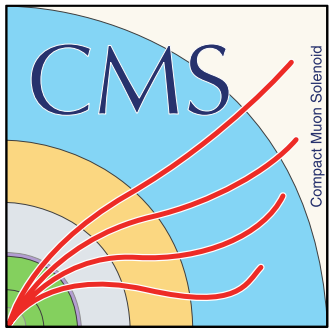


The CMS Endcap Timing Layer upgrade: Recent progress and test beam results from LGAD sensors coupled with the ETROC2 electronics

LUCA MENZIO ON BEHALF OF THE CMS ETL GROUP

20TH FEBRUARY 2025 – VIENNA CONFERENCE OF INSTRUMENTATION

Outline

- Overview – Introduction
  - High Luminosity LHC
  - The MIP Timing Detector
- The Endcap Timing Layer of CMS
  - LGADs Market Survey
  - ETROC2
    - Latest Test Beam Results
- Summary

The High Luminosity LHC

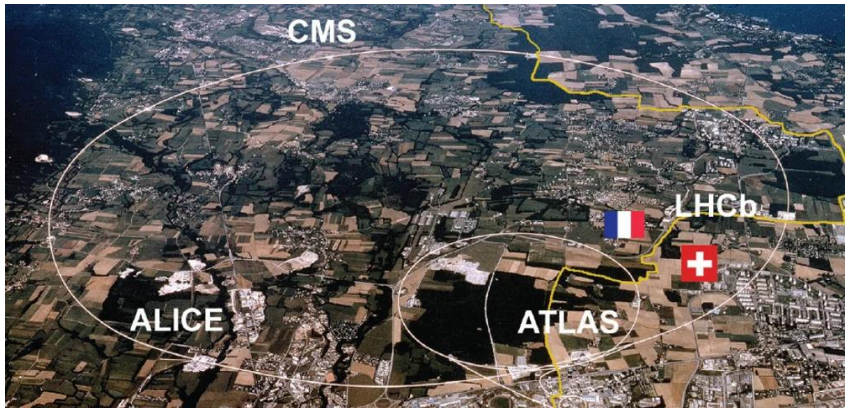
The LHC is set to undergo a significant upgrade, **High Luminosity (HL)-LHC**, enhancing both the accelerator and its experiments.

Key improvements include:

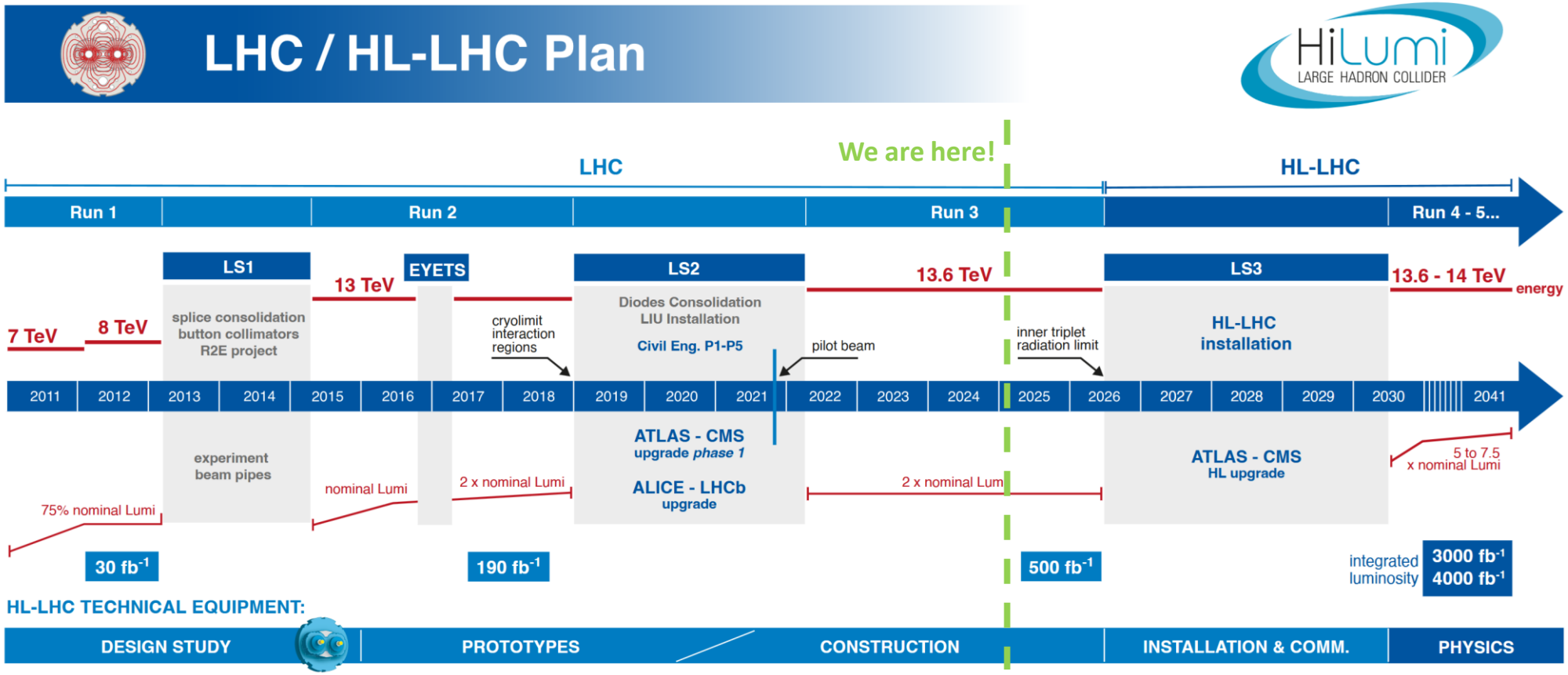
- New superconducting magnets
- Improved beam collimation
- New high-power superconducting links with negligible energy dissipation
- and several other new features

These upgrades will **boost the instantaneous luminosity** by a factor of **4 to 7.5** from its **current nominal value** (~10^{34} $cm^{-1}s^{-1}$).

All major High Energy Physics experiments at LHC are **preparing** to cope with this transformation.



