Upgrade of the CMS Electromagnetic Calorimeter for High-Luminosity LHC

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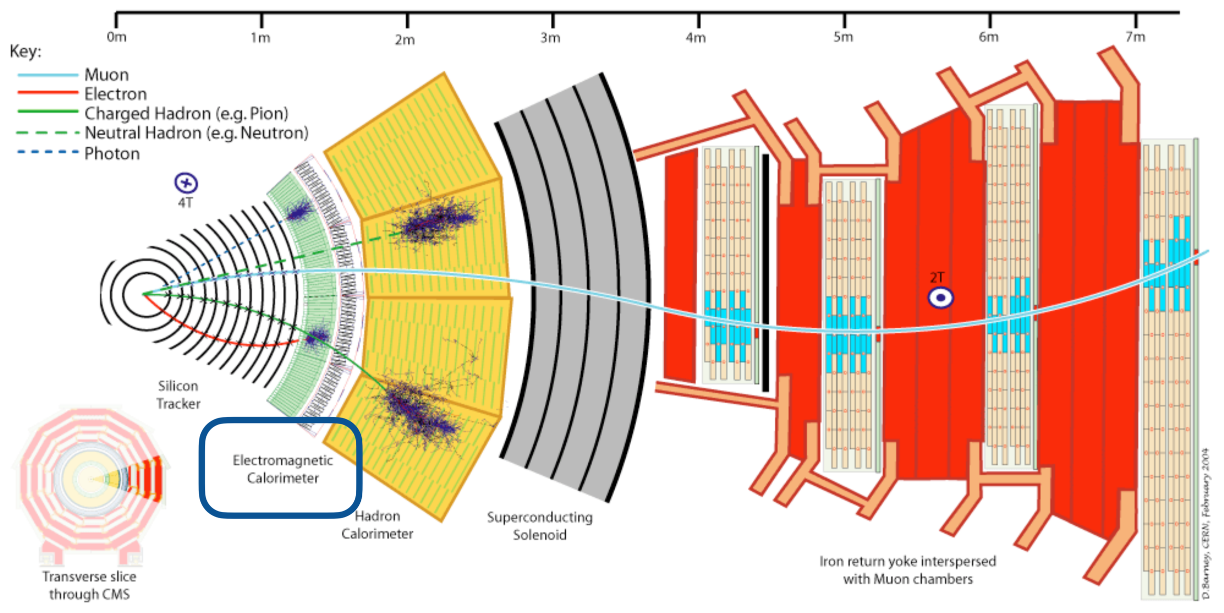
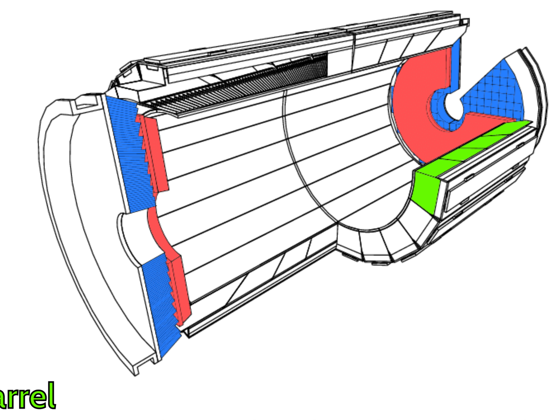
INTRODUCTION

THE CMS DETECTOR

The CMS (*Compact Muon Solenoid*) experiment, operating at the Large Hadron Collider (CERN, Switzerland), is a **multi-purpose detector**, consisting of sub-detectors nested around the interaction point of the LHC collisions. Their combined information is used to infer the **nature and properties of particles.**



THE CMS ELECTROMAGNETIC CALORIMETER (ECAL)

