The CMS Electromagnetic Calorimeter: overview, lessons learned during Run 1 and future projections

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Abstract. The Electromagnetic Calorimeter (ECAL) of the Compact Muon Solenoid (CMS) experiment at the LHC is a hermetic, fine grained, homogeneous calorimeter, containing 75,848 lead tungstate scintillating crystals. We highlight the key role of the ECAL in the discovery and elucidation of the Standard Model Higgs boson during LHC Run I. We discuss, with reference to specific examples from LHC Run I, the challenges of operating a crystal calorimeter at a hadron collider. Particular successes, chiefly in terms of achieving and maintaining the required detector energy resolution in the harsh radiation environment of the LHC, are described. The prospects for LHC Run II (starting in 2015) are discussed, building upon the experience gained from Run I. The high luminosity upgrade of the LHC (HL-LHC) is expected to be operational from about 2025 to 2035 and will provide instantaneous and integrated luminosities of around $5 \times 10^{34} / cm^2 / s$ and 3000/fb respectively. We outline the challenges that ECAL will face and motivate the evolution of the detector that is thought to be necessary to maintain its performance throughout LHC and High-Luminosity LHC operation.

1. Introduction
The CMS detector [1] is a multipurpose particle physics experiment at the CERN Large Hadron collider (LHC) optimized to investigate electroweak symmetry breaking via the search of the standard model (SM) Higgs boson.

The performance of the high resolution CMS electromagnetic calorimeter is important because electrons and photons are essential ingredients in at least three of the Higgs boson decays channels: $H \rightarrow \gamma \gamma, H \rightarrow ZZ^{(*)} \rightarrow 4e \pm, H \rightarrow WW^{(*)} \rightarrow e\nu e\nu$. The key physics channel driving the design of the CMS electromagnetic calorimeter (ECAL) was $H \rightarrow \gamma \gamma$. This decay mode is the most sensitive for a low mass SM Higgs boson ($m_H < 150$ GeV). The branching ratio is very small, $\approx 0.002$ but the signature is clean: a narrow resonance of two high transverse energy ($E_T$) photons over a non resonant background of di-photon events [2]. The large irreducible background originates from the QCD production of two photons while the reducible part comes from events in which at least one of the photons originates from misidentification of jet fragments.

The discovery potential increases with the instrumental invariant mass resolution and background rejection. This translates to a need for efficient photons and electrons identification, high energy and position resolution. The width of the diphoton resonance of a SM Higgs boson is totally dominated by the instrumental invariant mass resolution of the electromagnetic calorimeter. The ECAL design requirements were:

- Excellent energy and position/angle resolution up to $|\eta| < 2.5$, to match the tracker coverage.
• Hermeticity, compactness and high granularity
• Fast response (∼25 ns) and particle id, energy and isolation measurement at trigger level
• Large dynamic range (5 GeV to 5 TeV) and excellent linearity (at the per-mill level)
• Radiation tolerance (ECAL was designed for 14 TeV and $L = 10^{34}$ cm$^{-2}$ s$^{-1}$, and for a total luminosity of 500/fb)

In the following we discuss the challenges of operating the CMS electromagnetic crystal calorimeter at a hadron collider, in particular in achieving and maintaining the required energy resolution in the harsh radiation environment of the LHC. We summarise the role of ECAL in the discovery of the Higgs boson. We also present the prospect for the LHC Run II starting in 2015 and the challenges that ECAL will face with the High Luminosity (HL) upgrade of LHC, based on the experience gained during Run I.

2. The CMS electromagnetic calorimeter
The CMS electromagnetic calorimeter (ECAL) [3] (see Fig. 1) is a hermetic, homogeneous, fine grained lead tungstate (PbWO$_4$) crystal calorimeter. The choice of an homogeneous medium was made to obtain a better energy resolution by minimizing sampling fluctuations [4]. Very dense crystals offer the potential to achieve the required excellent performance and compactness. The CMS design enabled the electromagnetic calorimeter to fit within the volume of the CMS superconducting solenoid magnet.