Towards the HL-LHC upgrade



Timeline source: https://hilumilhc.web.cern.ch/content/hl-lhc-project

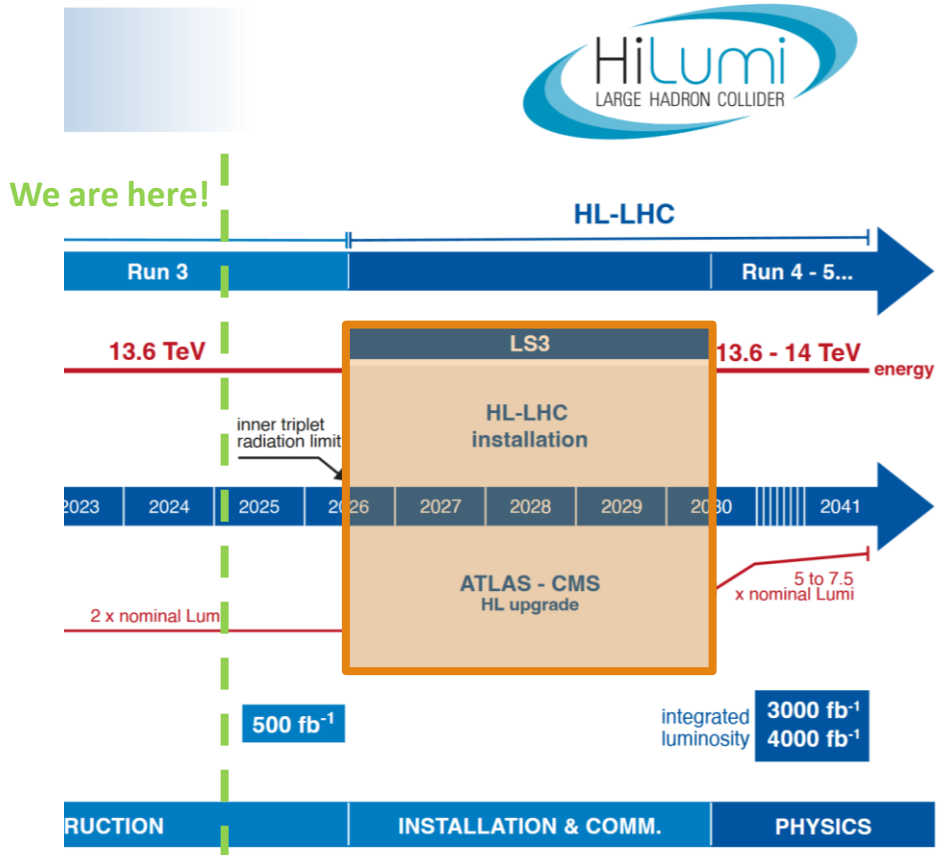
Towards the HL-LHC upgrade

The **CMS experiment** is undergoing a major upgrade.

To cope with the conditions present in the HL phase:

- More events per bunch crossing
- More radiation damage

Specifically, more events per bunch crossing (up to 200 events instead of the present 30-60) lead to a degradation of physics performance.



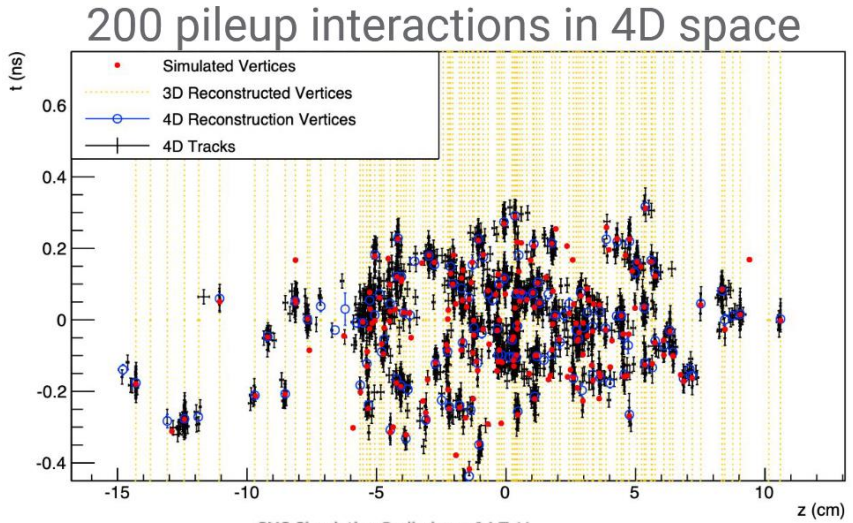
Timeline source: https://hilumilhc.web.cern.ch/content/hl-lhc-project

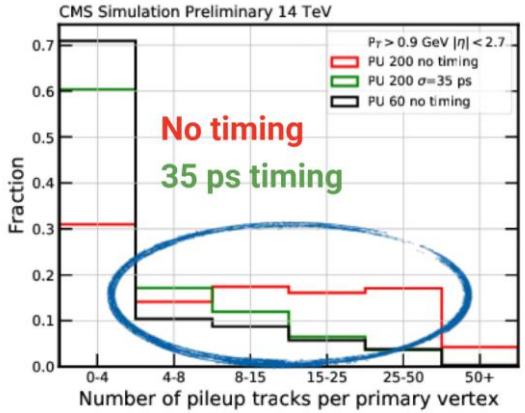
Towards the HL-LHC upgrade

Given the high pile-up, it becomes likely that the **vertex** position of two events **overlaps**, leading to an incorrect event reconstruction.

The proposed solution consists in **tagging** the **track time**, and distinguish the events based on their temporal information and not on their spatial information only.

The solution consists of a novel detector layer dedicated to distinguishing tracks in time: the **MIP Timing Detector (MTD)**

