# Precise time and energy measurement with a homogeneous calorimeter

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**Abstract.** The CMS experiment at LHC has a 15 years experience with the energy measurement of electrons and photons produced in high-luminosity high-energy collisions with a homogeneous electromagnetic calorimeter (ECAL). The $PbWO_4$ crystal calorimeter must operate at a high rate in a harsh radiation environment: changes in detector response need to be corrected for and dedicated techniques are used to mitigate the large number of overlapping interactions (pileup). It also measures the arrival time of the particles with a precision $O(150\,\mathrm{ps})$. After the upgrade of the readout electronics for the LHC Phase-2, the time resolution will reach 30 ps for energies higher than about 50 GeV. This will be particularly important with the foreseen average pileup level up to 200. A summary of the performance of the CMS ECAL from its development to the ongoing Run 3 is presented, along with the results measured with the upgraded electronics at recent beam tests.

## 1 Introduction

The Compact Muon Solenoid (CMS) is a multipurpose particle physics experiment located at the CERN Large Hadron Collider (LHC) optimized to study pp collisions at the TeV scale [1]. One of the primary goals of CMS was the discovery of the Higgs boson. Among the most sensitive channels is the $H\to\gamma\gamma$ decay, characterized by a narrow resonance, whose width is totally dominated by the energy resolution of the electromagnetic calorimeter (ECAL), and a smooth background. To maximize the Higgs boson discovery potential through, for example, its diphoton decay channel, the CMS ECAL target standalone energy resolution was $\leq 0.5\%$ for high-energetic particles [2]. Even if the time resolution was not the driving factor when designing the CMS ECAL, precise time measurements are highly beneficial for particular physics analyses. The ECAL time information will be particularly important for primary vertex identification at the harsher conditions of High-Luminosity (HL)-LHC, or LHC Phase-2.

## 2 Building the CMS ECAL (1993 - 2008)

The physics requirements led to the design of a hermetic, homogeneous, fine-grained lead tungstate ($PbWO_4$) crystal calorimeter. Lead tungstate exhibits a high density $\delta = 8.3\,\mathrm{g/cm^3}$, a small radiation length $X_0 = 0.89\,\mathrm{cm}$ and a Molière radius $R_M = 2.2\,\mathrm{cm}$. These characteristics allowed the construction of a compact calorimeter, with the choice of a homogeneous medium to minimize sampling fluctuations. A total of 75848 crystals are installed, 61200 in the barrel (EB), divided into 36 supermodules with 4 modules each, and 7324 in each of the two endcaps (EEs). A silicon Preshower (ES) detector is placed in front of the EEs to better identify and reject photons from the $\pi^0$ decays. About 80% of the scintillation light is emitted in 25 ns, which is the typical spacing of two LHC bunches. Electrons and photons deposit their energy in several crystals, with around 97% contained in a $3 \times 3$ array.

The scintillation light is detected by avalanche photodiodes (APDs) and vacuum photo-triodes in the EB and EEs, respectively. The basic ECAL unit is composed of an array of $5 \times 5$ crystals, called readout-unit (RU). The photo-detectors signals are shaped and pre-amplified by the Multi-Gain Pre-Amplifier ASIC in three parallel amplification stages, ×1, ×6, and ×12. Each of the three analog outputs is digitized at 40 MS/s by a 12-bit multichannel ADC. An integrated logic selects the highest not-saturated signal. Trigger primitives are generated in the Front-end (FE) boards with RU granularity and then sent to the off-detector electronics. Electromagnetic candidates are formed by summing the energies in adjacent trigger primitives at the Level-1 (L1) trigger level.

The ECAL energy resolution was thoroughly studied before the LHC collisions at electron beam tests in ideal conditions, thus without magnetic field, no material upstream and non-irradiated crystals. For electron impinging on the center of a $3\times3$ crystal array, the stochastic term was measured to be 2.8%, while the constant term, dominant at higher energies, was found to be 0.3% [3]. The target energy resolution was fully achieved. A time stability of 1 ns is required to avoid a bias in the energy reconstruction.