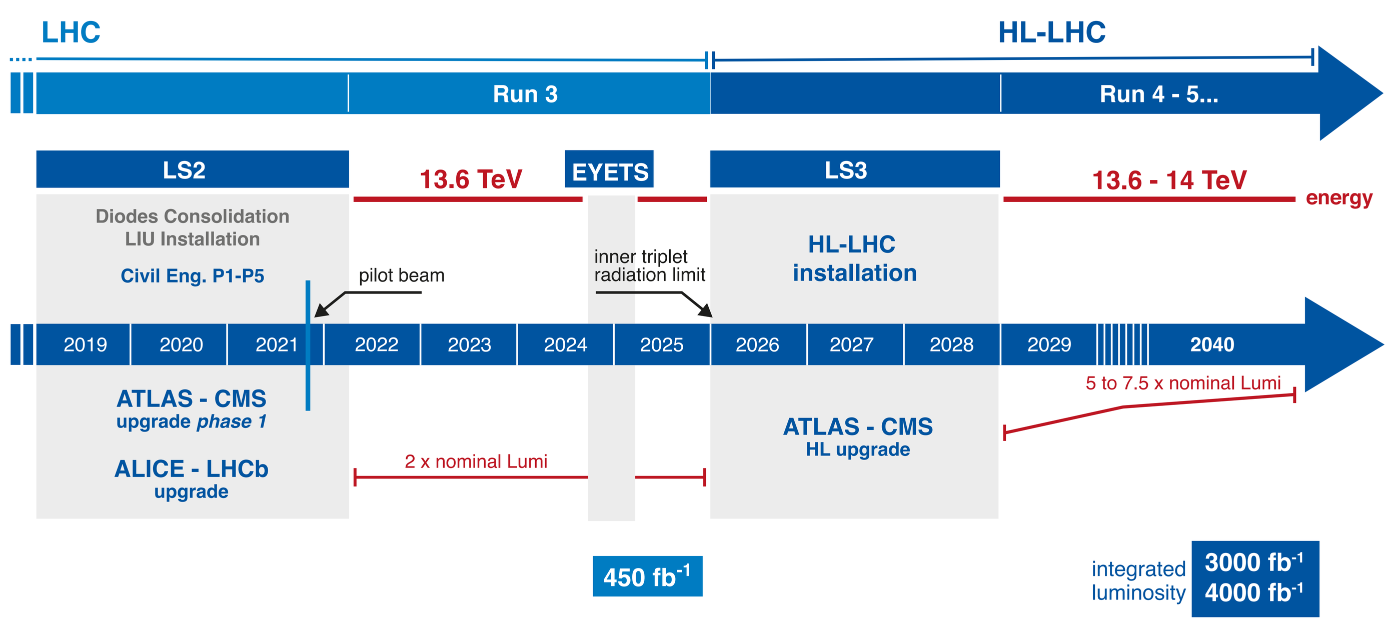


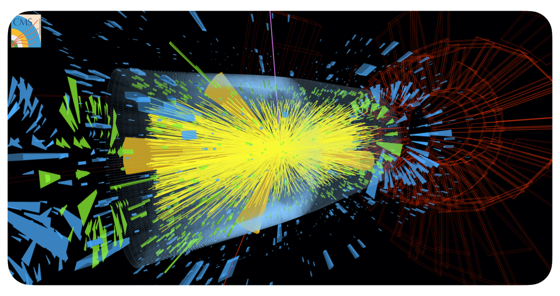
Barrel
61200 crystals, Avalanche Photo-Diodes (APD)
Endcaps
14648 crystals, Vacuum-Photo-Triodes (VPT)

The ECAL [1] is a **homogeneous, hermetic, $PbWO_4$-based detector.** Its design was led by the $H \rightarrow \gamma\gamma$ search needs, and its **excellent performance** was crucial for the Higgs boson discovery (2012). Its key parameters are:

- small Molière radius: r_M = 2.19 cm
- high density: ρ = 8.28 g/cm^3
- short radiation length X_0 = 0.89cm
- fast light emission: ~80% of light within 25 ns

THE HIGH-LUMINOSITY LHC (HL-LHC)

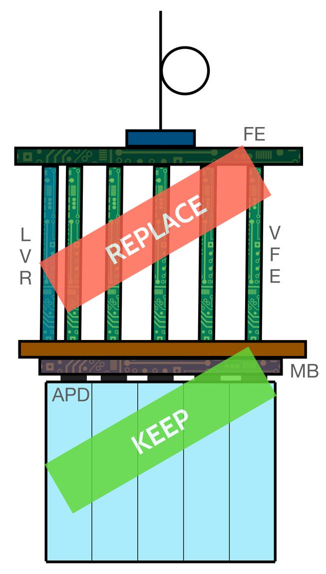




Pileup of about 140-200 will be typical at HL-LHC (up to 80 in Run3).

The ongoing Run3 will conclude the first phase of the LHC program. In the HL-LHC phase, the accelerator complex will deliver an instantaneous luminosity up to 7.5x larger than the design value (10^{34} cm^{-2}s^{-1}). The ECAL endcaps will be replaced, as the radiation damage will be unsustainable beyond 500 fb^{-1}. **The ECAL barrel will be upgraded** [2] to cope with the harsher collision environment, maintain the current energy resolution and **provide precise timing** to contribute to the 4D vertex reconstruction.