The 75,848 crystals are arranged in a central barrel section (EB), with pseudorapidity coverage up to $|\eta|=1.48$, closed by two endcaps (EE), extending coverage up to $|\eta|=3.0$. Crystals are projective and positioned slightly off-pointing (∼3°) relative to the interaction point (IP) to avoid cracks aligned with particle trajectories. The calorimeter has no longitudinal segmentation, the measurement of the photon angle relies on the primary vertex reconstruction from the silicon tracker.

The crystal length in EB is 230 mm (220 mm in EE) corresponding to ∼26 (25) radiation lengths. The transverse size of the crystals at the front face is 2.2×2.2 cm$^2$ in EB (2.86×2.86 cm$^2$ in EE). The total crystal volume is 11 m$^3$ and the weight is 92 t. The barrel calorimeter is organized into 36 supermodules each containing 1,700 crystals while the endcaps consist of two dees, with 3,662 crystals each.

A preshower detector (ES), based on lead absorber and silicon strips sensors (4,288 sensors, 137,216 strips, 1.90×61 mm$^2$ with x-y view), placed in front of the endcaps at 1.65 < $|\eta|$ <2.6, improves the photon-π$^0$ separation. The total thickness of the ES is ∼3 radiation lengths.

![Figure 1. Schematic view of the CMS electromagnetic calorimeter.](image-url)
2.1. Crystal properties

The main features of $\text{PbWO}_4$ scintillating crystals are high density (\(\delta = 8.28 \text{ g/cm}^3\)), extremely short radiation length and small Molière radius (\(X_0 = 0.85 \text{ cm}\), \(R_M = 2.19 \text{ cm}\)), allowing the realization of a homogeneous compact calorimeter with high granularity. It produces fast signals, 80% of the light is emitted in 25 ns. This is important since the LHC collision rate is 40 MHz. The light emission peak is at \(\sim 420 \text{ nm}\). The crystals are transparent to their entire scintillation emission spectrum.

The major drawbacks are: the reduced light yield (LY), only \(\sim 100\) photons per MeV for a 23 cm long crystal, that requires the use of a photodetector readout system with internal gain; a strong light yield dependence on temperature (\(\Delta \text{LY}/\Delta T = -2\%/\degree\text{C}\) at \(\sim 18\degree\text{C}\)) which imposes a requirement on temperature stability of \(\pm 0.05\degree\text{C}\) in EB.

Most of the crystals were produced (\(\sim 10,000\) crystals/year) in Russia (Bogoroditsk Techno-Chemical plant) with a small contribution from China (Shanghai Institute of Ceramics).

The energy, position and time resolution of arrays of crystals have been throughly studied at beam tests with no magnetic field, no material upstream of the crystals, no radiation damage, and a negligible channel response variation. The obtained energy resolution, for central impact of electrons on a 3 $\times$ 3 crystal array, has a stochastic, a noise and a constant term \([5]\): \(\sigma_E/E = 2.8%\sqrt{E} + 0.128 \text{ GeV/E} + 0.3\%\) where \(E\) is measured in GeV. The constant term is dominated by the longitudinal non-uniformity of light collection. Material upstream of ECAL can result in photon conversion and electron Bremsstrahlung that can both affect all terms in the energy resolution. The CMS goal was to achieve a constant term below 1\% \([6]\).

The time resolution is also excellent (\(<100\) ps for \(E > 20\) GeV) and has been measured at beam tests using the time difference between adjacent crystals belonging to the same electromagnetic shower. The ECAL time information can be exploited as an alternative method to determine the position of the primary vertex in events with low track multiplicity (see talk by Daniele Del Re at this conference).

