Prospects for a precision timing upgrade of the CMS PbWO$_4$ crystal electromagnetic calorimeter for the HL-LHC

V Ciriolo for the CMS Collaboration

1 Dipartimento di Fisica G. Occhialini, Università degli Studi & INFN of Milano-Bicocca, Piazza della Scienza, 3, 20126, Milano
E-mail: vincenzo.ciriolo@cern.ch

Abstract. Particle detectors with a timing resolution of order 10 ps can improve event reconstruction at high-luminosity hadron colliders tremendously. The upgrade of the Compact Muon Solenoid (CMS) crystal electromagnetic calorimeter (ECAL), which will operate at the High-Luminosity Large Hadron Collider (HL-LHC), will achieve a timing resolution of around 30 ps for high-energy photons and electrons. The benefits of precision timing for the ECAL event reconstruction at HL-LHC will be discussed in this presentation. Simulation and test beam studies carried out for the timing upgrade of the CMS ECAL will be presented and the prospects for a full implementation of this option will be discussed.

1. Introduction
The Compact Muon Solenoid (CMS) [1] is a general purpose experiment, whose physics program ranges from the study of the Standard Model (SM) to the investigation of beyond Standard Model (BSM) theories, exploiting the proton-proton collisions delivered by the Large Hadron Collider (LHC) [2] at CERN.

The CMS electromagnetic calorimeter (ECAL) [3], located inside the 3.8 T superconducting solenoid, was designed to measure the energies of electrons and photons with high precision (better than 1% for photons with 60 GeV energy). The ECAL is a hermetic, homogeneous calorimeter made up of 75848 lead tungstate (PbWO$_4$) scintillating crystals, 61200 in the barrel region (EB), covering |$\eta$| < 1.479 pseudorapidity region and 14648 divided in two endcaps (EE), providing coverage up to |$\eta$| = 3. The scintillation decay time is such that about 80% of the scintillation light is emitted within the LHC bunch crossing interval (25 ns). The scintillation light is read by means of avalanche photodiodes (APD) in the barrel region and vacuum phototriodes in the endcaps. The signal is shaped with a 42 ns time constant, digitized at a rate of 40 MHz and ten samples are saved for each hit.

Although the ECAL was not designed to perform precision timing measurements, the fast rise time of the pulse, the electronics shaping time and digitization rate enable sub-nanosecond timing resolution. This feature is currently exploited to reduce the background due to particles produced in consecutive bunch crossings (out-of-time pileup), cosmic rays and spurious signals and to perform analyses targeting long-lived particles decaying to photons, which are predicted by some BSM theories [4].
A High Luminosity phase of the LHC (HL-LHC) [5], also called LHC Phase II, is planned to begin in 2026. Thanks to the upgrade of the LHC components, the ultimate instantaneous peak luminosity will possibly reach \( L = 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{s}^{-1} \), resulting in a potential integrated luminosity of 4500 fb\(^{-1}\) at the end of the HL-LHC life. Such a high instantaneous luminosity implies a number of concurrent collisions per bunch crossing (pileup) as high as 200. To successfully exploit the data that will be collected during the HL-LHC phase, new methods to mitigate the pileup effects must be developed. Precise timing measurements of electromagnetic deposits in the ECAL can provide a viable way to reduce the impact of the pileup.

2. Current ECAL barrel timing performance

Several factors impact the calorimeter single channel timing resolution for an electromagnetic shower:

- The electromagnetic longitudinal shower development fluctuations, the time spread of the light propagation, and the rise and the decay time of scintillation
- The electronics noise dominated, in the long term, by the photodetector dark current
- The data acquisition (DAQ), in particular the clock distribution jitter

The time resolution \( \sigma_t \) can be expressed as the sum of three terms accounting for the different contributions:

\[
\sigma_t^2 = \left( \frac{N \sigma_n}{A} \right)^2 + \left( \frac{S}{\sqrt{A}} \right)^2 + C^2
\]

where \( A \) is the measured pulse amplitude, \( \sigma_n \) is the RMS of the noise in each sample, and \( N, S, \) and \( C \) are the coefficients related to the electronics noise, the stochastic, and the constant term, respectively. The ECAL timing performance has been tested both during dedicated test beams and in situ with data collected during proton-proton collisions [6].