## 3 LHC collisions in Run 1 (2010 - 2012)

Several factors must be considered to provide precise energy measurements when taking data at LHC [4]. Hadrons can directly ionize the APDs, generating large signals ("spikes") in isolated channels. If not rejected, the spikes

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would saturate the trigger. Spike-rejection is accomplished by evaluating the ratio of the energy in the highest deposit crystal and its neighbours, maintaining a 99% trigger efficiency for electrons and photons and a 96% spike rejection efficiency. The ECAL response varies due to the absorbed dose and the consequent creation of colour centers that reduce the transparency of the crystals. In absence of collisions, spontaneous recovery through annealing is observed. During LHC collisions, a monitoring system continuously injects a laser light at 447 nm (Photonics), close to the scintillation emission peak of PbWO$_4$, into each crystal and reference PN diodes. Transparency corrections are then computed from the ratio of the laser signals from the crystals to those from the diodes. Energy deposits from simultaneous collisions (pileup) and changes in the APDs dark current increase the noise term of the energy resolution. The energy deposits in ECAL are spread due to interactions with the upstream tracker material and distributed along the radial direction by the intense CMS magnetic field. A specific algorithm aggregates these deposits into "superclusters" to recover the radiated energy. Multiple physics processes are used to intercalibrate the channels response, including W and Z bosons decaying in electrons and $\pi^0$ and $\eta$ mesons decaying into two photons.

The ECAL energy resolution is determined with a maximum likelihood fit on the dielectron invariant mass from Z$\to$ee decay events, whose electron energies range from approximately 40 GeV at $\eta = 0$ to around 80 GeV at $|\eta| = 1.5$. The cluster shape parameter R9, defined as the ratio of the energy contained within the $3 \times 3$ array of crystals centered around the crystal with maximum energy deposit to the total energy of the supercluster, is used to select electrons with low or no bremsstrahlung emissions before ECAL. In Figure 1, the energy resolution measured during LHC Run 1 for both data and Monte Carlo (MC) simulation for electrons with R9 $\geq$ 0.94 is reported. The resolution depends on the amount of tracker material in front of ECAL and, therefore, is better at low pseudorapidity. In the vicinity of the module boundaries (vertical lines) it is slightly degraded due to the energy lost in the gap and material between two modules. Despite the challenging LHC environment with high radiation and pileup, the CMS ECAL during LHC Run 1 provided extremely precise energy measurement, and it played a fundamental role in the discovery of the Higgs boson [5].

## 4 Challenges in Run 2 (2015 - 2018)

LHC Run 2 was highly successful with a total of 138 fb$^{-1}$ collected by the CMS experiment. However, the experimental conditions were notably more challenging, as the collision center of mass energy was raised from 8 TeV to 13 TeV and the peak luminosity was doubled to $2 \cdot 10^{34}$cm$^{-2}$s$^{-1}$. Consequently, several updates were introduced [6]. Thanks to a firmware update, the FE boards automatically detected and masked problematic signals with configurable thresholds, maintaining an optimal trigger efficiency and reducing downtime. Because of the larger response changes due to the higher beam intensity, the energy corrections at the trigger level increased in frequency, from once to twice a week, and in granularity, from pseudorapidity regions to single crystals. The higher luminosity allowed the use of Z$\to$ee events not only for absolute scale measurement, but also for channel intercalibration. A new amplitude reconstruction algorithm was deployed to mitigate pileup contributions [7]. Thanks to these developments, if the pileup effects are factored out, the Run 2 ECAL energy resolution performance matches that of Run 1, as illustrated in Figure 2, where the remaining difference can be ascribed to the higher level of noise due to the expected APDs dark current increase.

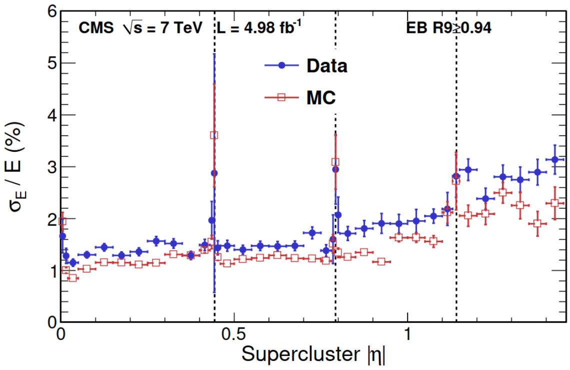

**Figure 1.** ECAL energy resolution measured with low bremsstrahlung electrons from Z$\to$ee events from LHC Run 1 data and MC simulations [4].

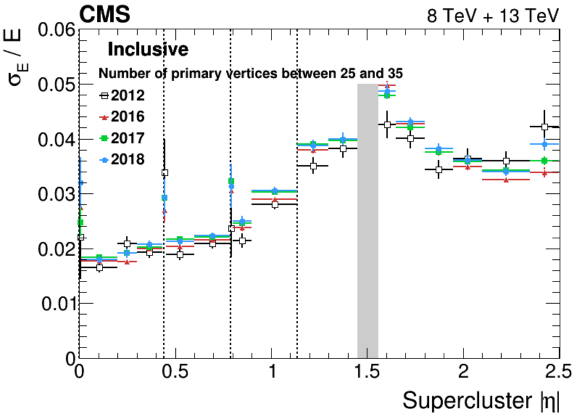

**Figure 2.** ECAL energy resolution measured from Z$\to$ee events from LHC Run 1 (2012) and Run 2 (2016, 2017, 2018) data [6].