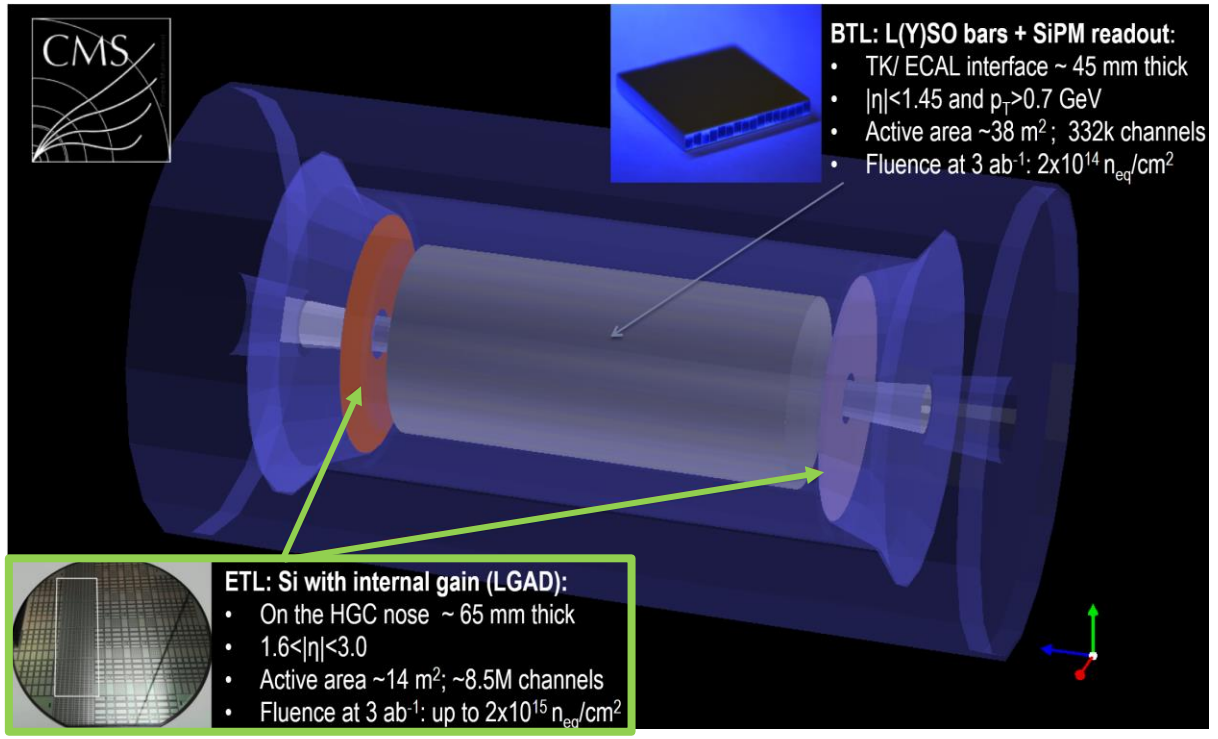




The MIP Timing Detector (MTD)

In MTD, the MIP timing layer is positioned in between the tracker and the calorimeter.

- **Barrel Timing Layer (BTL)**
  - $|\eta| < 1.45$
  - LYSO crystals read with SiPMs
  - Lower expected integrated fluence: 2×10^{14} n_{eq}/cm^2
- **Endcap Timing Layer (ETL)**
  - $1.6 < |\eta| < 3.0$
  - **Low Gain Avalanche Diodes (LGADs)**
  - Highest expected radiation: 2.5×10^{15} n_{eq}/cm^2
  - Fraction of sensors exposed to a fluence < 1×10^{15} n_{eq}/cm^2: 90%



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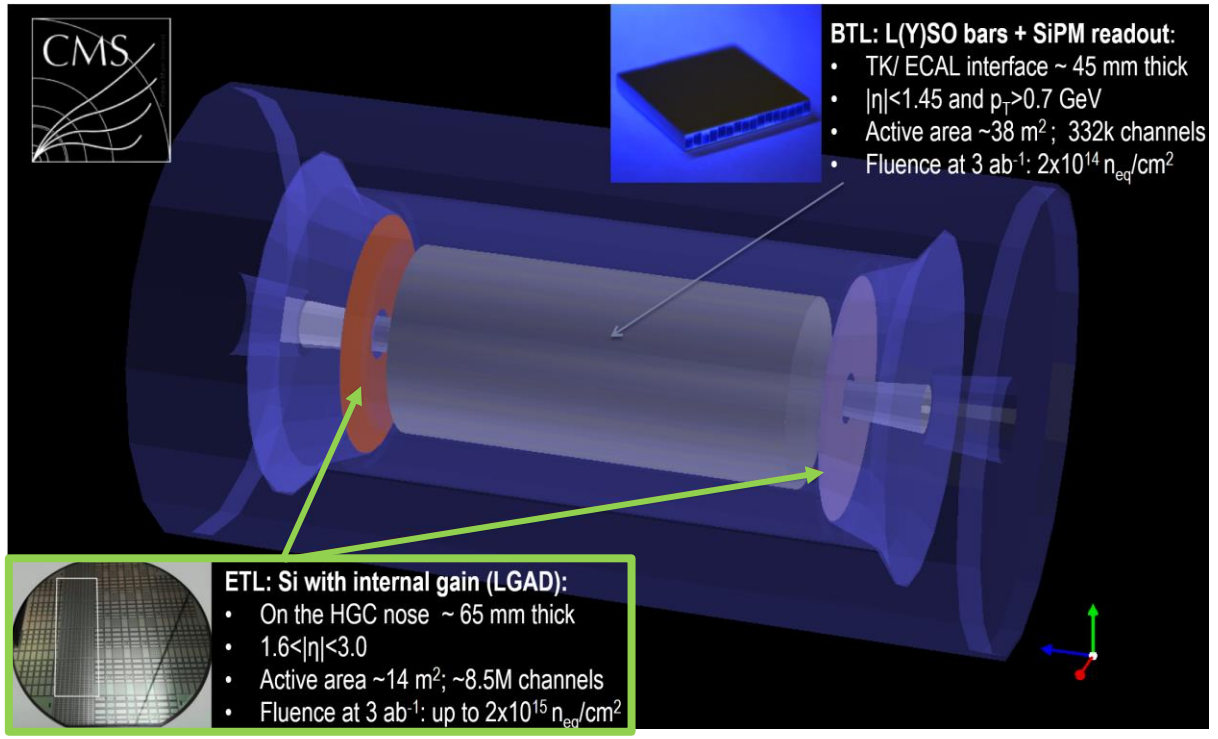
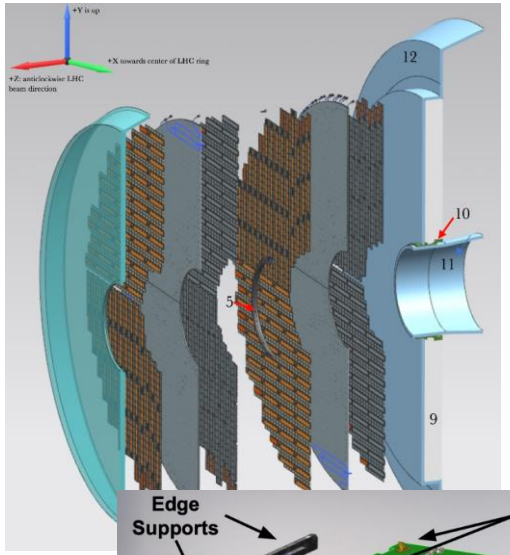
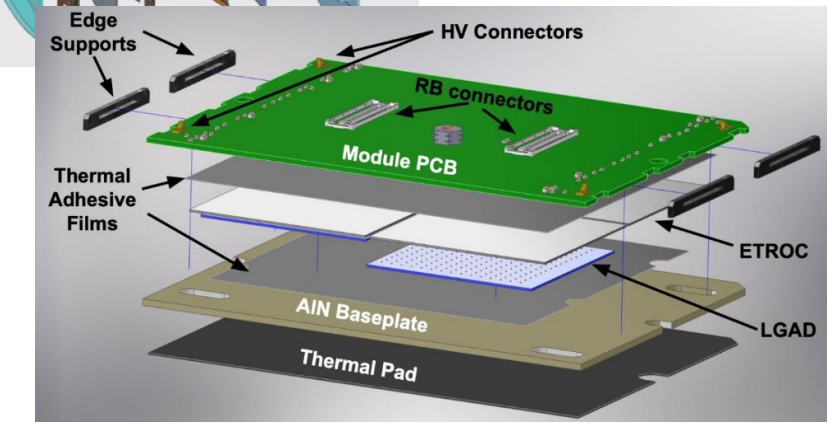


In this talk we will see some of the ETL latest results

The Endcap Timing Layer





The Endcap Timing Layer will cover ~14 m^2 with silicon LGAD devices coupled with the corresponding read-out ASIC, ETROC.

