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Precision calorimetry at high luminosity: the CMS electromagnetic calorimeter from the LHC Run 2 to the HL-LHC

Dario Soldi[a,*] **on behalf of the CMS collaboration**

[a] *INFN - Torino,*
Via Pietro Giuria 1, 10126, Torino, Italy

E-mail: dario.soldi@to.infn.it

The CMS experiment at the LHC is equipped with a high granularity lead tungstate crystal electromagnetic calorimeter (ECAL) offering an excellent energy resolution. The ECAL was crucial in the discovery and subsequent characterization of the Higgs boson, particularly in the two photon and two Z boson decay channels. The LHC has reached an unprecedented luminosity during Run 2 (2016-2018), leading to a high numbers of proton-proton interactions per bunch collision (pileup), exceeding the design value and resulting in a very high radiation environment. We will present how we maintain the high performance of the calorimeter in these difficult conditions, challenging for both the calibration and the reconstruction. A new readout is being developed to operate the calorimeter at the high-luminosity LHC (HL-LHC) with an even higher luminosity, reaching an average pileup of up to 200. Precise signal time measurement and limitation of the dark current induced by radiation damaged are key ingredients to maintain a high energy resolution in the HL-LHC conditions. This upgrade of the CMS electromagnetic calorimeter will be presented.

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*Speaker

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1. Introduction

1.1 The CMS experiment

The Compact Muon Solenoid (CMS) detector [1] is a general-purpose detector which has been designed to explore particle physics at the TeV energy scale exploiting the proton-proton collisions delivered by the Large Hadron Collider (LHC) at CERN. The CMS detector is characterized by a superconducting solenoid of 6 m internal diameter, providing a 3.8 T magnetic field. Within the solenoid volume are silicon pixel and strip trackers, a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator Hadron CALorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

1.2 The ECAL detector

The CMS ECAL is a high-resolution, hermetic and homogeneous electromagnetic calorimeter, built of scintillating lead tungstate crystals ($PbWO_4$) divided into a barrel (EB) and two endcap (EE) parts. The barrel covers the pseudorapidity region $|\eta| < 1.48$ and consists of 61200 crystals. The endcaps are each made up of 7324 crystals and extend the coverage up to $|\eta| < 3.0$. The $PbWO_4$ crystals are characterized by a short radiation length (0.89 cm), high density (8.28 g/cm^3), and small Molière radius (2.2 cm). These characteristics produced a fast, compact, high granularity and radiation resistant detector.

In the barrel, an energy resolution of about 1% is achieved for unconverted or late-converting photons that have energies in the range of tens of GeV. The remaining barrel photons have a resolution of about 1.3% up to $|\eta|= 1$, rising to about 2.5% at $|\eta|= 1.4$. In the endcaps, the resolution of unconverted or late-converting photons is around 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [2]. The excellent ECAL energy resolution, as well as its timing performance, are fundamental aspects for the physics reach of the experiment.

2. The ECAL changes from LHC Run 1 to Run 2

The scintillation light is read out with avalanche photodiodes (APD) in the barrel and vacuum phototriodes (VPT) in the endcaps. The electrical signal from the photodetectors is amplified and shaped by a multi-gain preamplifier. The output is digitized by a 12 bit ADC running at 40 MHz, which records, at each trigger, 10 consecutive samples used to reconstruct the signal amplitude. During LHC Run 1 a digital filtering algorithm was applied, where the signal amplitude is estimated as the linear combination of the N = 10 samples, S_i:

$$\hat{\mathcal{A}} = \sum_{i=1}^{N} w_i \times S_i \tag{1}$$

where w_i indicates weights calculated by minimizing the variance of $\hat{\mathcal{A}}$, and providing an optimal filtering of the electronics noise, that is estimated on an event-by-event basis by averaging the first three digitized pedestal-only samples.

The LHC running conditions during Run 2 differed from Run 1 in two principal ways: the center-of-mass energy was increased from 8 TeV to 13 TeV and the bunch spacing was changed from 50 ns to 25 ns. The higher bunch intensity has an impact on the ECAL reconstruction, thus the detector must provide an effective pile-up (PU) mitigation mechanism both for in-time and out-of-time physics events while coping with a higher particle rate and an increased radiation level.
Due to a very precise and reproducible pulse shaping of the ECAL electronics, it is possible to fit the acquired values with the signal shape waveform together with additional pulse hypotheses at different bunch crossings. This algorithm, called *multi-fit*, provides an estimate of the out-of-time energy deposits and removes it from the genuine in-time event, thus providing a better amplitude reconstruction of the in-time pulse shape [3].
Moreover, the higher luminosity of Run 2 implies a higher irradiation dose for the crystals. As a consequence, the crystals and the read-out suffer from radiation-induced aging, resulting in a loss of light output. Figure 1 shows the relative response of ECAL crystals to laser light as a function of time, for different regions of η. The loss of transparency is larger at higher η, where the endcaps are located, due to heavier radiation damage. This is relevant for the Phase 2 upgrade. To mitigate these aging effects, ECAL relies on precise calibration maintained over time, despite the severe irradiation conditions. Each channel is monitored with a dedicated laser system which scans each crystal response every 40 minutes. The corrections are provided and applied every 48 hours [4].

