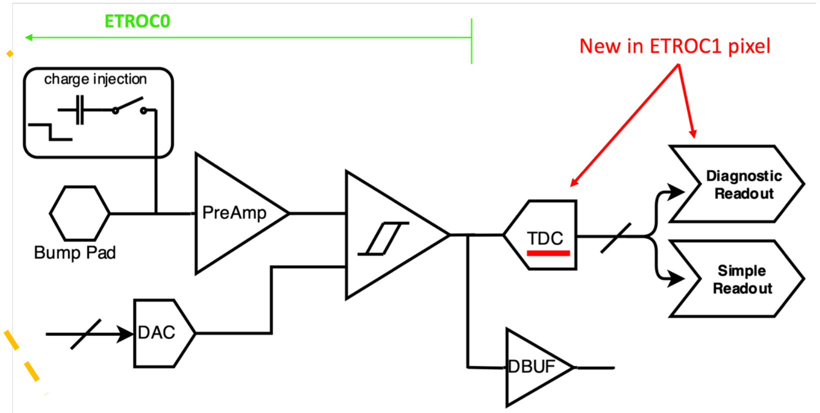


ETROC1



ETROC1 is the 2nd prototype version: 4x4 pixel + TDC
- ETROC0 front-end
- ETROC TDC: new design optimized for **low power**
- Low power achieved using simple delay cells with **self-calibration**
- Measured **TDC performance** as a **6ps contribution** to the resolution



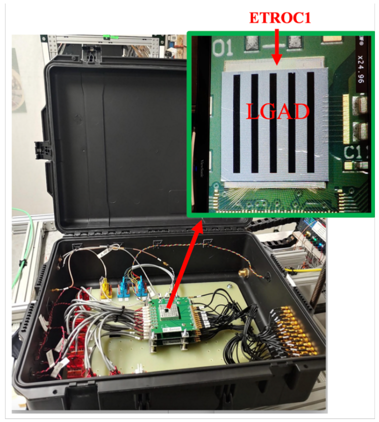


40 MHz noise observed on bump bonded ETROC1 + LGAD

- Coupled through the sensor due to 40MHz clock activity in the circular buffer memory
- The noise can be suppressed by setting the discriminator threshold to ~8 fC
  → under investigation

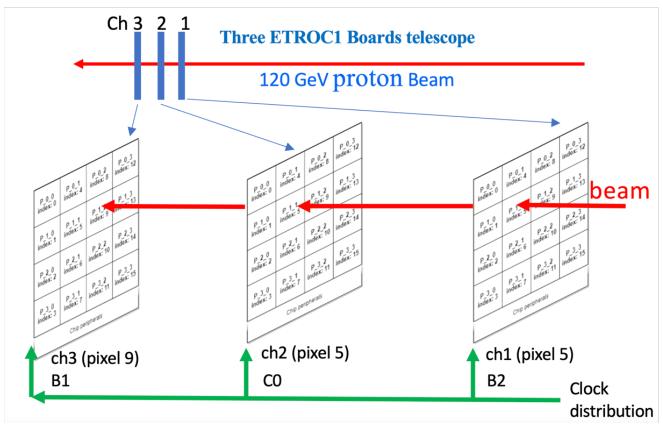
ETROC1

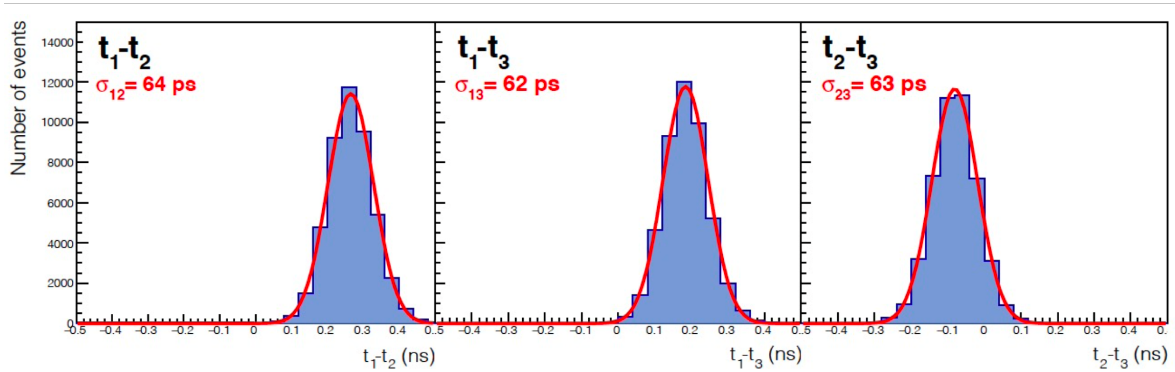
ETROC1 beam telescope at FNAL beam facility