2.1. Beam tests measurements

The time resolution of the ECAL PbWO\(_4\) crystals has been measured during beam tests [6]. An entire supermodule has been irradiated with electron beams of energies between 15 GeV and 250 GeV and was read out with the same electronics used during ECAL operations at CMS. The time information is extracted from a fit of the pulse shape and the time resolution was extracted from a fit of the distribution of the differences between the time measured by two adjacent crystals sharing a comparable amount of energy to a Gaussian function. The results as a function of the amplitude of the signal are reported in Fig. 1. The measured constant term is about 20 ps. For electrons with energy higher than 25 GeV, a typical threshold applied in CMS analyses, the resolution is about 50 ps.

2.2. In situ measurement

The ECAL time resolution has been measured also in situ, with proton-proton collisions delivered by the LHC [7]. The reconstructed time of two electromagnetic clusters due to electrons produced in the decay of Z bosons, corrected for their time of flight, has been compared and the time resolution has been extracted from a gaussian fit of the distribution of their difference. The constant term found with this method is about 190 ps, much higher than the value obtained at the beam test. In order to better understand the causes of such a performance, the time resolution has been estimated with another method, which considers the time of the two most energetic crystals of the same electromagnetic cluster. In this case, a single channel resolution of about 74 ps has been found. Moreover, selecting only crystals of the same or different readout unit, constant terms of about 67 ps (Fig. 2 left) and 130 ps (Fig. 2 right), have been measured, respectively.
Figure 1. Time resolution extracted from a gaussian fit of the distribution of the difference between the time measured by two neighboring crystals as a function of $A/\sigma_n$ at beam tests with electrons of energy ranging from 15 GeV to 250 GeV. The equivalent energy scale is overlaid.

Figure 2. Time resolution assessed with a gaussian fit of the distribution of the difference of time measured by neighboring crystals of the same electromagnetic shower belonging to the same readout unit (left) and to different readout units (right). A fit with a function accounting for a noise term and constant contribution is superimposed.

3. ECAL upgrade for the High-Luminosity phase of the LHC (HL-LHC)
To preserve its performance at the HL-LHC, the ECAL will be subject to an upgrade plan [9]. The endcaps will be replaced by a new high-granularity calorimeter (HGC) [10] because of the
high radiation dose expected in the forward region. In the barrel region, the crystals and the APDs will be maintained, while the upgrade of the ECAL electronics system is mandatory to fulfill the requirements of the phase II trigger system: latency up to 12.5 $\mu$s and accept rate up to 750 kHz, instead of the current values of 4.5 $\mu$s and 100 kHz, respectively. Hence, the ECAL barrel upgrade plan foresees the replacement of the Very Front-End (VFE) and Front-End (FE) readout electronics. This opens the possibility to investigate additional features to enhance the performance of the ECAL at the HL-LHC. In addition, studies of the effect of APD ageing have showed that the APD dark current will increase and will induce, at the end of the HL-LHC, an equivalent noise value of about 400 MeV. To mitigate this effect, the operating temperature of both crystals and APDs will be lowered from 18$^{\circ}$C to 8$^{\circ}$C. Furthermore, to cope with the electronics noise and the contamination due to pileup, the shaping time of the preamplifier will be reduced from 42 ns to 21 ns, providing a $\sqrt{2}$ reduction of the (dominant) parallel noise.

3.1. Benefits from ECAL precision timing

The large number of pileup events per bunch crossing will cause a degradation of the detector performance in terms of energy resolution, in particular for neutral deposits, and $H \to \gamma\gamma$ vertex identification. The addition of high-precision timing, with resolution of order 30 ps, to the high spatial granularity of the ECAL can help preserve the excellent detector performance.

Monte Carlo simulation studies, targeting some of the analysis of the CMS physics program at the HL-LHC, have been performed to assess the benefits that precision timing in the ECAL can provide, as a standalone detector or in association with a dedicated timing detector sensitive to minimum ionizing particles (MIPs) [11].