Each Endcap is instrumented with two disks, reaching a combined track resolution better than 50 ps time resolution until the detector's end of life

The elemental unit of ETL is the "ETL module", a structure housing 4 **LGAD+ETROC pairs** (called hybrids), the mechanical connection to the cooling system, and a PCB interfacing to the read-out board.

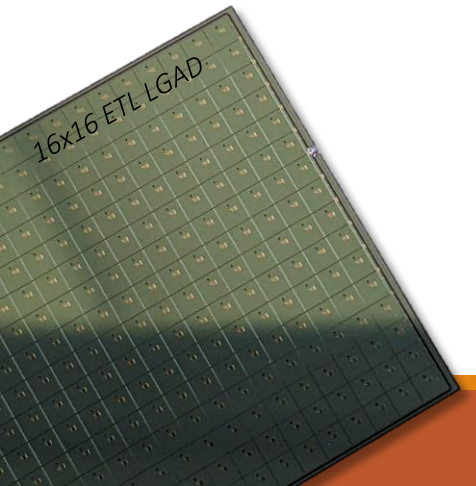
Each hybrid is composed of a 16x16 LGAD array, with 1.3 mm pixel pitch, bump-bonded to the read-out chip, ETROC

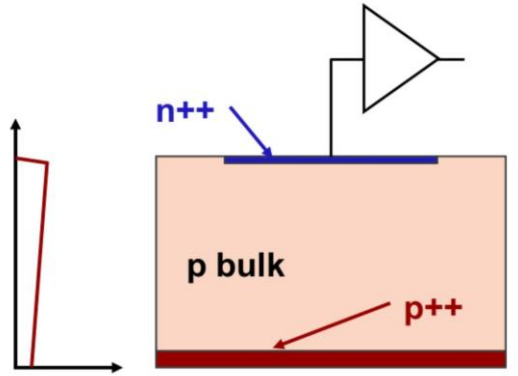
The Endcap Timing Layer Sensors

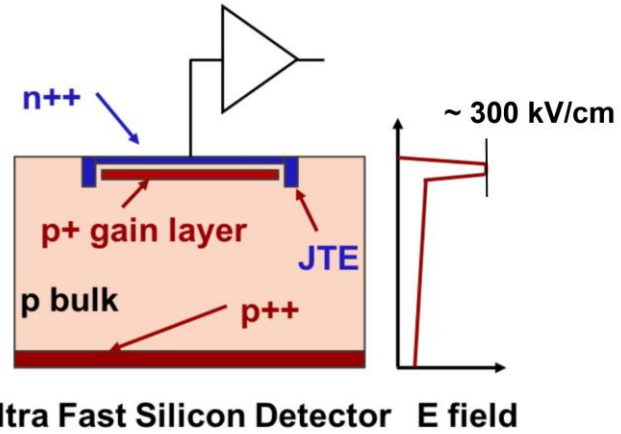
The ETL Sensors are **LGADs** specifically designed for timing in HEP – Ultra Fast Silicon Detectors.

In the past years, this technology was developed to withstand the requirements of ETL:

- **Gain ~10-30** – optimized for S/N
- **50 µm active thickness**:
  - Low Landau fluctuations
  - Fast signal rise time







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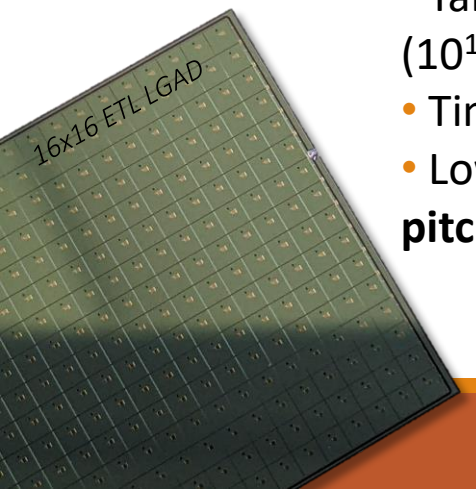
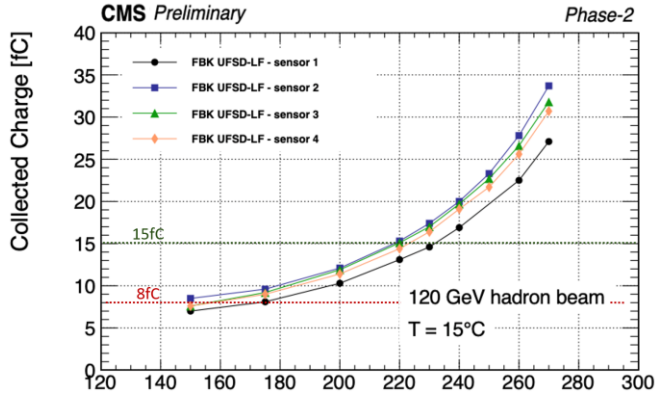
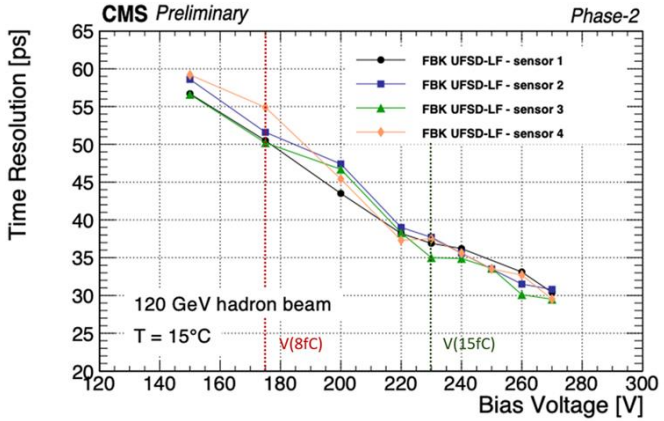
In the past years, this technology was developed to withstand the requirements of ETL:

- **Gain ~10-30** – optimized for S/N
- **50 µm active thickness**:
  - Low Landau fluctuations
  - Fast signal rise time
- Target: **signal > 8 fC** at the End of Operations (10^{15} n_{eq}/cm^2 in the innermost region)
- Time resolution < **50 ps** at End of Operations
- Low capacitance: **16x16 array** of LGADs with **1.3 mm-pitch**







Results obtained with single-pad sensors and discrete electronics @ SPS

The ETL Sensors Market Survey

The sensors **vendors** are being **evaluated** to match the ETL requirements following the **CMS guidelines**.