THE ECAL BARREL UPGRADE



Off-detector electronics replacement
To cope with the higher output bandwidth from Front End (FE) to upgraded CMS Level-1 (L1) trigger

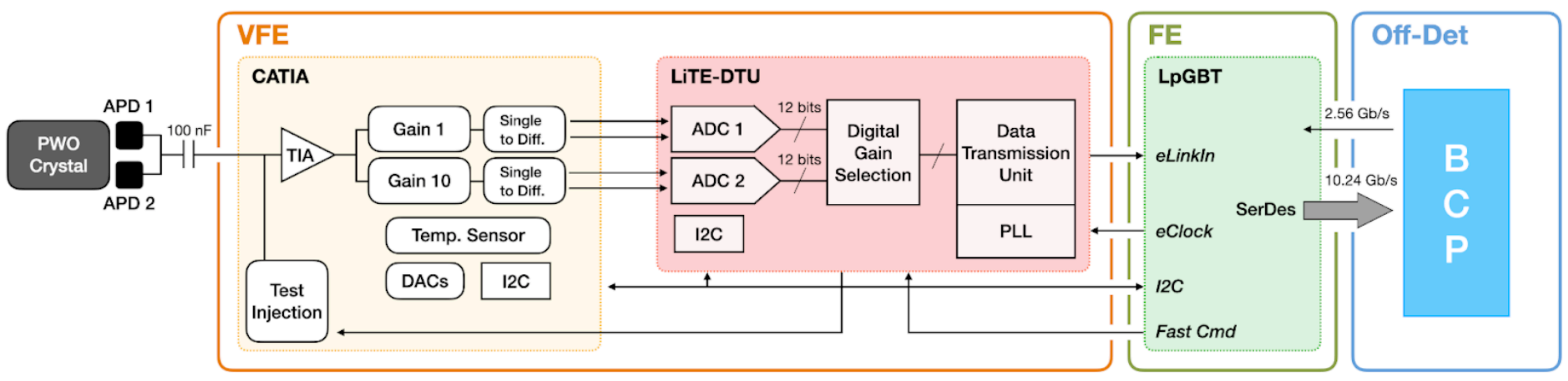
On-detector electronics replacement
New pre-amplifier and ADC with 160 MHz sampling

Lower operational temperature
To mitigate APDs electronic noise

The ECAL barrel crystals will be kept, and they will retain 30-50% of the light output after 3000 fb^{-1}.

THE UPGRADED SYSTEM AND ITS PERFORMANCE

THE NEW READOUT ELECTRONICS LAYOUT



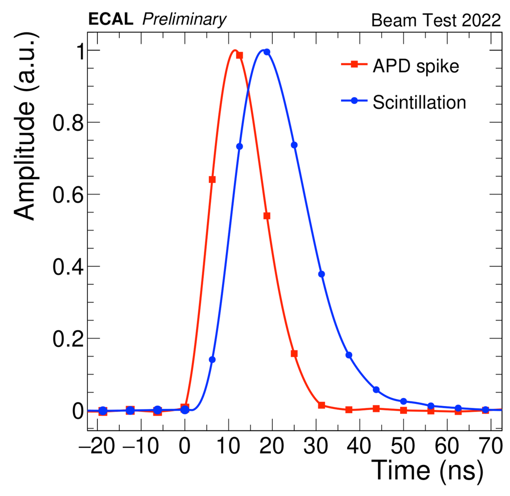
The upgraded CMS L1 trigger will have an increased event rate (750 kHz) and latency (12.5 µs), 7.5x and 3.3x w.r.t the current system. The ECAL readout must comply with fast data transmission. With the current readout capabilities, the trigger bandwidth would be saturated by the so-called "spikes", i.e. signals from APD direct ionization by hadrons. The amplifier bandwidth and sampling rate are optimised for **noise reduction, pileup mitigation, precise timing and on-the-fly pulse discrimination.**

CATIA Trans-impedance amplifier
- 2x bandwidth (~35 MHz) w.r.t current electronics
- 2 TeV dynamic range with 2 gain outputs
- Minimal pulse shaping for precise timing and improved signal discrimination

LITE-DTU Analog-to-digital converter
- 160 MHz sampling frequency, 12 bit resolution
- Lossless data compression (2.08→1.08 Gb/s)

lpGBT Transceiver
- Fast, radiation-hard 10 Gb/s optical links
- Trigger data granularity: single-crystal (x25 w.r.t. current system)