![Figure 2. ECAL Front-End electronic chain.](image)

2.2. Photodetectors and electronics readout chain

For the purposes of light collection the crystals are equipped in the barrel with Hamamatsu avalanche photodiodes (APD, two for each crystal, 5$\times$5 mm$^2$ each, 75\% Q.E) read in parallel. The gain is set at \(\sim 50\) and they are insensitive to the 4T magnetic field. In the endcap region the scintillation light from each crystal is readout by vacuum photo-triodes (VPT, 280 mm$^2$, 20\% Q.E.). The gain is set at \(\sim 10\) and they operate in a magnetic field almost parallel to their axis. The gain of the APDs is sensitive to temperature (-2.3 \% \degree C). The temperature dependence of the VPT response is assumed to be negligible relative to the temperature sensitivity of the crystals. Accordingly a less stringent temperature stability requirement of 0.1\degree C is assumed for the endcap dees.
To provide the desired resolution over the full energy range of signal events, the readout system measures energies over a wide dynamic range (between 50 MeV and 2 TeV); it is fast to minimize event pile-up, has low power consumption and uses radiation hard components. In order to minimize external noise contributions most of the readout chain is mounted directly on the detector. This has also the advantage of reducing the number of Gigabit optical links to the off-detector readout. The On-detector electronics (see Fig. 2) has been designed to read 5x5 crystals, forming a trigger-tower in the EB (a super-crystal in EE). In the VFE cards (Very Front End) the signals from photodetectors are pre-amplified and shaped by an ASIC Multi Gain Pre-Amplifier chip which consists of three parallel amplification stages with nominal gain 1, 6 and 12. Each of the three analog outputs are digitized in parallel by a multi channel 40 MHz, 12 bit ADC, with an integrated logic that selects the highest not saturated signal.

A time window of 10 samples is readout for every L1 Trigger. From the ten time samples we reconstruct (Fig. 3) the pedestal $P$, the signal amplitude $A$, and the time at the maximum $T_{\text{max}}$ using a digital filtering technique, weights, fit and ratio methods. We subtract $P$ on an event by event basis. The electronic noise is about 40 MeV/channel in EB.

Trigger primitives are generated from the summed amplitudes of 25 crystals in the FE (Front End) cards and sent to the Off-detector electronics. Electrons and photon candidates are formed at L1 by summing $E_T$ in adjacent trigger towers.

All front-end ASICs were developed in 0.25 $\mu$m technology, which is intrinsically radiation hard (see also talks by Jean-Baptiste Sauvan and by Philippe Gras at this conference).

3. ECAL operation and environmental stability

CMS is a complex experiment with $\sim$100M readout channels; nevertheless during collisions about 98% of the CMS total channels have been operational. The ECAL detector has been stably and efficiently running with very few single dead channels (99.1% active channels in EB, 98.4% in EE, 96.8% in ES), with little evolution in their number, and causing less than 1% downtime. This is a very good result for a detector that has no intrinsic redundancy. This has been possible due to the continuous work of a relatively small number of scientists, whose constant dedication has allowed ECAL and the CMS experiment to outperform any expectation. A number of bad channels with low voltage supply problems have been fixed in the current long LHC shutdown period.

Fluctuations in temperature affect the LY of the crystals and the APD gain. A cooling system maintains the environmental temperature to be stable within specifications: $\Delta T < 0.02^\circ C$ in EB ($< 0.05^\circ C$ in EE) [7]. Also the stability of the bias voltages has been within specifications. The contribution of environmental instabilities to the energy resolution constant term has been below 0.1%.

3.1. ECAL trigger

The single-photon L1 Trigger has been continuously operated unprescaled, with a low threshold ($E_T=15$ GeV) and with an efficiency $>99\%$ for photons relevant for the $H \rightarrow \gamma\gamma$ analysis (leading photons with $E_T > 33$ GeV). This result has been possible following the implementation of the online rejection of spikes (anomalous isolated energy deposits caused by direct ionization of the APD sensitive volume [8]). If untreated, these would cause the eventual saturation of the bandwidth assigned to electron and photon triggers in CMS. Thanks to the flexibility of the front end electronics, we are able to suppress the spike contribution to the L1 trigger by a coarse analysis of the lateral energy deposit inside each trigger tower. The spike rejection obtained is 96% maintaining a trigger efficiency for electrons and photons of 99%.

