Triggering on electrons and photons with the CMS experiment at the LHC

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Abstract. Throughout the year 2011, the Large Hadron Collider (LHC) has operated with an instantaneous luminosity that has risen continually to around $4 \times 10^{33}$ cm$^{-2}$s$^{-1}$. With this prodigious high-energy proton collisions rate, efficient triggering on electrons and photons has become a major challenge for the LHC experiments. The Compact Muon Solenoid (CMS) experiment implements a sophisticated two-level online selection system that achieves a rejection factor of nearly $10^6$. The first level (L1) is based on coarse information coming from the calorimeters and the muon detectors while the High-Level Trigger (HLT) combines fine-grain information from all sub-detectors. In this intense hadronic environment, the L1 electron/photon trigger provides a powerful tool to select interesting events. It is based upon information from the Electromagnetic Calorimeter (ECAL), a high-resolution detector comprising 75848 lead tungstate (PbWO$_4$) crystals in a “barrel” and two “endcaps”. The performance as well as the optimization of the electron/photon trigger are presented.

1. Introduction
The CMS detector has been designed to study proton-proton and heavy ion collisions produced by the LHC, to search for new particles and physics processes [1]. From the millions of collisions produced per second only 300 events per second can be stored offline. The search for new physics crucially relies on the trigger system performance used to select them [2]. The CMS trigger system is organised in two consecutives steps [3]: the L1 trigger utilizes coarse energy deposits in the calorimeters and signals in the muon systems to reduce the rate from about 20 MHz to 100 kHz; this followed by the HLT, implementing selection algorithms (in commercial computers) based on finer granularity and higher resolution information from all sub-detectors in regions of interest identified at L1 (output rate about 300 Hz). The CMS ECAL provides a precise measurement of the energies and positions of incident electrons and photons for both triggering and offline analysis purposes. The energy measured by the hadronic calorimeter (HCAL) is used to help identify and isolate electromagnetic signals. A set of configuration parameters enables the performance of the electron/photon trigger to be optimized for the wide range of luminosities experienced at the LHC.

2. From ECAL to the Level-1 trigger
2.1. ECAL and the trigger primitive generation
The CMS ECAL, composed of a Barrel (EB) and two Endcaps (EE), comprises 75848 lead tungstate (PbWO$_4$) scintillating crystals equipped with avalanche photodiode (APD) or vacuum...
2.2. Electron/Photon trigger path and algorithm
The TCCs [4] transmit groups of TPs to the Regional Calorimeter Trigger (RCT), which in turn combines pairs of TPs into L1 trigger candidates in each region of interest (4 × 4 TT). The Global Calorimeter Trigger (GCT) then sends the four most energetic candidates to the Global Trigger (GT), which generates the final L1 decision by applying $E_T$ threshold cuts (named EG thresholds in the case of ECAL-based candidates). The electron/photon algorithm is based on a 3 × 3 trigger tower sliding window as shown in Figure 1. The $E_T$ of an electron/photon candidate corresponds to the central TP of the sliding window summed with the largest deposit in one of its 4 adjacent towers. Electromagnetic showers are characterized by a compact lateral extension: candidates must have their central tower containing 2 adjacent strips with a significant fraction of the tower $E_T$ (typically 90%). This criterion is characterized by the Fine Grain (FG) veto bit that is enabled only for candidates with $E_T > 4$ GeV. Moreover, the associated HCAL energy contribution is required to be below a threshold (typically H/E < 5% only for the central tower and for candidates with $E_T > 2$ GeV). Non-isolated electron/photon candidates must pass these criteria. In addition, isolated candidates must have a quiet neighbourhood characterized by at least five adjacent TT among the 8 nearest ones with their $E_T$ below 3.5 GeV.
3. Online anomalous signals and their suppression
Anomalous signals were observed in the EB shortly after collisions began in the LHC: these were identified as being due to direct ionization within the APDs, thus producing fake isolated signals, with high apparent energy. These “spikes” can induce large trigger rates at both L1 and HLT if not removed from the trigger decision. On average, one spike with $E_T > 3$ GeV is observed per 370 minimum bias triggers in CMS at $\sqrt{s} = 7$ TeV. If untreated, 60% of the EG trigger candidates, above a threshold of 12 GeV, would be caused by spikes. At high luminosity these would be the dominant component of the 100 kHz CMS L1 trigger rate bandwidth [5].