This **Market Survey** is based on a series of test performed both in the lab and in test beams to assess the LGADs performance and the production uniformity.

Unirradiated Sensors

1	Full depletion voltages (< 50V)	5	$I_{leakage}$ in small/large sensors at V(8fC) (<1μA/10μA)
2	Gain Layer depletion voltages spread ($\sigma_{distribution}$ < 2%)	6	Time Resolution at V(8fC) (<70ps)
3	Breakdown voltages (130-250V)	7	Time Resolution at V(15fC) (<50ps)
4	V(8fC)	8	Micro discharge noise at V(20fC) (absent)

Irradiated sensors (up to 10^{15} n_{eq}/cm^2)

1	V(8fC)/thickness (<12V/μm)
2	Breakdown voltages (V(8fC) + 30V)
3	Time Resolution at V(8fC) (<70ps)
4	Micro discharge noise at V(8fC) (absent)

To be measured at -25 °C

Vendors evaluated for the MS

1. **Teledyne**
2. **Micron**
3. **FBK**
4. **HPK**
5. **IHEP**

Passed the Market Survey

Outline

- Overview – Introduction
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  - The MIP Timing Detector
- The Endcap Timing Layer of CMS
  - LGADs Market Survey
  - **ETROC2**
    - Latest Test Beam Results
- Summary

The Endcap Timing Layer ASIC

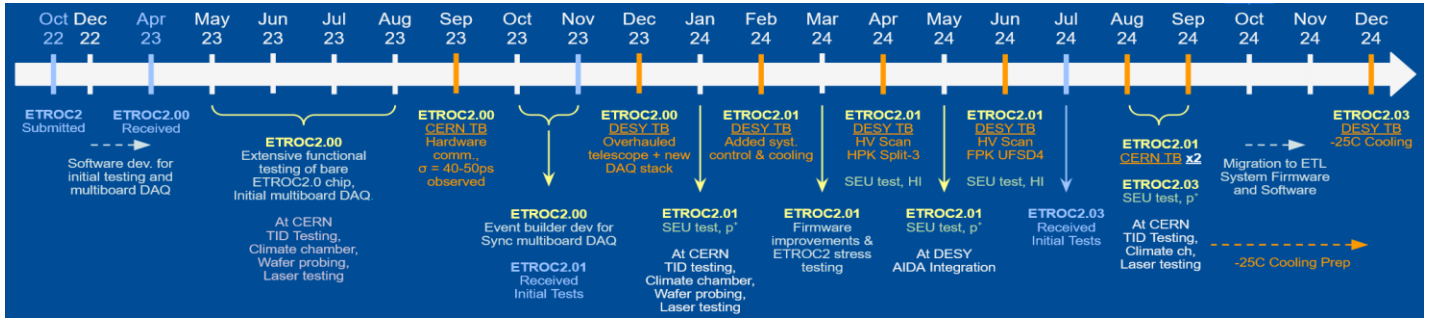
ETROC is the readout ASIC developed to interface with the ETL LGADs

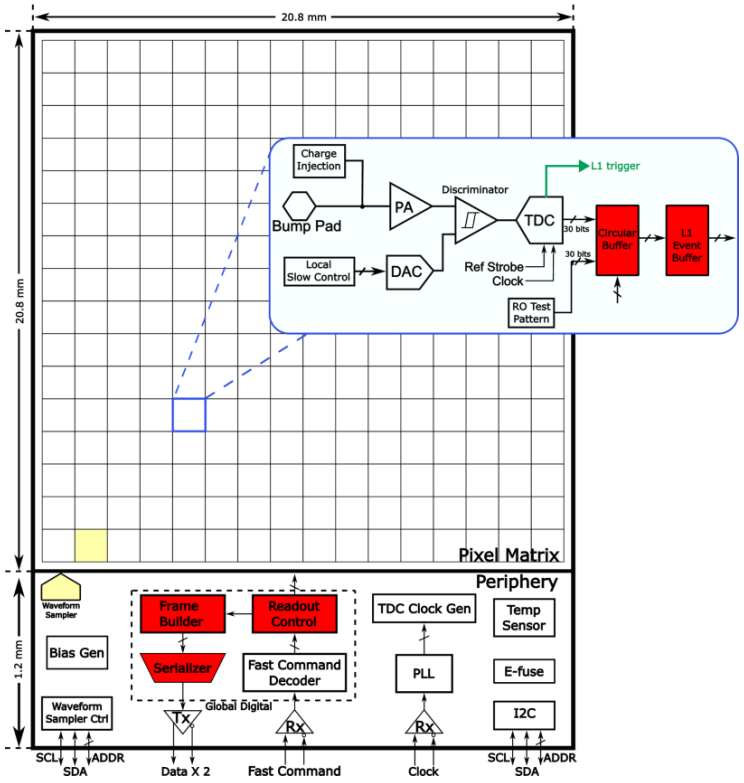
- A single channel consists of a preamplifier, discriminator and a Time to Digital Converter (TDC), plus a buffer for data storage
- ETROC2 has 16x16 channels and utilities

This talk reports some of the latest results obtained with **ETROC2** bump bonded to **16x16 LGADs**

The following results are obtained **with a single hybrid** (not on the full ETL module)

A lot of work...

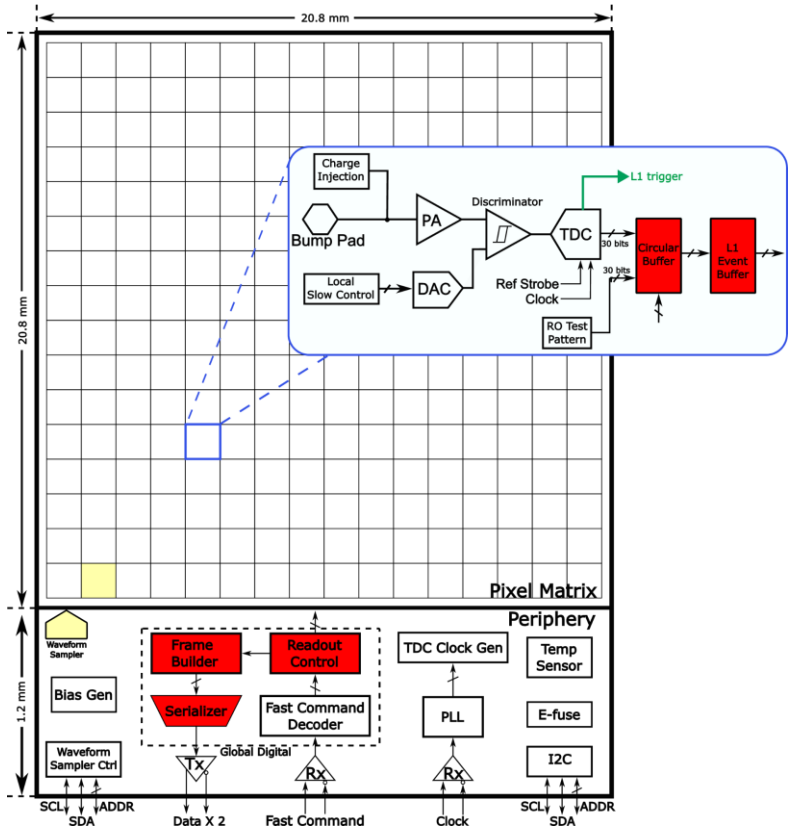




ETROC2 Overview

The **Endcap Timing Readout Chip (ETROC)** is designed to achieve 40-50 ps time resolution per hit.