The timing cut and a simple shower-shape algorithm is applied on the anomalous signals surviving the L1 Trigger at the next High Level Trigger (HLT).
3.2. ECAL response variation and corrections

The ECAL crystal response varies under irradiation due to the formation of colour centers that absorb the light and reduce the transparency of the $\text{PbWO}_4$ (we have no evidence yet of damage to the scintillation mechanism itself). This damage is partially recovered in a few hours at room temperature (thermal annealing of the colour centers). Damage and recovery during LHC cycles are monitored by laser light injected, during the LHC orbit gaps, into each crystal, through optical quartz fibres [9]. Blue light (447 nm) is used while infrared and green light provide complementary measurements at other wavelengths. An optical switch directs light to one half-supermodule or one quarter-Dee in turn. A complete cycle takes $\sim 45$ min. The laser light is also injected into PN diodes to follow the laser pulse to pulse variations with an accuracy of 0.1%. ECAL signals are compared and normalized, event by event, to the reference PN diodes. The resulting transparency corrections (see section 4) are ready for prompt reconstruction in less than 48 hours.

Fig. 4 shows the relative response variation measured by the laser monitoring system in 2011 and 2012 (Run I). The response is averaged in various pseudorapidity intervals. The LHC instantaneous luminosity varied from $10^{33}\text{cm}^{-2}\text{s}^{-1}$ in April 2011 to $7 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ at the end of 2012. Damage and recovery during LHC cycles is evident and the crystal transparency correction plays a crucial role in particular for the crystals in the endcaps. The observed response change is from 6% (in EB) to 70% (in EE). We observe steady recovery during the low luminosity Heavy Ions run (November 2012) and in periods without beam. During the present LHC shutdown we are following the transparency recovery taking data whenever possible.

The corrections validity is checked regularly using i.e. electrons from W decays (Fig. 5).
In 2012 we applied weekly transparency corrections at L1 and HLT to account for the response loss observed in the endcaps and to keep constant the trigger energy thresholds. See Fig. 6. In 2015 this will be extended also to the barrel because of the expected increase in LHC luminosity ($1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$).

Secondary irradiation effects are: the slow increase of leakage current, and therefore noise, due to bulk damage in the ES sensors [10] and in the APDs and a small reduction of signal due to the conditioning of the VPT photocathodes.

4. Energy reconstruction and energy resolution

In the CMS calorimeter the crystal lateral dimensions are comparable to the Molière radius. Therefore the electron and photon electromagnetic shower energy is deposited over several crystals especially if the photons/electrons interact in the upstream tracker material.

Clustering and containment corrections are fundamental to reconstruct the particle’s original energy. Energy deposits are spread due to secondary emission (Bremsstrahlung and conversions) in the tracker material and distributed along $\phi$ by the intense CMS magnetic field. The clustering algorithm therefore uses a dynamic window in $\phi$ to form Superclusters [11] (see Fig. 7).

To obtain the most accurate estimate of electron and photon energy in a Supercluster of crystals we use the following formula:

$$E_{e/\gamma} = F_{e/\gamma} \ G \ \Sigma_i S_i(t) \ C_i \ A_i + E_{ES}$$

where the factors for the absolute energy calibration and related corrections are: $G$, the absolute energy scale factor (GeV/ADC count) and $F_{e/\gamma}$, the energy containment corrections (depending on the particle kind, geometry, clustering, upstream material). The factors related to the equalization of channel response are: $A_i$, the single channel amplitude (in ADC counts); $C_i$, the inter-crystal calibration coefficient; and $S_i$, the correction for time-dependent response variations (or crystal transparency correction).

