Performance and upgrade of the CMS electron and photon trigger for Run 2

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Abstract. The CMS experiment implements a sophisticated two-level online trigger selection system that achieves a rejection factor of nearly $10^5$. The first level (L1) trigger is based on coarse information coming from the calorimeters and the muon detectors while the high-level trigger combines fine-grain information from all sub-detectors. In the near future the LHC will increase its centre of mass energy to 13 TeV and progressively reach an instantaneous luminosity of $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$. In order to guarantee a successful and ambitious physics program under this challenging environment, the CMS trigger and data acquisition system must be consolidated. In particular the calorimeter L1 trigger hardware and architecture will be changed. The aim is to maintain the current thresholds and improve performance. This programme will be achieved using the $\mu$TCA architecture with fast optical links and latest generation FPGAs. Sophisticated object reconstruction algorithms, as well as online pile-up corrections, are being developed that will make use of these new hardware capabilities. For electron and photon reconstruction and identification, the first version of the new algorithms has been tested against the current algorithms. It shows a reduction of the trigger rate by a factor of two for isolated objects, an improved energy resolution of about 30%, and a position resolution reduced by more than four.

Introduction
The Compact Muon Solenoid (CMS) detector [1] has been designed to study proton–proton and heavy ion collisions produced by the LHC. Only a few hundreds of events per second can be recorded offline and a trigger system is used to select events of interest [2]. The trigger is organised in two stages: the Level-1 (L1) hardware-based trigger reduces the rate to 100 kHz, and the High-Level Trigger (HLT), based on a farm of computers, reduces the rate to 300 to 600 Hz. This system performed extremely well during the Run 1 of the LHC from 2010 to 2012, even with the significant pile-up conditions at the end of the run. After the first long shutdown the LHC will restart in 2015 with an instantaneous luminosity greater than $10^{34} \text{cm}^{-2}\text{s}^{-1}$ and an average number of pile-up events of 45 or higher. To avoid a significant increase in energy thresholds, which would be detrimental for physics, an upgrade of the L1 trigger system is required for Run 2 [3].

In the following, the current electron and photon L1 trigger and the new architecture that is being installed for the Run 2 are presented. Future algorithms for the reconstruction and identification of electrons and photons based on this new architecture are described and their expected performance are shown.
1. Current electron and photon level-1 trigger

The CMS ECAL is composed of a barrel (EB) and two endcaps (EE) and is made of lead tungstate (PbWO$_4$) scintillating crystals. In the EB, matrices of 5 × 5 crystals (in the pseudorapidity ($\eta$) and azimuthal angle ($\phi$) directions) are combined into trigger towers. In the EE, crystals are arranged in a more complicated way due to the X-Y geometry of the detector, but the resulting trigger towers mimic an $\eta/\phi$ layout similar as in the EB. These trigger towers form the basic inputs to the electron and photon L1 trigger. The transverse energies $E_T$ measured by the crystals in a given trigger tower are summed by the front-end electronics into a trigger primitive that is sent to Trigger Concentrator Cards (TCC) situated off-detector.

The TCCs transmit groups of trigger primitives to the Regional Calorimeter Trigger (RCT), which builds and identifies electron and photon candidates (denoted in the following as $e/\gamma$ candidates) formed by pairs of trigger towers. The identification of the candidates is based on:

- the lateral extension of the energy in the most energetic tower (which is compact for electromagnetic showers) that is encoded into a Fine Grain veto bit;
- the associated $E_T$ deposited in the hadronic calorimeter (HCAL) that is required to be small (typically < 5% of the $E_T$ deposited in the ECAL);
- the $E_T$ deposited in the four corners around the candidate, used to separate isolated from non-isolated candidates (isolated candidates must have at least one of the four corners with $E_T < 3.5$ GeV).

Successfully identified candidates are passed to the Global Calorimeter Trigger (GCT) with a regional granularity of 4 × 4 trigger towers (an RCT region of interest). The GCT builds L1 jets as well as global event quantities ($E_T$ sum and missing $E_T$), sorts the $e/\gamma$ candidates, and sends the different calorimetric objects to the Global Trigger (GT). The GT also uses the L1 muon information and decides whether a given event is accepted or not.

2. Architecture of the future calorimeter level-1 trigger for Run 2

A new architecture is needed for Run-2 data taking because of the increased instantaneous luminosity and the greater pile-up. Without improved architecture and reconstruction algorithms, a substantial increase of trigger thresholds would be required by the end of the Run 2. Typically a double-electron trigger, with thresholds of 13 GeV on one leg and 7 GeV on the other leg, was giving a rate of about 5 kHz in 2012 in Run 1. This would increase to about 50 kHz for the expected Run-2 conditions. This is not manageable given the total bandwidth of 100 kHz. Refined algorithms, with improved identification criteria and pile-up corrections, are needed in order to reduce the rates in such conditions while maintaining high signal efficiency and low thresholds. Such algorithms need to view the full calorimeter at the level of trigger towers and require large computing power. These requirements can be fulfilled with higher bandwidth optical links as well as faster and larger Field-Programmable Gate Arrays (FPGAs) compared to the current hardware.