From preliminary analysis of the data from ongoing beam test at FNAL, **the total time resolution per hit** for each LGAD+ETROC1 layer has reached:

$$\sigma_i = \sqrt{(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)/2} \sim \textbf{42-46 ps}$$





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 instrumented with **Low-Gain Avalanche Diodes (LGADs)** and read-out by **ETROC ASIC**

- The latest LGAD productions have been measured both in the laboratory and during beam tests, to ensure they meet all the specifications:
    - **Highly uniform sensors**: leakage current, gain and breakdown voltage
    - **Timing resolution < 40 ps** up to **2.5×10^{15} n_{eq}/cm^2**
    - No-gain region width **< 120µm** in wider layout
    - Beam test results showed **100% efficiency** and **uniform time resolution** across the whole active area of large LGAD arrays

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

Backup

Towards HL-LHC

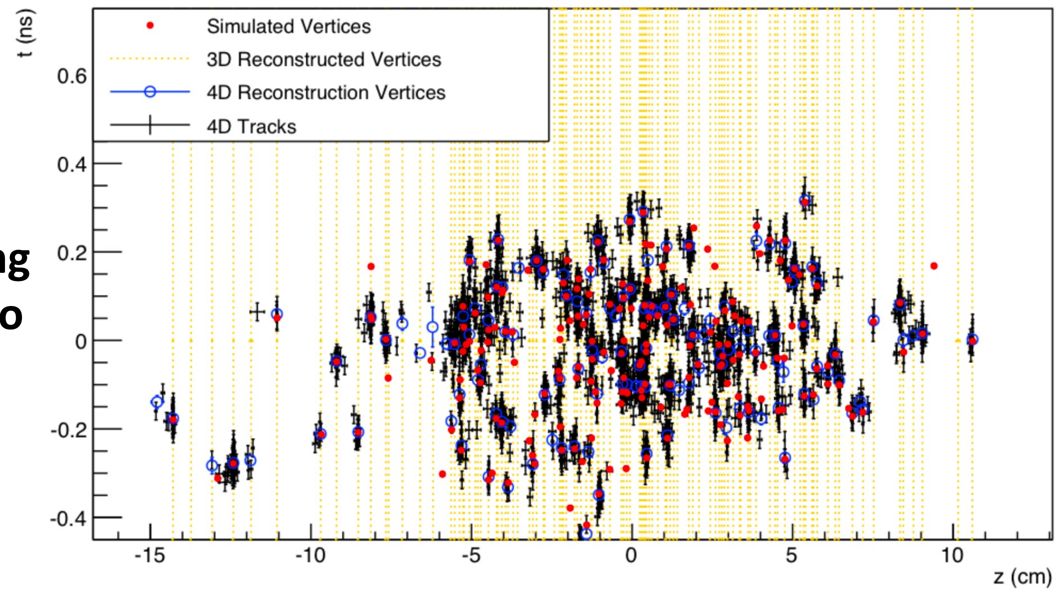
At High Luminosity LHC instantaneous luminosity will increase by a factor ~ 5

- 140-200 proton-proton collisions per bunch crossing
- Difficult in object reconstruction and particle identification due to spatial overlap of tracks