- **Low power**: 1 W/chip @1.2 V, < 4 mW/ch
- **SEE protection** for control
- Measuring LGAD signal time of arrival
  - Front-end: **PA** + **Discriminator** + low power **TDC**
  - L1 latency circular buffer
  - L1A-driven readout with zero suppression
- 40 MHz reference clock
- 21 mm x 23 mm, **TSMC 65 nm technology**, 1p9m
- **16x16 array** with **1.3 mm-pitch** to match the LGAD sensor



ETROC Test Beams

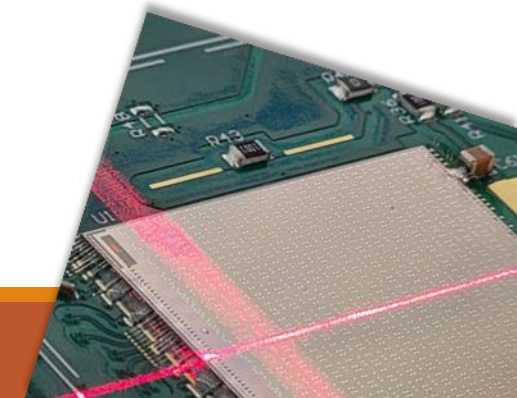
ETROC coupled with LGADs has been extensively studied in the last years. In 2024 many test beams were performed

- Two main facilities: **SPS** H6 (120 GeV p/π) and **DESY** (4 GeV e^+/e^-)

A telescope of 3 or more layers has been used, to be able to extract time resolution without an external time reference.

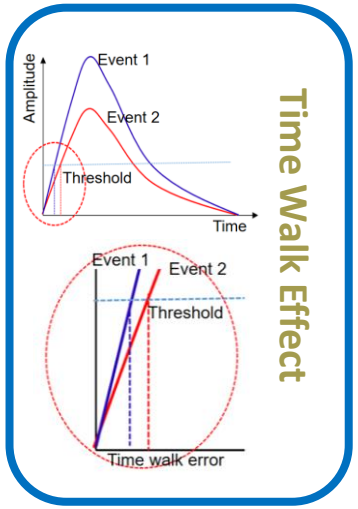
$$\sigma_i = \frac{1}{\sqrt{2}}\sqrt{\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2}$$

Recently, temperature control was added, as well as integration with the AIDA telescopes present onsite (more info here)



Latest Results – ETROC + Sensors

The Time Of Arrival (TOA) recorded by ETROC has to be adjusted with a **time walk correction** using the Time Over Threshold (TOT)



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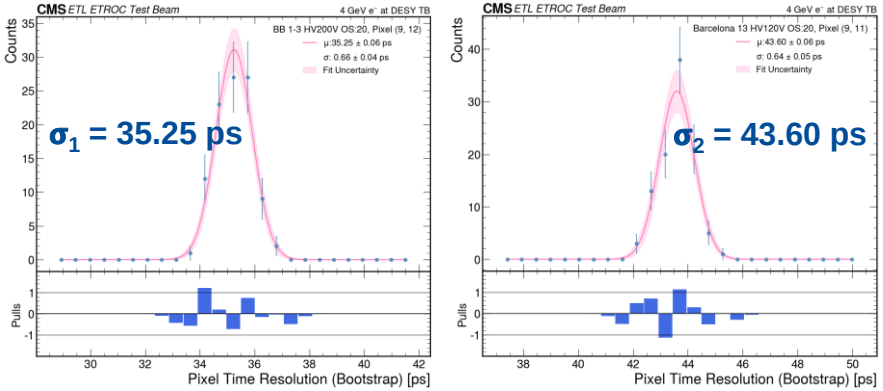
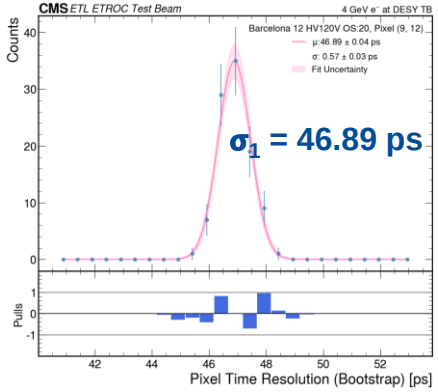
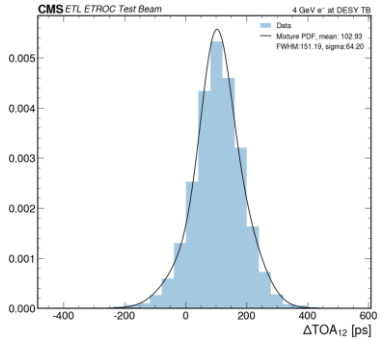
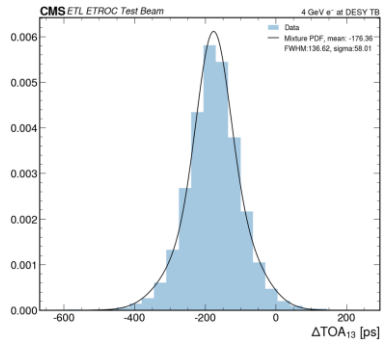
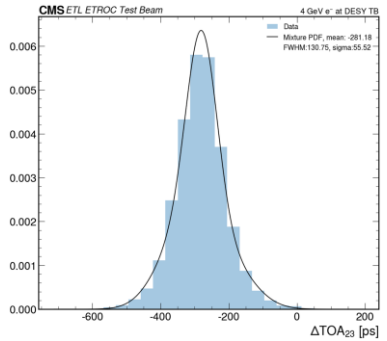