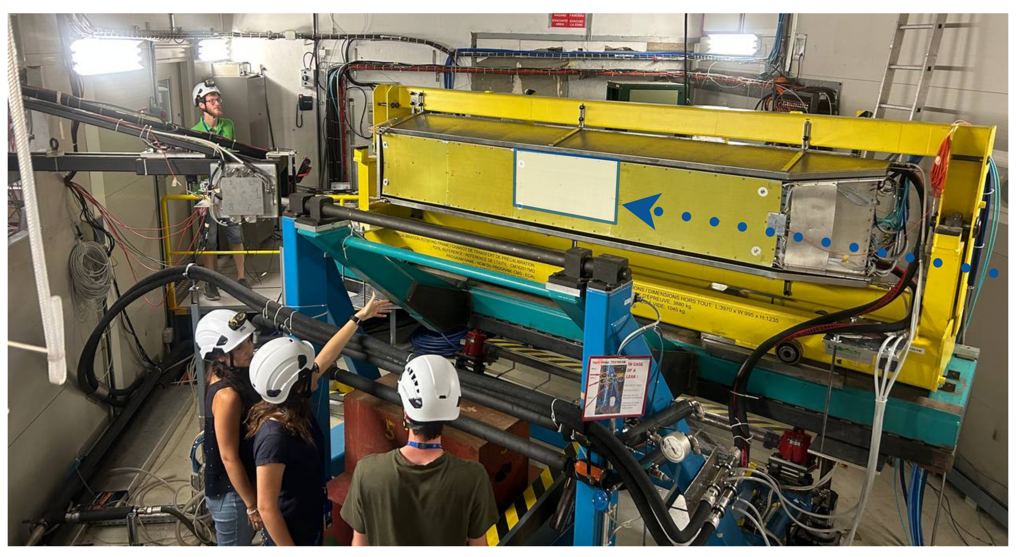
BCP FPGA-based aggregator
- Decompression and basic signal reconstruction
- Pre-processed data streamed to L1 trigger

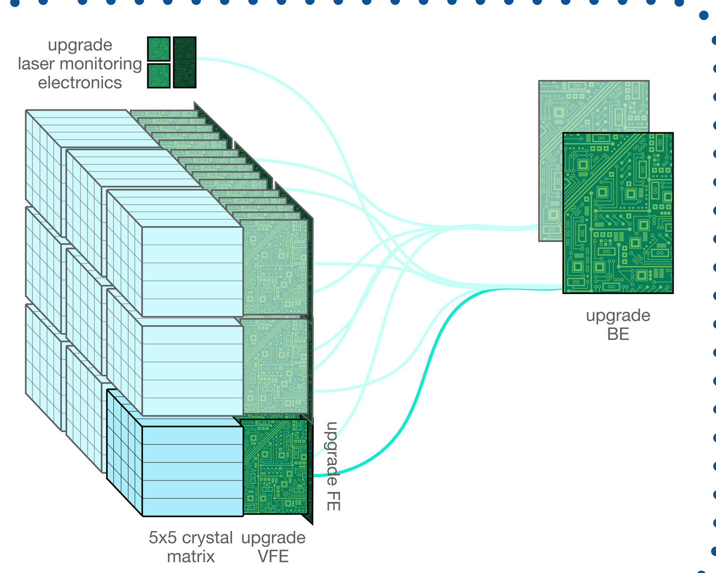


Comparison of the pulse shape from a scintillation event or from a direct hit in the APD.