After applying the Supercluster algorithm, the energy of the e/$\gamma$ candidate is estimated from the sum over the index $i$ of the signal amplitudes ($A_i$) of the individual crystals in the Supercluster, weighted with the channel dependent coefficients to correct for time response variation ($S_i$), to equalize the channel response ($C_i$), to calibrate the ADC to energy conversion ($G$) and to correct for imperfect clustering and geometric effects ($F_{e/\gamma}$). For EE clusters the preshower energy is also added ($E_{ES}$).
Fig. 8 shows the impact of the clusterisation process on the $Z \rightarrow e^+e^-$ energy scale and resolution from the incorporation of more sophisticated clustering and energy containment correction algorithms in EB and in EE: using fixed 5×5 crystals arrays, then the raw Supercluster energy and then including the $F_e$ correction.

The invariant mass of electron pairs from $Z \rightarrow e^+e^-$ at different levels of energy reconstruction is shown in Fig. 9: with both electrons in EB for the left plot (in EE, right plot) without any correction (violet), without time-dependent corrections $S_i$ (red) and with all corrections (blue).

Fig. 10 shows the stability of the resolution measured from $Z \rightarrow e^+e^-$ events in the endcaps as a function of time. The re-reconstruction of data, following a calibration based on the full
The variable \( R_9 = E_{3 \times 3}/E_{SC} \) defined as the ratio of the energy in a simple \( 3 \times 3 \) array of crystals to the energy in the Supercluster is used to identify electrons with little radiation in the tracker or unconverted photons. According to MC, \( \sim 70\% \) of the photons with \( R_9 > 0.94 \) are truly unconverted while all the photons with \( R_9 < 0.94 \) converted upstream of ECAL.

We derive electron energy resolution from the \( Z \rightarrow e^+e^- \) peak width. The quantity \( \sigma_e/E \) is extracted, in \( \eta/R_9 \) bins, from an unbinned maximum likelihood fit to the invariant mass distribution of \( e^+e^- \) pairs. The result for electrons with \( R_9 > 0.94 \) is given in Fig. 11. The energy resolution is better than 2\% for \( |\eta| < 0.8 \) and between 2\% and 5\% elsewhere. The impact on the resolution from the material upstream of ECAL is particularly evident at \( \eta > 1 \).

Resolution is also degraded near detector cracks between ECAL modules (vertical lines in the plot). The differences between data (in blue) and MC (in red) come from various effects not yet perfectly simulated (such as imperfect description of the upstream material). The amount of material in front of ECAL is shown in Fig. 12. Fig. 13 shows the energy corrections as a function of \( \eta \) for different intervals of \( R_9 \).

The resolution of the MC used for the \( H \rightarrow \gamma\gamma \) analysis has been tuned to match the data for different \( R_9 \) categories by adding an extra smearing term.

![Figure 12. Material in front of ECAL as a function of \( \eta \).](image1.png)

![Figure 13. \( W \rightarrow e\nu \) electron candidates. Particle energy corrections as a function of \( \eta \) in different intervals of \( R_9 \).](image2.png)

Calibrations procedure exploits different samples of events to intercalibrate, verify and tune monitoring and algorithmic corrections. For more details see talk by Alessio Ghezzi at this conference.

### 5. Role of ECAL in the Higgs discovery

On 4\textsuperscript{th} July 2012 the CMS and the ATLAS collaboration announced the observation of a new particle, consistent with the SM Higgs boson, at a mass around 125 GeV [12] [13]. Five channels had been examined by CMS: \( H \rightarrow \gamma\gamma, H \rightarrow ZZ^{(*)} \rightarrow 4 \) leptons, \( H \rightarrow WW^{(*)}, H \rightarrow bb, H \rightarrow tt \), all critically dependent on ECAL.