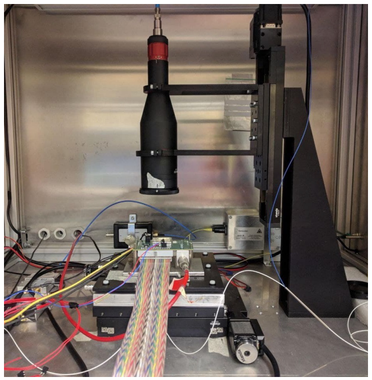
The add of timing information will help to separate overlapping events in space

- Creation of a timing detector providing 4D tracking
- A timing detector with 30-40ps of resolution will reduce the effect of high pile-up

The Minimum Ionizing Particle Timing detector (MTD) has been designed to accomplish this task



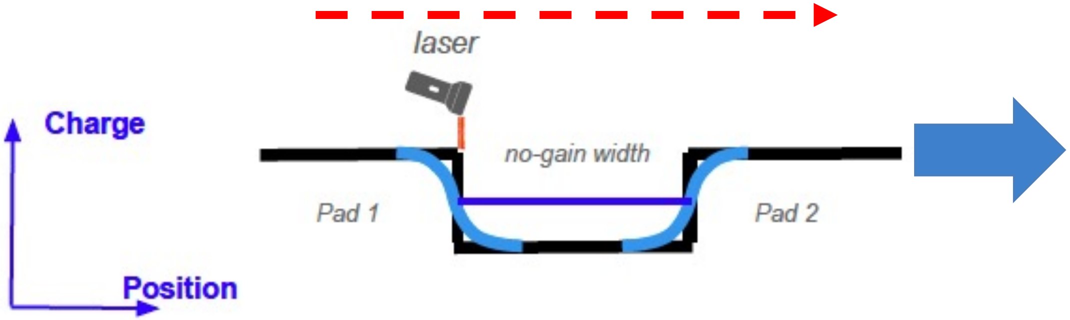
Laboratory measurements: no gain distance

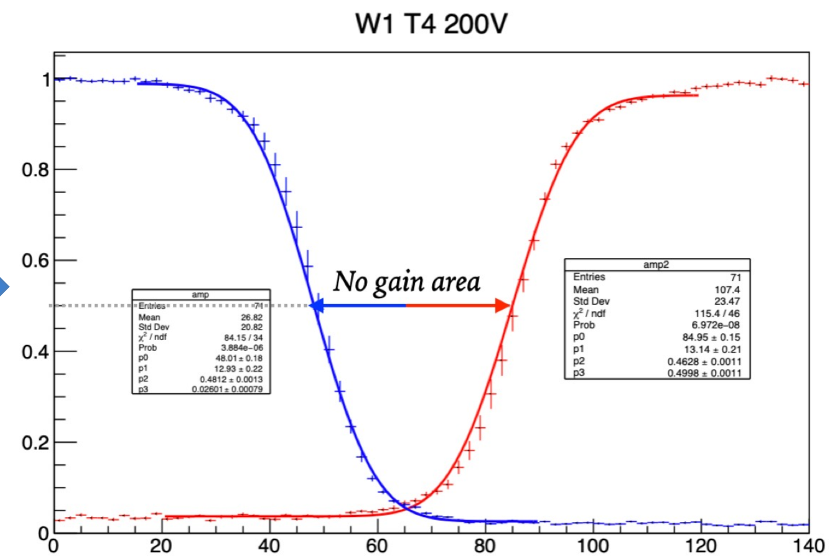


No-gain distance between adjacent pads is performed with Particulars Transient Current Technique setup:

- 1060 nm picosecond laser with ~ 10 µm spot
- Charge vs laser position fitted with S-curve: convolution of gain layer step function and laser gaussian beam profile
- No-gain distance is defined as the distance between the points at 50% of the two S-curves maximum