From delta TOA to time resolution







An estimate of the resolution is extracted for **each pixel**

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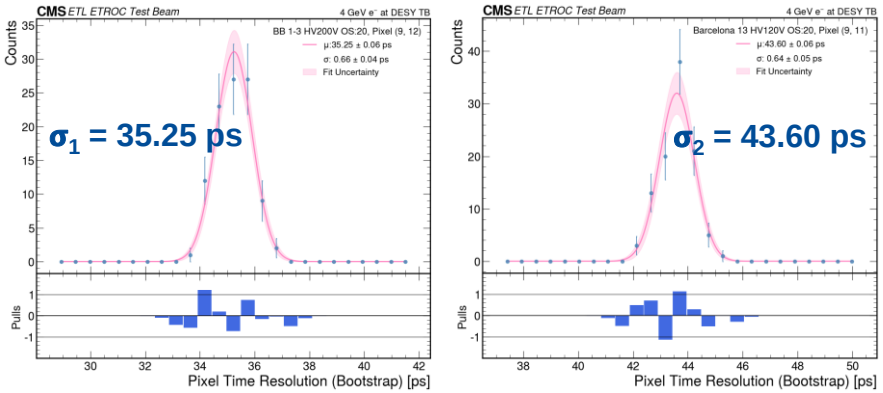

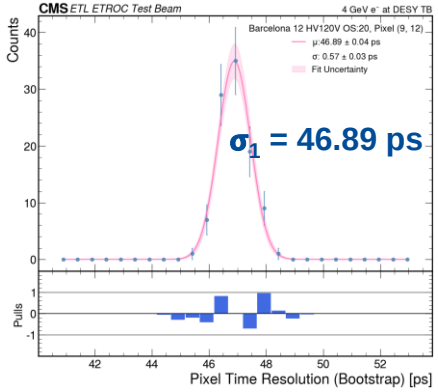

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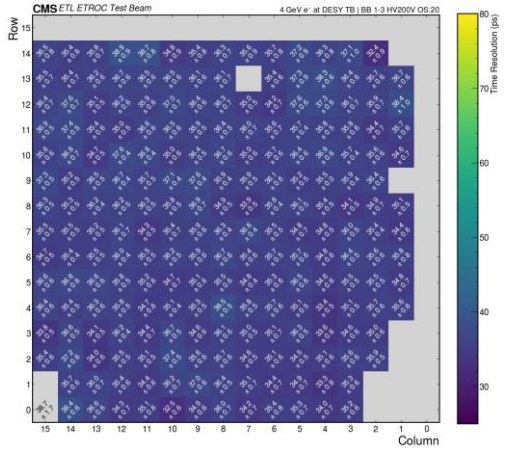
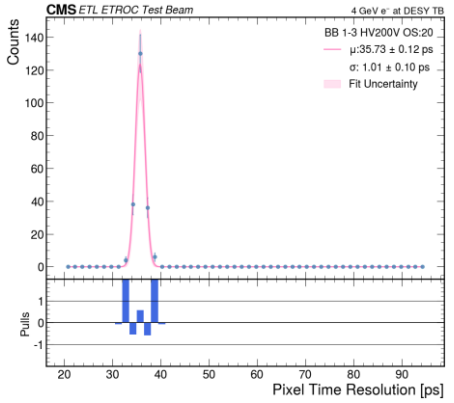
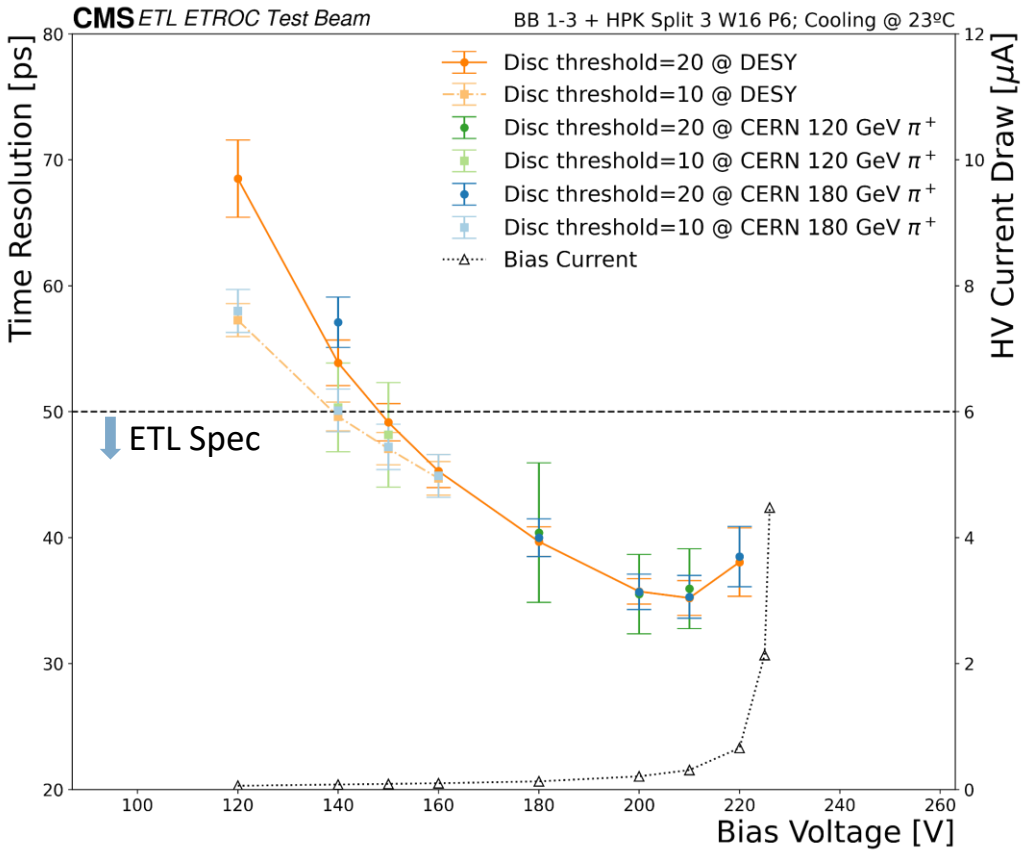




Time resolution is bootstrapped over the whole **16x16 array**

Latest Results – ETROC + Sensors



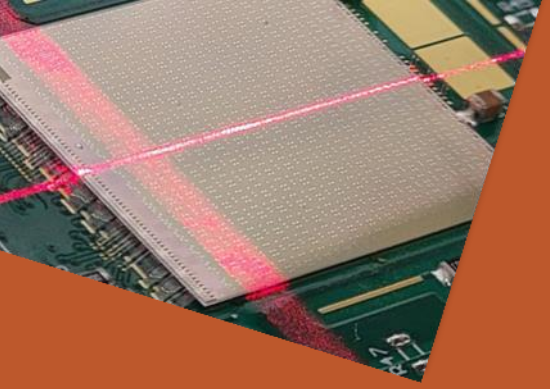
Data from ETROC2 with HPK LGADs

About **70 V range within spec**!