3.1. Spike identification and removal
In the CMS ECAL the energy of an electromagnetic (EM) shower is distributed over several crystals, with up to 80% of the energy in a central crystal (where the electron/photon is incident) and most of the remaining energy in the four adjacent crystals. This lateral distribution can be used to discriminate spikes from EM signals. A “Swiss-cross” topological variable $s = 1 - E_4/E_1$ ($E_1$ : $E_T$ of the central crystal; $E_4$ : summed $E_T$ of the 4 adjacent crystals) has been implemented offline to serve this purpose. A similar topological variable has also been developed for the on-detector electronics: the “strip Fine Grain Veto Bit” (sFGVB). Every TP has an associated sFGVB that is set to 1 (signifying a true EM energy deposit) if any of its 5 constituent strips has at least two crystals with $E_T$ above a programmable “sFGVB threshold”, of the order of a few hundred MeV. If the sFGVB is set to zero, and the trigger tower $E_T$ is greater than a “killing threshold”, the energy deposition is considered spike-like. The trigger tower energy is set to zero and the tower will not contribute to the triggering of CMS for the corresponding event.

3.2. Optimisation of the online spike removal algorithm
As the sFGVB threshold is a single value, the electron/photon efficiency depends upon the particle energy: the higher the threshold, the more low-energy real EM deposits would be initially flagged as spikes. However, these fake spikes may not pass the killing threshold so they would still be accepted. With a very low sFGVB threshold, spikes could be accepted due to neighbouring crystals having noise. A detailed emulation of the full L1 chain has been developed in order to optimize the two thresholds to remove as large a fraction of the anomalous signals as possible whilst maintaining excellent efficiency for real electron/photon signals.

In order to determine the removal efficiency, data were taken in 2010 without the killing thresholds active. Spike signals identified offline (with the “Swiss cross”) were then matched to L1 candidates in the corresponding RCT region and the emulator used to evaluate the fraction of L1 candidates that would have been eliminated. In a similar fashion the efficiency for triggering on real electrons/photons could be estimated.

Three killing thresholds have been emulated ($E_T = 8, 12, 18$ GeV), combined with six sFGVB thresholds (152, 258, 289, 350, 456, 608 MeV). Figure 2 shows the electron efficiency (fraction of electrons triggered after spike removal) versus the L1 spike rejection fraction, for all sFGVB thresholds mentioned above (one point for each threshold value) and a killing threshold of 8 GeV. The optimum configuration was chosen to be an sFGVB threshold of 258 MeV and a killing threshold of 8 GeV. This corresponds to a rejection of 96% of the spikes, whilst maintaining a trigger efficiency for electrons above 98%. With these thresholds the efficiency for higher energy electrons is even larger: 99.6% for electrons with $E_T > 20$ GeV.

Table 1 summarises the rate reduction factors obtained for L1 EG algorithms considering the working point discussed above. This optimized configuration was tested online at the beginning of 2011. It gave a rate reduction factor of about 3 (for an EG threshold of 12 GeV), and up to a factor of 10 for $E_T$ sum triggers (which calculate the total EM energy in the whole calorimeter system).
Figure 2. Electron efficiency as a function of the spike rejection at L1. Each point corresponds to a different spike removal “sFGVB” threshold. The “killing threshold” is set to 8 GeV).

Figure 3. Fraction of spike-induced EG triggers as a function of the number of reconstructed vertices for the 2011B data (triangles) and High pileup runs (squares). The red points represent the spike removal working point used in 2011 and the green points the optimized working point for 2012.