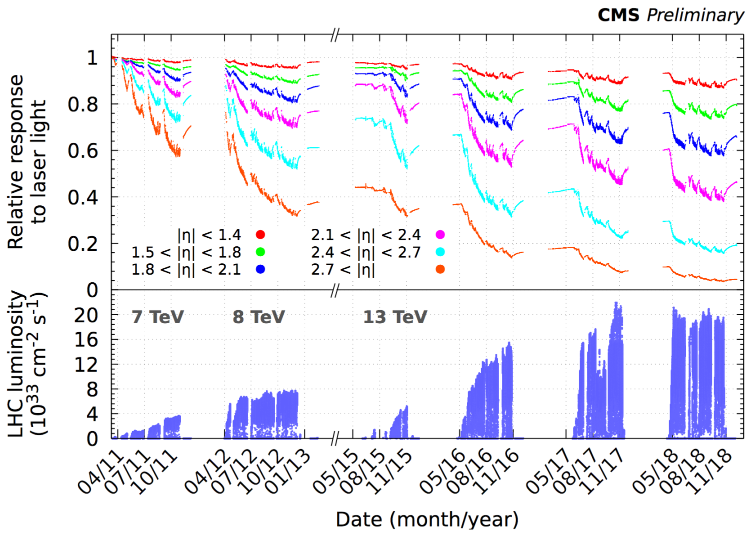


Figure 1: ECAL crystals relative response to laser light as a function of time, for different regions of pseudorapidity. The lower panel shows the instantaneous luminosity reached by LHC during operation [5].

3. The challenges of Phase 2

By 2026, the LHC will be upgraded towards high luminosity operation, boosting its instantaneous luminosity to $5 \times 10^{34}\ cm^2 s^{-1}$, in order to obtain an extensive dataset (~3000 fb^{-1}) for new physics searches. This will lead to unprecedented radiation levels and a significant increase of the average PU from 40 – 60 to 200 vertices per event. In such an environment, ECAL must maintain similar performance to what was achieved during Run 2.

The higher luminosity will result in a loss of crystal transparency and will increase the noise in the APDs. It will also increase the probability of anomalous high energy events ("spikes"), induced by hadrons interacting directly with the APD core instead of the crystal. Moreover the trigger rate will increase from 100kHz to 750 kHz, requiring a higher data-transfer bandwidth.
To face the challenges of Phase 2, several actions are required [6]:

1. The endcap part of ECAL will be substituted with a new High Granularity calorimeter, to sustain the radiation in region at high η;

2. The ECAL operating temperature will be reduced from 18° to 9° C to mitigate the radiation-induced increase in the APD dark current;

3. The ECAL barrel electronics will be upgraded in order to meet the higher rate and bandwidth requirements, achieve precision timing, provide good spike rejection and have a full detector read-out at the hardware level of CMS trigger.

3.1 The new electronics

To maintain the reconstruction performance during the Phase 2 conditions, when the PU will reach of 140-200 vertices per event, the calorimeter must provide a time resolution of about 30 ps. In fact, 200 PU implies a reduction of primary vertex reconstruction efficiency of the 30% for the golden mode $H \to \gamma\gamma$. The vertex localization efficiency can be improved if a timing of 30 ps is reached. For instance, an estimated 10% improvement is achieved in the fiducial cross-section sensitivity and $H \to \gamma\gamma$ resolution [7]. For this reason the new ECAL readout chain is specified to deliver the desired time resolution of 30 ps for energies higher than 50 GeV.
The new electronics [6], shown in Figure 2, is characterized by a trans-impedance amplifier (CATIA) read out by 12 bit ADCs with a sampling frequency of 160 MS/s. The ADCs are hosted in a chip (LiTE-DTU) that also performs data compression and reduction to fit in the fast radiation tolerant optical links (CERN lpGBT/VL) used to stream the crystal data off-detector. In the off-detector electronics, a new implementation of the trigger will utilize the granularity of the data at crystal level. As in the current version of the electronics, the system is composed by a multi-gain and multi-channel ADC solution to satisfy both the requirements on dynamic range and resolution. The upgraded front-end is thus composed by two gain channels, one amplified by a factor of 10, to fit the gain toggle for photons. CATIA amplifies and converts the input photo-current signal