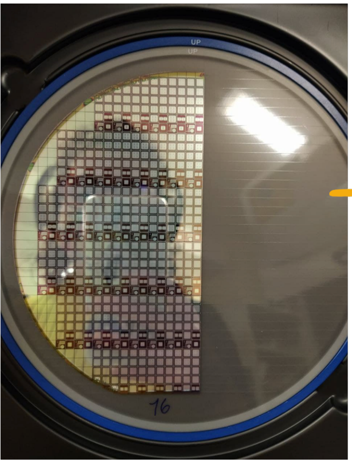
1D scan along the optical window

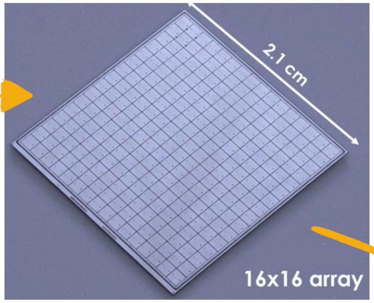




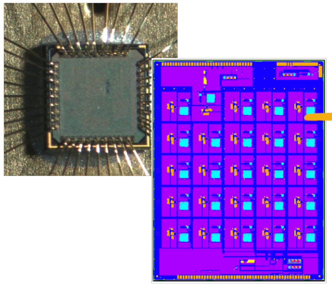
ETL design

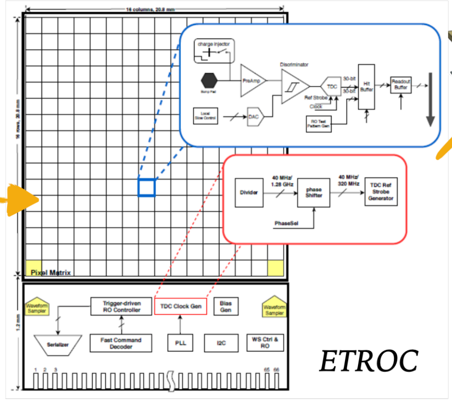
Final sensor:
16x16 array
1.3x1.3 mm^2 pixels



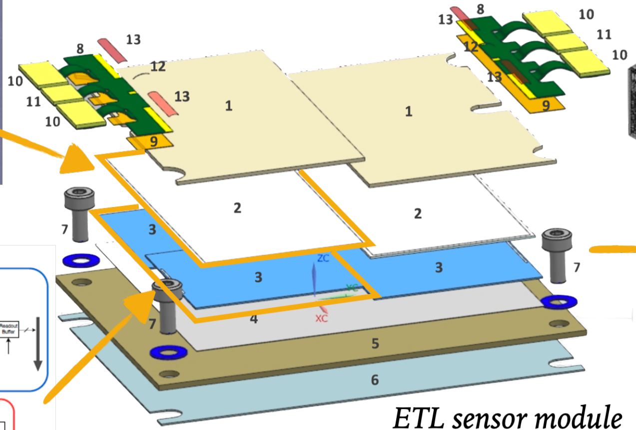


R&D productions

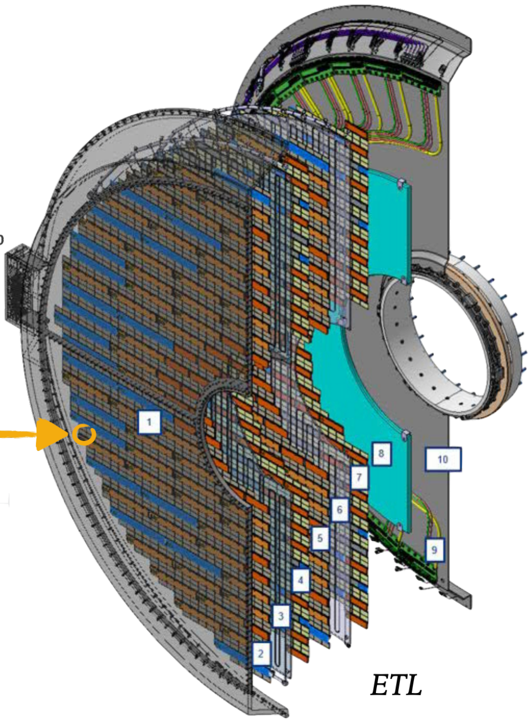




ETROC



ETL sensor module



ETL