Table 1. Rate reduction factors obtained for L1 EG algorithms considering a 258 MeV sFGVB threshold and an 8 GeV killing threshold on the Ecal Trigger Primitives.

| EG Threshold (GeV) | 12  | 15  | 20  | 30  |
|--------------------|-----|-----|-----|-----|
| Rate reduction factors | 3.4 | 4.3 | 6.0 | 9.6 |

4. Level-1 electron/photon trigger efficiency

The trigger efficiency has been measured with electrons from $Z \rightarrow \text{ee}$ events, using a tag and probe method. The dataset represents the full 4.98 fb$^{-1}$ collected in 2011. Both the tag and the probe are required to pass tight identification cuts in order to reduce significantly the background contamination. The tag electron must also trigger the event at L1 while the probe electron is used for the efficiency studies. The invariant mass of the tag and probe system should be consistent with the Z boson mass ($60 \text{ GeV}/c^2 < M_{ee} < 120 \text{ GeV}/c^2$). This approach results in a pure unbiased electron sample. The trigger efficiency is given by the fraction of probes above a given EG threshold, as a function of the probe $E_T$. In order to trigger, the location of the highest energy TT within the electron supercluster must match a corresponding region of an L1 candidate in the RCT.

The trigger efficiency curves are shown in Figure 4 for an EG threshold of 15 GeV. The $E_T$ on the x-axis is obtained from the fully reconstructed offline energy. In the EE this includes the preshower energy that is not available at L1. As a consequence the trigger efficiency turn-on point for the EE is shifted to the right with respect to the EB. For both EB and EE, corrections for crystal transparency changes were not included at L1 in 2011, which further affects the turn-on curve (section 5.2). The width of the turn-on curves is partly determined by the coarse trigger granularity, since only pairs of TTs are available for the formation of L1 candidates, which leads to lower energy resolution at L1. An unbinned likelihood fit has been used to derive the efficiency curves. Parameters of the turn-on curves are given in Table 2.
Figure 4. Electron trigger efficiency at L1 ("EG" threshold : 15 GeV $E_T$), as a function of $E_T$ for electrons in the EB (black dots) and EE (red dots).

Table 2. L1 electron trigger turn-on curve parameters. This table gives the electron $E_T$ thresholds for which an efficiency of 50 %, 95 % and 99 % are reached for EB and EE separately. The last entry corresponds to the efficiency obtained at the plateau of each curve shown on Figure 4.

| EG15 | EB       | EE       |
|------|----------|----------|
| 50%  | $16.06^{+0.01}_{-0.01}$ GeV | $19.05^{+0.05}_{-0.06}$ GeV |
| 95%  | $22.46^{+0.07}_{-0.07}$ GeV | $27.06^{+0.58}_{-0.43}$ GeV |
| 99%  | $28.04^{+0.10}_{-0.10}$ GeV | $34.57^{+1.48}_{-1.10}$ GeV |
| 100 GeV | $99.95^{+0.01}_{-0.88}$ % | $99.84^{+0.10}_{-0.28}$ % |

Figure 5. EE L1 electron triggering efficiency before (red) and after (green) laser transparency corrections are applied at the ECAL TP level.

Table 3. EE L1 electron trigger turn-on curve parameters. This table gives the electron $E_T$ thresholds for which an efficiency of 50 %, 95 % and 99 % are reached before and after laser corrections applied. The last entry corresponds to the efficiency obtained at the plateau of each curve shown on Figure 5.

| EG15 | EE       | EE (corr) |
|------|----------|-----------|
| 50%  | $19.11^{+0.03}_{-0.06}$ GeV | $17.79^{+0.03}_{-0.06}$ GeV |
| 95%  | $27.05^{+0.01}_{-0.01}$ GeV | $24.46^{+0.10}_{-0.23}$ GeV |
| 99%  | $34.36^{+0.01}_{-0.01}$ GeV | $30.78^{+0.21}_{-0.48}$ GeV |
| 100 GeV | $99.84^{+0.01}_{-0.60}$ % | $99.89^{+0.01}_{-0.67}$ % |

In the EE the material budget in front of the detector causes more bremsstrahlung which, together with the more complex TT geometry, causes the turn-on curve to be wider than that for the EB. Some masked or faulty regions (0.2% in EB and 1.3% in EE) result in the plateaus being slightly lower than 100% (99.95 % in EB and 99.84 % in EE) – Table 2. The effect on efficiency of the L1 spike removal has been verified to be negligible, but this will require further optimization as the number of collisions per bunch crossing increases in the future (section 5.1).