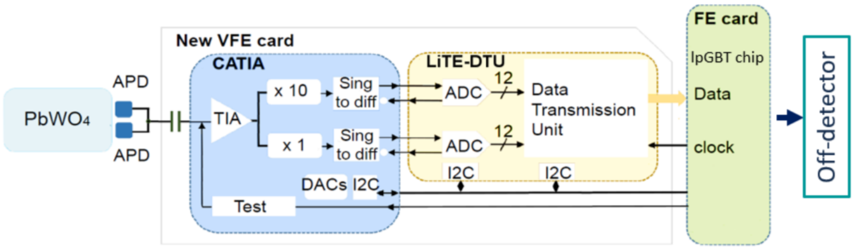
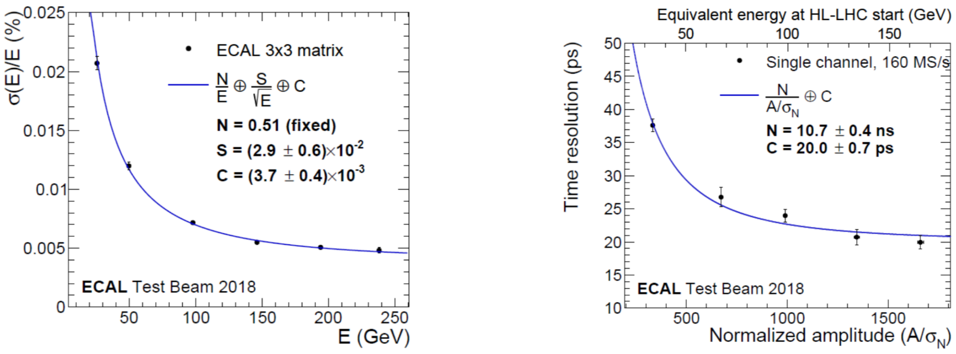
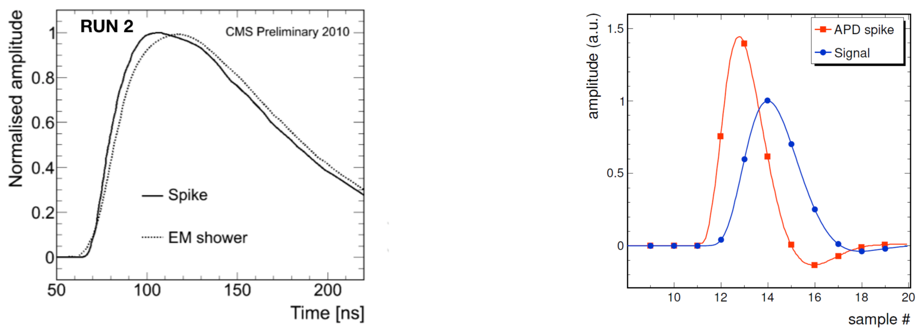


Figure 2: Scheme of the new ECAL readout electronics for the Phase 2 upgrade.



(a) (b)

Figure 3: CATIA energy resolution (a) and time resolution on a single crystal (b) obtained from the test beams at CERN [8].



(a) (b)

Figure 4: Comparison between legacy amplifier (a) and CATIA (b) responses for an electron shower in the crystal with respect to a spike signal [6].

coming from the APD into a voltage signal. The output dynamic range, in equivalent energy of electrons and photons, is between 50 MeV and 2 TeV. Tests on the first version of CATIA, coupled with a commercial ADC, have been carried out at the H4/H2 beam line of the CERN SPS with electrons of momentum range between 25 and 250 GeV [8]. The main results obtained during the test beam are shown in Figure 3. The energy resolution matches with the legacy electronics performance, and the measurements on single crystals show that 30 ps time resolution can be achieved for electromagnetic showers with an energy greater than 50 GeV. Figure 4 shows the signal pulses for an electron shower compared to a spike for (left) the legacy amplifier and (right) CATIA, where the improved discrimination against spikes is evident.

CATIA is followed by the LiTE-DTU chip for the conversion, compression and transmission of the signals. The LiTE-DTU receives the input from CATIA and performs a digitization of the pulses at 160 MS/s, together with the selection of the gain which must be transmitted to avoid saturation of the signal. Simulations on the correlation between the time resolution and the sampling rates have been performed in order to optimize the ADC sampling frequency. A time resolution of 30 ps can be obtained sampling the signal with a frequency equal or above 120 MS/s. The choice for the sampling rate at 160 MHz is consistent with the clock frequency generated for the lpGBT links and allows some margin. Several tests are ongoing to characterize the full electronics chain, both in terms of performance and radiation hardness.

4. Conclusions

The transition from Run 1 to Run 2 conditions and to the Phase 2 era for the CMS ECAL calorimeter have been presented. In Run 2, the increased pileup and radiation levels required a new algorithm to reconstruct the in-time signals. In addition, a laser system has been in place to constantly monitor and calibrate the ECAL to maintain energy resolution and good stability over time. For Phase 2, further interventions are need to mitigate the challenging conditions of the HL-LHC, where ECAL will face higher rates, pileup, radiation levels, and anomalous signals. The ECAL readout electronics will be upgraded to meet these challenges and also provide precision timing while maintaining good energy resolution. Preliminary results for the new CATIA preamplifier are very promising.

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