The first two modes are the so called \textit{golden modes} and have been used to extract the best and most recent measurement by CMS of the boson mass \( M_{Higgs} = 125.7 \pm 0.3_{\text{stat}} \pm 0.3_{\text{syst}} \) GeV. The 68\% confidence level contour plot of the Higgs mass estimation versus signal strength from the two golden modes and their combination is shown in Fig. 14. The decay rates are consistent with the SM predictions.
5.1. The ECAL benchmark search channel: $H \rightarrow \gamma \gamma$

The experimental signature is a small narrow excess of events in the $M_{\gamma 1 \gamma 2}$ invariant mass spectrum on a large falling background:

$$M_{\gamma 1 \gamma 2} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1 - \cos \theta_{\gamma 1 \gamma 2})}$$

The search for the Higgs boson through its two photon decay channel depends on identifying efficiently the two photons, measuring accurately their energies and their relative opening angle.

In two photon events an important contribution to the invariant mass resolution comes from the resolution of the opening angle between the two photons. ECAL has no longitudinal segmentation and the photon direction is obtained from the shower position and the identification of the interaction vertex (IP).

The large length of the interaction region (∼6 cm) would lead to a large uncertainty on the photon direction (see Fig. 15). But Higgs are produced in association with tracks from underlying events, initial state gluon radiation etc. The efficiency of correct assignment of the IP vertex, within 1 cm of the true vertex, has been estimated with simulation and data samples to be ∼83% for $H \rightarrow \gamma \gamma$ events and close to 100% for events where the two photons have a combined transverse energy $>100$ GeV.

The combined shape of the expected SM Higgs invariant mass distribution for the $\gamma \gamma$ decay channel, estimated using the photon energy resolution is shown in Fig. 16 and Fig. 17 with an invariant mass resolution of 1.76 GeV for data taken at 7 TeV and 1.87 GeV for data taken at 8 TeV, for simulated $M_{Higgs}=120$ GeV and 125 GeV respectively.

Fig. 18 is an event display of a proton-proton collision producing two high energy photons, observed as large and isolated energy deposits in ECAL barrel. The invariant mass is around 125 GeV and the event is a candidate $H \rightarrow \gamma \gamma$ decay.
An excess of events has been seen at a $M_{\gamma\gamma} = 125\text{GeV}/c^2$. Fig. 20 shows the diphoton mass spectrum (Moriond 2013). The signal significance is just over $3\sigma$ but better results available soon. This suggests the presence of a new boson with integer spin, but different from unity.
5.2. $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons

The search for the Higgs boson through its decay to two Z bosons subsequently decaying into 4 leptons (4 muons, 2 muons and 2 electrons, 4 electrons) has a low and well defined background. The 4 electron final state is particularly challenging because the softest electron often has $p_T < 15$ GeV. This is a difficult kinematic region due to the magnetic field and Bremsstrahlung. The tracker improves the ECAL electron energy measurement at very low $p_T$.

Fig. 19 is an event display of a p-p collision producing four high energy electrons, seen as large and isolated energy deposit in ECAL barrel. The invariant mass is around 125 GeV and the event is a candidate $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons decay. An excess of events has been seen in all 4 lepton channels at about $125$ GeV/$c^2$. Fig. 21 shows the four lepton mass spectrum. The signal significance is over $6\sigma$.

6. Future perspectives

So far CMS has collected a total of about $30$ fb$^{-1}$ at 7 TeV in 2011 and at 8 TeV in 2012. Although until now the peak Lumi has been below foreseen maximum ($\sim 7 \times 10^{33}$cm$^{-2}s^{-1}$), the number of collisions per crossing has been higher due to LHC running at 20MHz. The experiments have been performing well and we have already experienced without problems $\sim 80$ reconstructed vertices in a special run in 2012. LHC Run II, that starts in 2015, will be at higher energy ($\sim 13$ TeV) and at an instantaneous luminosity up to $\sim 2 \times 10^{34}$cm$^{-2}s^{-1}$, but, from past experience in Run I, we expect that the ECAL will perform well under these conditions. We expect to collect $\sim 300$ fb$^{-1}$ by the end of nominal LHC operation in 2023.