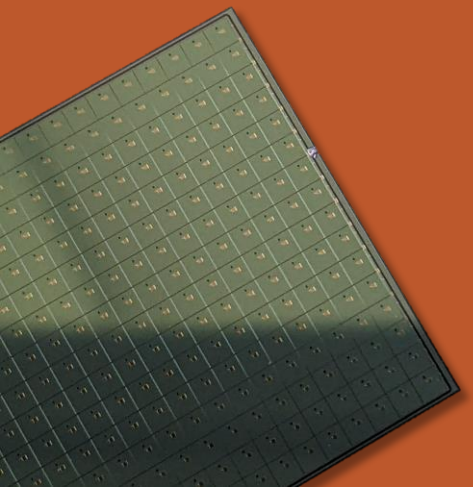
ETROC2 proved to be **able to reproduce** on large arrays (16x16) **the results obtained with discrete electronics** on single pads

Down to **~35 ps**

ETROC2 is becoming the **final version of ETROC** (skipping ETROC3), after some minor modifications to the metal layers



Summary



With the **High Luminosity** program at the **LHC**, significant upgrades to parts of the experiments will be required.

The CMS experiment is preparing to introduce a new **MIP Timing Detector (MTD)** to counteract the effects of increased luminosity. This new subdetector will consist of two portions: the **Endcap Timing Layer (ETL)** and the **Barrel Timing Layer (BTL)**.

1. The **LGADs** of the ETL deliver the desired performance and the vendors are being selected, following the CMS guidelines
2. ETL readout ASIC **ETROC** was validated in multiple tests, among which an extensive beam campaign
   - The low noise design of the ASIC proved to be **able to reach** a timing resolution of **~35ps with LGAD+ETROC** on beam
   - Seen these performances, **ETROC2** is becoming the **final version** of the ASIC, skipping ETROC3

The ETL System Test group is working towards achieving these results on full-sized module

Stay Tuned!

Final Remarks

1. Some of the measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

2. The research leading to these results has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101057511.

3. This work was supported by Fermi Research Alliance, LLC, with the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Contract DE-AC02-07CH11359.


The End

Backup slides

The CERN SPS sensors beam test

This acquisition campaign involved unirradiated single-pad test structures from W1.

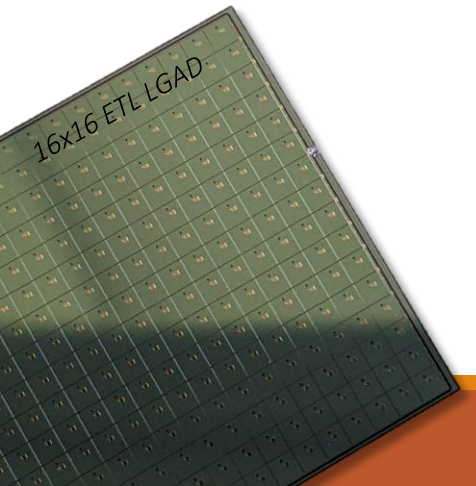
→ The beam is a 120 GeV/c hadron beam (p/π) at H6, SPS CERN (PPE156)

→ 9 Devices were tested simultaneously: **4x single pads**, 2x 2x1 structures (interpad measurement) and 3x 16x16 arrays (stability over time on beam) in a cold box held at 15 °C, with constant humidity.

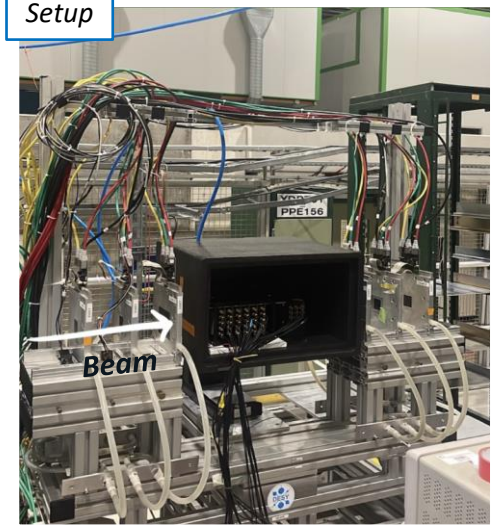
→ State-of-the-art discrete electronics (Santa Cruz Board)

→ Read using a Teledyne-Lecroy 8ch Oscilloscope

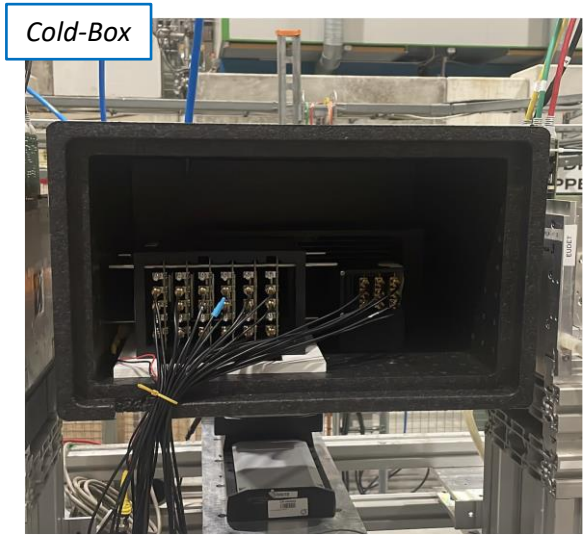
- up to 20 GS/s, 2 GHz, 12 bit



Setup



Cold-Box



The Sensors Market Survey Table

#	Parameter (from MS table)	Cuts	Temperature
-	Nominal thickness	(Value: 55 um)	
1	Bulk depletion voltage	< 50 V	room T
2	Breakdown voltage due to gain with all pads and the guard ring connected to ground	130-280 V	-25°C
-	Value of V(8 fC) and V(15fC)		room T
3	Maximum leakage currents for the large-size sensor without (with) carbon at V(8 fC) - with GR	1 µA (10 µA)	room T
4	Number of pads in small-size sensors, with leakage current higher than 5 times the mode of the pad current	< 10 %	-25°C or room T
5	Time jitter at V(8 fC) measured on multiple pads (measured in small-size sensors with state-of-the-art electronics)	< 50 ps	-25°C or room T
6A	Time resolution at V(8 fC), measured in small-size sensors with state-of-the-art electronics	< 70 ps	-25°C
6B	Time resolution at V(15 fC), measured in small-size sensors with state-of-the-art electronics	< 50 ps	-25°C
7	Pad isolation	> 0.1 GOhm	-25°C or room T
8	Spread of the gain layer depletion voltage within a large-size sensor (defined as the StD of the distribution of the pads gain layer depletion voltage)	< 2%	room T
9	No-gain distance between pads (V > V_BD - 70)	< 140 µm	-25°C or room T