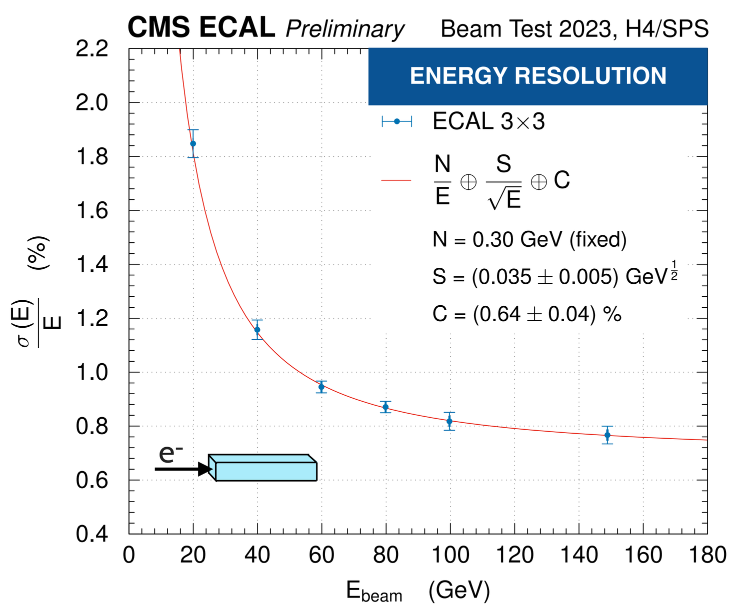
THE TEST BEAM SETUP

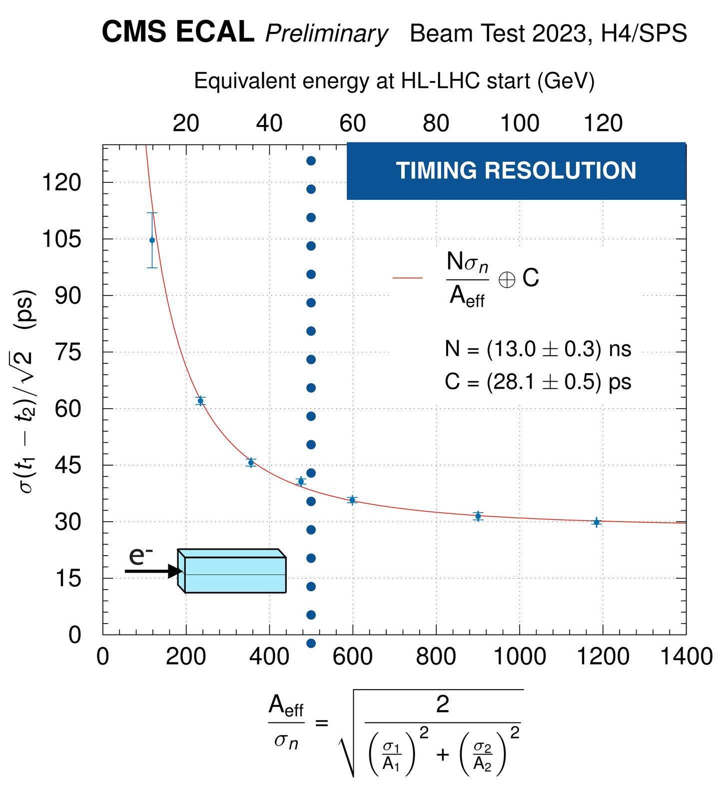
Test beam campaigns are being carried out at the secondary beamline H4 branching from SPS (*Super Proton Synchrotron*, CERN), where pure electron beams with Δp/p = 0.5% in 20 < p < 250 GeV are provided. In the 2023 campaign, 9 readout units of 5x5 crystals of a spare ECAL supermodule have been equipped **with close-to-final prototypes of the full readout chain**; an additional unit for the upgraded readout of the laser, monitoring the light output of crystals, was included. The experimental setup includes hodoscopes for the beam position monitoring and MCP detectors for external time reference.





PERFORMANCE ON BEAM





The ECAL upgraded system must meet several physics benchmarks. It is required that the current energy resolution is maintained, i.e. that **the constant term C is within 1%**. With the current system, the timing resolution is ~180 ps. The ECAL timing resolution should be **below 30 ps for e/γ above 50 GeV** to enhance the CMS vertex reconstruction efficiency by 10% at HL-LHC. The ongoing analysis of test beam data shows **excellent physics performance**.

CONCLUSION

The HL-LHC operations will be extremely challenging for data-taking and for online and offline event reconstruction. The radiation-hardness of the detectors and of their readout electronics must be ensured, as well as the fast transmission of high-quality data. While the ECAL endcaps will be replaced, the barrel will be refurbished with a new readout system. The outstanding energy resolution achieved by the legacy system will be maintained, and the timing resolution will be drastically improved. A large system, implementing close-to-final versions of the upgraded system prototypes, has been validated on beam, and the data analysis shows that the target physics performance is met. The Very Front End ASICs are in the pre-production phase, while the Front End and BCP boards design is being finalised. Newer versions of the readout elements will be tested in future test beam campaigns.

References
[1] The CMS electromagnetic calorimeter project, CMS Collaboration (CERN-LHCC-97-033, CMS-TDR-4)
[2] The Phase-2 Upgrade of the CMS Barrel Calorimeters, CMS Collaboration (CERN-LHCC-2017-011, CMS-TDR-015)