5. Further optimization of the electron and photon trigger
The full dataset recorded in 2011 has been used to study the effect of pileup on the spike removal procedure, the impact of crystal transparency changes on the trigger efficiency as well as the implementation of a new L1 EG calibration.
5.1. Spike removal optimisation for higher pileup
At the end of 2011 the pileup had reached a maximum of about 40, with an average around 25, exceeding the original design criteria of CMS. This is expected to increase throughout 2012. Efficient identification of EM showers at trigger level becomes more and more challenging. As pileup events act as noise in the calorimeter, they can degrade trigger object resolution and reduce the probability to observe isolated spikes. The fraction of spike-induced EG triggers has been measured as a function of the number of vertices (roughly equivalent to the number of pileup events) in Figure 3. The fraction of spike-induced EG triggers reaches 10% for collisions including more than 20 pileup events (red points). Using the L1 trigger emulator, a more efficient working point (sFGVB threshold=350 MeV, killing threshold = 12 GeV) for the spike removal algorithm reduces this fraction to 6% (green points), but still preserves the same high efficiency for real electrons and photons.

5.2. Mitigation of crystal transparency changes at the trigger level
Under irradiation the ECAL crystals lose some of their transparency, part of which is recovered when the radiation stops (between LHC fills, for example). The effect of this is that the response of the ECAL varies with time. This is mitigated by the use of a sophisticated laser system that frequently monitors the transparency of each crystal [6] and allows offline corrections to the measured energies to be made [7]. In 2011 the levels of radiation in ECAL were quite small, especially in the EB, but improvements in L1 efficiency could be made if corrections to the TT energies had been included, to reflect the changes in response. Figure 5 shows the improved turn-on curve for the EE if corrections had been included at L1 in 2011, while Table 3 summarizes the parameters of the turn-on curves and compares them with the actual EE turn-on curve in 2011 (Figure 4). From 2012 the corrections to the TT energies are calculated on a weekly basis and applied at L1 in order to keep the high trigger efficiency and low triggering threshold energies.

5.3. Implementing a Level-1 $E_T$ calibration
At the RCT level, input TPs are corrected by a calibration factor before being summed to form L1 candidates. The calibration factors are $\eta$ dependent they are intended to correct for material effects upstream of ECAL (Section 4). Figure 6 shows the calibration factors used during the 2011 data taking period. They were obtained by compiling the ratio of the offline reconstructed electron $E_T$ with its L1 $E_T$ counterpart as a function of $\eta$ using simulated $Z \rightarrow ee$ events. The same matching procedure used in Section 4 was implemented here. The introduction of these corrections had the effect of sharpening the efficiency curves and moving the turn-on points closer to the actual EG algorithm thresholds. Using the full 2011 dataset, new RCT calibration factors were derived using the same procedure. Figure 6 shows the new RCT calibration factors obtained after correcting for the transparency change over the duration of the 2011 physics data taking period.

6. Conclusion
The results presented here display excellent overall performance of the electron/photon trigger and demonstrate the flexibility of this system. A reprogramming of the front-end electronics and ECAL TCC has allowed the implementation and optimization of a spike removal algorithm at L1, which rejects a majority of spikes (>96%) whilst having a negligible impact on electron/photon triggering efficiency. Further optimizations were achieved on the spike removal procedure in high pileup conditions, the calibration of the EG candidates as well as the mitigation of the ECAL crystal response change with time. These improvements have been implemented in 2012 in order to guarantee the best possible physics performance.
Figure 6. 2011 L1 EG calibration factors as a function of $\eta$ for $Z\rightarrow ee$ simulated events (blue points). 2012 EG calibration factors (red points) derived from $Z\rightarrow ee$ selected events using the full 2011 dataset. ECAL crystal transparency changes have been corrected at the TP level prior to compute this ratio (Section 5.2).

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