## 5 Time resolution

The ECAL timing performance has been studied before Run 1 using beam test electrons. The resolution for large energy deposits ($>$ 20 GeV) was measured to be better than 100 ps [8]. During the LHC operations, time-dependent changes and clock distribution instabilities can degrade the performance. For Run 1, by measuring the time difference of the electrons from Z$\to$ee decays, the timing resolution was estimated to be 190 ps in EB and 280 ps in EEs with the electrons detected in two different RUs.

Analogously, it was measured during Run 2 as a function of an effective amplitude defined as

$A_{\mathrm{eff}} = (A_1 A_2) / \sqrt{A_1^2 + A_2^2}$, with $A_1$ and $A_2$ the amplitudes of the two electrons, normalized to the electronic noise $\sigma_n$. The results are shown in Figure 3. Despite the noise increase from $\mathcal{O}$(70 MeV) in 2016 to $\mathcal{O}$(100 MeV) in 2018, the more frequent updates of the time synchronization constants through the course of Run 2 led to an improvement in the time resolution. The final result of $\mathcal{O}$(150 ps) is well within the physics requirements. The precise ECAL timing information is being fully exploited in beyond Standard Model (SM) long-lived particle searches [9] and can also be used to constrain the position of the reconstructed primary vertices.

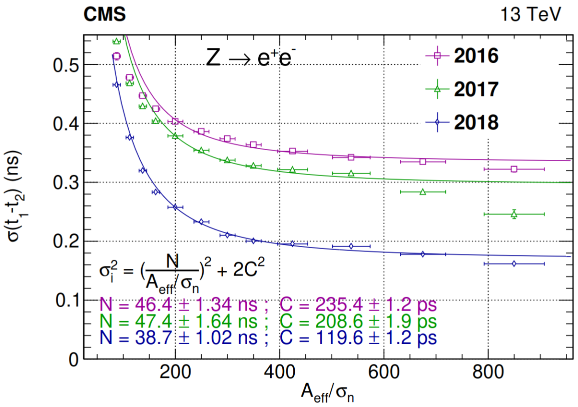

**Figure 3.** ECAL time resolution measured with Z→ee from LHC Run 2 data [6].

## 6 Run 3 performance (2022 - ongoing)

ECAL faces even more challenging conditions during LHC Run 3, with approximately 55 pileup events, which is more than double the value encountered during Run 1 [10]. Despite the noise increase due to radiation damage, ECAL continues its excellent performance maintaining the energy resolution at the percent level for all its pseudorapidity coverage, as reported in Figure 4. Multiple improvements have been implemented, including trigger-level correction updates for every LHC fill, automatic DAQ procedures to recover from Single Event Upsets and a fully automated validation framework for the calibration.

## 7 CMS ECAL at HL-LHC (2029 - 2040)

The main goal of the HL-LHC is to deliver to the experiments an unprecedented dataset corresponding to a luminosity of 3000 $\mathrm{fb}^{-1}$ for precise Higgs boson coupling measurements, SM precision tests, and new physics searches [12]. ECAL must be upgraded to maintain its current performance under the HL-LHC conditions up to the end of its operations [13]. Moreover, new trigger requirements must be met, with L1 rates up to 750 kHz and latency at 12.5 µs, compared to the current 100 kHz and 4 µs, and single-crystal granularity for the L1 trigger primitives. Furthermore, ECAL aims to achieve a time resolution of 30 ps for particles with energy $E \geq 50$ GeV. This will enable the identification of primary vertices, such as $H \rightarrow \gamma\gamma$, with a precision of up to 1 cm, significantly improving the reconstruction with the pileup level estimated to increase up to 200. The energy resolution performance are expected to match the current one.

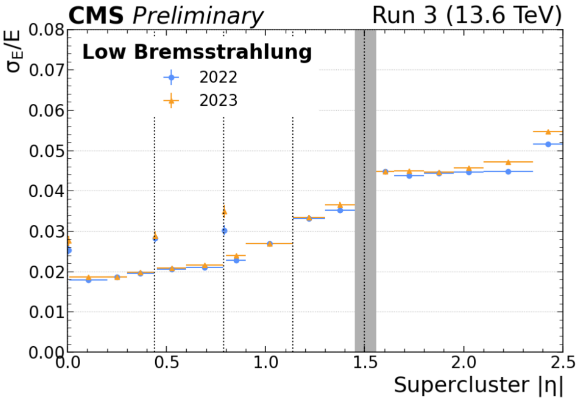

**Figure 4.** ECAL energy resolution measured with low bremsstrahlung electrons from Z→ee events from LHC Run 3 data [11].