One of the benchmarks is the location accuracy of the Higgs boson diphoton decay vertex. A precision of about 1 cm along the beam axis (z-coordinate) is crucial to measure the Higgs boson mass with high resolution. At the HL-LHC the efficiency of the current algorithms in reconstructing the z-coordinate of the vertex within this interval will be considerably lower. However, if the time of arrival of photons in the calorimeter could be precisely measured, the location along the beam axis of the vertex could be assessed via triangulation. In Fig. 3, it is possible to see the improvement in the $m_{\gamma\gamma}$ resolution with precision timing only in the ECAL (blue) and with the further addition of a dedicated timing detector in the barrel region (red). The gain in resolution will result in a higher effective integrated luminosity and higher precision in the measurement of the Higgs boson properties.

The benefits from precision timing in ECAL also involve analyses searching for long-lived particles (LLPs), which are predicted by some extensions of the SM. For example, the decay of the lightest neutralino ($\chi^0_1$) to a gravitino ($\tilde{G}$) and a photon, in the gauge-mediated SUSY breaking (GMSB) scenario [12], where the $\chi^0_1$ can be long-lived, has been studied. For a long-lived neutralino, the photon coming from the $\chi^0_1 \to \tilde{G} + \gamma$ decay, is produced at some distance from the primary interaction vertex and reaches the detector later than the other particles produced at the interaction point. In these kind of analyses, the time of arrival of the photon at the ECAL can be exploited to identify the signal. The timing capabilities of the detector play a key role in order to extend the sensitivity of the analysis to short particle lifetimes and high mass. The gain in sensitivity as a function of the lifetime and mass due to precision timing is shown in Fig. 4, for different CMS upgrade scenarios representing the current time-of-flight resolution (red), a resolution of 30 ps in photon reconstruction (green) and a resolution of 30 ps in photon and vertex reconstruction (blue). The latter scenario requires a dedicated MIP timing detector in addition to the ECAL upgrade. The vertex time resolution would be otherwise limited to 180 ps by the time spread of the collisions within the same bunch crossing.
Figure 3. Diphoton invariant mass distribution for $H \rightarrow \gamma\gamma$ decays in several timing detector configurations. The contribution of the individual categories of the analysis are weighted according to their signal to background ratio.

3.2. Beam tests results

The performance of the PbWO$_4$ crystals read out by APDs as well as the performance of the new electronics developed for the HL-LHC phase, have been assessed during several test beam campaigns, during which a 5 × 5 matrix of crystals read out with APDs has been irradiated with electron beams of different energies and read out with different VFE configurations. The crystal time information has been extracted from a template fit of the pulse shape. A microchannel plate (MCP) detector, whose time resolution has been measured to be about 25 ps [13], has been located in the beam line upstream of the crystals and used as time reference. The distribution of the differences between the time measured by the crystal and by the MCP has been fitted with a gaussian function and the standard deviation extracted from the fit has been quoted as the time resolution $\sigma_t$.

The impact of a shorter shaping time is visible in Fig. 5, where the time resolution $\sigma_t$ as a function of the incoming electron beam energy is plotted. During this test beam, the current ECAL legacy VFE were employed. The measured constant term is 27 ± 5 ps.

In 2016, a prototype of the new phase II VFE, featuring the new Transimpedance Amplifier (TIA) has been implemented employing discrete components. In Fig. 6, the time resolution as a function of the amplitude over noise ratio is plotted for different sampling frequencies. A fast digitizer (CAEN V1742), with sampling frequency of 5 GHz, has been used in the data acquisition and lower sampling frequencies have been emulated at analysis level. Comparing the black points to the blue ones, which correspond to the digitizer sampling frequency (5GHz) and to the sampling frequency that will be employed during the ECAL operations (160 MHz) respectively, it is possible to see that the ultimate time resolution is already achieved for a sampling frequency of 160 MHz, while at 80 MHz (red and green points) the time resolution depends on the sampling phase. The measured constant term is about 18 ps and the goal time resolution of 30 ps is achieved for $A/\sigma$ of about 250, corresponding to 25 GeV deposits at the
Figure 4. Sensitivity to GMSB $\tilde{\chi}^0_1 \rightarrow \tilde{G} + \gamma$ signal expressed in terms of neutralino lifetimes for different time-of-flight resolutions, corresponding to the current detector (red), $\sigma_t=180$ ps time-of-flight resolution resulting from 30 ps ECAL timing resolution without timing at the vertex (green), and with an additional timing detector able to reconstruct the time of the vertex (blue).

Figure 5. Time resolution on $t_{APD} - t_{MCP}$ as a function of the beam energy.