The High Luminosity LHC (HL-LHC or Phase 2, $\sim 2025$-2035) will provide unprecedented instantaneous ($\sim 5 \times 10^{34}$cm$^{-2}s^{-1}$) and integrated luminosity ($\sim 3000$ fb$^{-1}$). The expected numbers of events per bunch crossing will be $\sim 140$ and radiation levels will be 6 times higher than for the nominal LHC design with a strong $\eta$ dependence in the endcaps.

The lead tungstate crystals forming the EB will still perform well, even after the expected 3000fb$^{-1}$ at the end of HL-LHC. Our main concern is the crystal transparency degradation with the integrated hadron fluence in the endcaps as indicated in Fig. 23. The simulation of the fractional response in EE has been tuned on data from highly irradiated crystals. In the fiducial region used for electron/photon physics ($\eta < 2.5$), at about 500 fb$^{-1}$, the response drop to 10% of the original signal. The reduction of light output causes a progressive deterioration of energy resolution, shown in Fig. 24, and trigger efficiency, with a strong $\eta$ dependence. We therefore plan to replace the ECAL endcaps before the start of HL-LHC.

![Figure 22. Simulation of fractional response from EE as a function of $\eta$, for different integrated luminosities.](image1)

![Figure 23. Deterioration of the energy resolution in EE as a function of $\eta$, for different integrated luminosities.](image2)

The APDs have recently been exposed to the levels of radiation expected at the end of HL-LHC. Although they will continue to be operational, there will be some increase in noise due
to radiation-induced dark current that will require mitigation. Triggering on electromagnetic objects with $\sim$140 pileup events necessitates a change of the front-end electronics. New developments in high-speed optical links will allow single-crystal readout at 40 MHz to upgraded Off-detector processors, allowing maximum flexibility and enhanced triggering possibilities. The VFE system will also be upgraded, to provide improved rejection of anomalous signals in the APDs as well as to mitigate the increase in APD noise. We are also considering lowering the EB operating temperature from 18 degrees C to $\sim$80C, in order to increase the scintillation light output and reduce the APD dark current.

For the Endcap Calorimetry upgrade two conceptual designs are currently being considered: an e.m. calorimeter built with a Shashlik design and a finely segmented calorimeter (a la CALICE). Both approaches require significant R&D and extensive studies.

For details see talks by Burak Bilki, Milena Quittnat and Alexey Drozdetskiy at this conference.

7. Conclusions

The CMS electromagnetic calorimeter meets the high expectations of the CMS design. A new boson has been discovered in the decay channels $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ(\ast) \rightarrow 4$ leptons with significant contributions from ECAL. The excellent resolution achieved in the ECAL barrel drives the sensitivity for $H \rightarrow \gamma\gamma$ (1% di-photon mass resolution for unconverted photons in the center of the barrel).

Work is ongoing to further optimise the calibration and time-dependent response corrections, and we expect that the ECAL will continue to perform well during the upcoming LHC Run II. A better understanding of systematic effects, such as local containment fluctuations and the effects of upstream material, is leading to a closer agreement between data and simulation.

The HL-LHC will impose severe requirements on the performance and radiation tolerance of the detectors. The ECAL barrel will remain performant up to 3000 fb$^{-1}$, following planned modifications to the front-end electronics (FE electronics, increase granularity of L1 trigger processors, 40 MHz data stream readout, VFE with faster shaping time, cooling). The endcaps will need to be replaced prior to HL-LHC to enable the full exploitation of the HL-LHC physics potential. The ECAL barrel will perform up to 3000 fb$^{-1}$ with some upgrade (FE electronics, increase granularity of L1 trigger processors, 40 MHz data stream, VFE with faster shaping time, cooling). The endcaps will work until 500 fb$^{-1}$ but they need to be replaced to enable full exploitation of the HL-LHC potential.

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