### 7.1 ECAL EB upgrade for HL-LHC

The endcaps of the calorimeters will be replaced by the new High Granularity Calorimeter detector [14]. In the EB, the crystals and their APDs will be retained, but operated at 9 °C to mitigate the APDs dark current increase. The FE and off-detector electronics will be fully replaced. Two new ASICS will be mounted on the upgraded Very Front-end (VFE) board. The Calorimeter Trans-Impedance Amplifier (CATIA) will amplify the signal in two gain channels, ×1 and ×10. The Lisbon-Turin ECAL - Data Transmission Unit (LiTE-DTU) will sample the signals with 12-bit resolution at 160 MS/s, selecting then the highest not saturated channel and performing a lossless data compression. New FE boards will send the signal to the upgraded off-detector system, which consists of a new custom board, called Barrel Calorimeter Processor (BCP). This will be equipped with powerful commercial FPGAs, will control the FE system, distribute the clock and compute the trigger primitives with spike rejection capabilities.

### 7.2 Timing resolution at beam test

Multiple beam test campaigns have been conducted to evaluate and characterize the ECAL upgraded readout, verifying the technological choices, the radiation hardness requirements of the components up to the end of HL-LHC, and the energy and timing performance [15]. These have validated the expected performance of the individual components and confirmed the ECAL energy performance.

In 2023, the first large-scale beam test with the whole upgraded electronics deployed was conducted at the H4 electron beam line at CERN/SPS. Two prototypes of the BCP managed 225 crystals of a spare supermodule equipped with a near-to-final version of all the components. The supermodule was located on a mechanical movable structure ensuring the same pointing geometry of CMS, thus with electrons impacting the crystals face perpendicularly. The timing resolution was evaluated by pointing the beam in between two crystals and computing the time difference of the two pulses reconstructed with a template fit. Only the electrons impinging within a $2 \times 2\,\mathrm{mm}^2$ square between the two crystals are selected. The time resolution of the single crystal is taken from the width of the distribution of the difference of the signal arrival times divided by $\sqrt{2}$, thus assuming the two crystals are identical. The time resolution is studied as a function of the effective amplitude $\mathrm{A_{eff}}/\sigma_\mathrm{n}$. The results for two crystals on different VFEs, FEs, and BCPs, which is the worst possible case for the clock distribution since they are on two independent electronics paths, are reported in Figure 5. If a noise $\sigma_n = 100\,\mathrm{MeV}$ is assumed at the HL-LHC start, as derived from simulations, at $\mathrm{A_{eff}} = 50\,\mathrm{GeV}$ a time resolution of $\sigma_t = (38.3 \pm 0.5)$ ps is achieved. Similar results are obtained for two channels on the same VFE, thus sharing the same clock distribution line. The design target time resolution is met for typical energies of photons coming from Higgs boson decays.

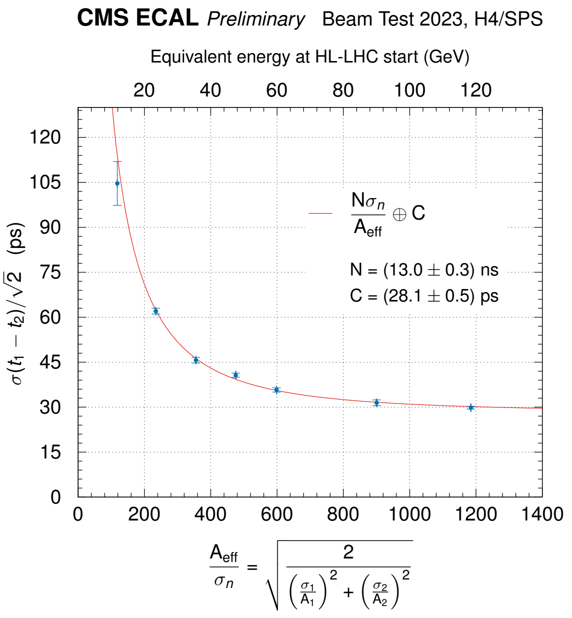

**Figure 5.** Single crystal time resolution for electrons measured with a near-to-final version of the upgraded electronics.

## 8 Conclusions

The CMS homogeneous crystal electromagnetic calorimeter provides precise energy and time measurements in a harsh radiation environment, contributing significantly to the successful CMS physics program. Detector ageing and increasingly challenging experimental conditions can potentially degrade the performance. However, expertise, innovative calibration techniques, and a flexible DAQ/trigger system allow to continuously meet the physics requirements. Beam tests preliminary results with the upgraded electronics show that the Phase-2 requirements are met, ensuring that the CMS ECAL will continue its successful journey at HL-LHC.

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