HL-LHC start and 60 GeV at the HL-LHC end.
4. Summary

The timing capability of the CMS ECAL has been measured with high energy electrons and photons during either test beam campaigns or in situ, with proton-proton collisions delivered by the LHC. At beam tests, a time resolution of better than 50 ps was measured for electrons with energy above 25 GeV. With proton-proton collisions, many other factors affect the time resolution, such as electronics noise, channel intercalibrations, and clock instability. In the ECAL barrel, a resolution of about 68 ps was measured considering adjacent channels belonging to the same electromagnetic shower and to the same readout unit. If channels belonging to different readout units are selected, the measured time resolution is about 130 ps.

In 2026, the HL-LHC will begin data taking, with an ultimate peak instantaneous luminosity of $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The ECAL barrel electronics must be replaced because of the stringent requirements of the new trigger system. A time resolution of 30 ps for high energy electromagnetic showers is desired for the new electronics design and has been achieved at beam tests.

Monte Carlo simulation studies have shown some of the benefits of the employment of precise timing information in the ECAL in event reconstruction. The Higgs boson diphoton decay vertex has been studied in detail since it is profoundly affected by the effect of pileup. In this analysis, time resolution of about 30 ps would enhance the efficiency in reconstructing the position of the vertex along the beam axis with the necessary accuracy ($\sim 1 \text{ cm}$), with a consequent gain in the $m_{\gamma \gamma}$ resolution and measurement sensitivity. Moreover, searches for long-lived particles will benefit from precision timing capabilities in the ECAL, improving their sensitivity to shorter particle lifetimes and higher masses.

References

[1] Chatrchyan S et al. (CMS), 2008 The CMS Experiment at the CERN LHC JINST 3 S08004.
[2] Evans L and Bryant P, 2008 LHC Machine JINST 3 S08001.
[3] CMS Collaboration, 1997 The CMS electromagnetic calorimeter project: Tech-
nical Design Report Technical Design Report CMS (Geneva: CERN) URL https://cds.cern.ch/record/349375.

[4] Chatrchyan S et al. (CMS), 2012 Search for new physics with long-lived particles decaying to photons and missing energy in $pp$ collisions at $\sqrt{s} = 7$ TeV JHEP 11 172 (Preprint 1207.0627).

[5] Apollinari G, Béjar Alonso I, Brüning O, Fessia P, Lamont M, Rossi L and Tavian L, 2017 High-Luminosity Large Hadron Collider (HL-LHC).

[6] CMS Collaboration, 2010 Time reconstruction and performance of the CMS electromagnetic calorimeter Journal of Instrumentation 5 T03011 URL http://stacks.iop.org/1748-0221/5/i=03/a=T03011.

[7] del Re D, 2015 Timing performance of the CMS ECAL and prospects for the future J. Phys.: Conf. Ser. 587 012003. 6 p URL https://cds.cern.ch/record/2158942.

[8] Orimoto T J, (CMS ECAL Group) 2008 The CMS ECAL Laser Monitoring System URL https://cds.cern.ch/record/1742291.

[9] CMS Collaboration, 2017 The Phase-2 Upgrade of the CMS Barrel Calorimeters Technical Design Report Tech. Rep. CERN-LHCC-2017-011. CMS-TDR-015 CERN Geneva URL https://cds.cern.ch/record/2283187.

[10] CMS Collaboration, 2017 The Phase-2 Upgrade of the CMS Endcap Calorimeter Tech. Rep. CERN-LHCC-2017-023. CMS-TDR-019 CERN Geneva URL https://cds.cern.ch/record/2293646.

[11] CMS Collaboration, 2017 Technical Proposal for a MIP Timing Detector in the CMS Experiment Phase 2 Upgrade Tech. Rep. CERN-LHCC-2017-027. LHCC-P-009 CERN Geneva URL https://cds.cern.ch/record/2296612.

[12] Strassler M J and Zurek K M, 2007 Echoes of a hidden valley at hadron colliders Physics Letters B 651 374 – 379 ISSN 0370-2693 URL http://www.sciencedirect.com/science/article/pii/S0370269307007721.

[13] Brianza L et al., 2015 Response of microchannel plates to single particles and to electromagnetic showers Nucl. Instrum. Meth. A797 216–221 (Preprint 1504.02728).