The new calorimeter L1 system [3] is being installed. It is based on $\mu$TCA crates, replacing the current VME crates and offering more bandwidth through external high-speed serial links. The system is composed of two processing layers instrumented with Virtex-7 FPGAs from Xilinx. The first layer is designed for data formatting and pre-processing. The second layer will be used for object reconstruction and identification. Two types of cards form the two layers and are based on the Advanced Mezzanine Cards (AMC) specifications. The cards are optimised for different tasks. The so-called CTP7 layer-1 cards, displayed in Fig. 1 (left), have a regional view of the calorimeter, that can potentially be extended through dedicated connections to the $\mu$TCA backplane allowing data sharing across different calorimeter regions. They are used for pre-processing data that only needs a reduced view of the detector. The so-called MP7 layer-2
cards, displayed in Fig. 1 (right), on the other hand, have access to the full calorimeter at trigger
tower level on single FPGAs via a large number of optical inputs. These cards are suitable for
running algorithms that need a large view of the detector.

Figure 1. The CTP7 (left) and MP7 (right) cards developed for the first and second layers of
the upgraded calorimeter L1 system

The current system will nevertheless be kept, with small changes, in order to be able to run
both the current and upgrade systems in parallel for commissioning the upgrade system. The
current Serial Link Boards (SLB) used to send trigger primitives from the TCCs to the RCT will
be replaced by a new optical version (oSLB) featuring a different configuration with 4.8 Gb/s
on a single link (compared to the 4 \times 1.2 Gb/s for the current copper links). Duplicated optical
outputs will be sent to the RCT and to the first layer of the upgraded system. In order to
accommodate the new optical links, the Receiver Mezzanine (RM) of the RCT will be replaced
by an optical version (oRM).

3. Future algorithms for electrons and photons at level-1
Sophisticated algorithms have been developed based on the capabilities of the new architecture. Improvements with respect to the current electron and photon reconstruction are:

- improved energy reconstruction with a dynamic clustering of trigger towers;
- better position reconstruction, with the tower granularity instead of the granularity of an
  entire RCT region;
- additional discrimination of electrons (or photons) and jets, based on the shape of the
  reconstructed clusters;
- more precise isolation criteria that account for the level of pile-up, without boundaries.

A better containment of the electron and photon energy (in particular for showering electrons
and converted photons) is obtained with dynamic clustering. The maximum size of the clusters
is limited (at most 8 trigger towers can be clustered) in order to minimize the impact of pile-up
energy deposits while including most of the electron or photon energy. An extended region in
the \( \phi \)-direction (at most 5 trigger towers) and a narrow region in the \( \eta \)-direction (at most 2
trigger towers) have been chosen (see Fig. 2 (left)) since electron and photon showers spread mostly along the \( \phi \)-direction due to the magnetic field.

The clusters of towers are built from a seed tower (the red tower on Fig. 2 (left)). The first and second neighbour towers (the orange and yellow towers on Fig. 2 (left)) are dynamically clustered if connected to the seed. The sum of the ECAL \( E_T \) of the seed and clustered towers is taken as the raw \( E_T \) of the cluster. A calibration is applied to this raw energy with factors depending on the \( \eta \)-position of the seed tower. The factors are obtained from \( Z \rightarrow ee \) events and are defined as the ratio of the offline fully reconstructed electron \( E_T \) to the associated raw L1 cluster \( E_T \).

The position of the reconstructed cluster is first taken from the centre of the seed tower. It is then refined, within the seed tower, based on the distribution of energy in the cluster.

This dynamic clustering leads to a large variety of cluster shapes that depend on the distribution of energy around the seed tower. Some cluster shapes are very unlikely to come from an electron or a photon. This is the case for large clusters involving many trigger towers, which probably come from jets. Small clusters (containing typically one to four trigger towers) are more compatible with electron or photon showers. This information, which is not available for a fixed size clustering, brings additional discrimination power between electrons (or photons) and jets.

\[\text{Figure 2.} \] The L1 \( e/\gamma \) clustering and isolation. A candidate is formed by clustering neighbour towers (orange and yellow) if they are linked to the seed tower (red). A candidate is considered as isolated if the \( E_T \) in the isolation region (blue) is smaller than a given value.

The full view of the detector in the second layer of the upgrade L1 calorimeter trigger system presents trigger tower information without boundaries. It is possible to implement more precise isolation criteria that account for the level of pile-up event-by-event. The \( E_T \) deposited in an isolation region as depicted in Fig. 2 (right) is computed. This isolation region has a size of \( 5 \times 9 \) trigger towers excluding the footprint of the \( e/\gamma \) candidate in ECAL (a \( 2 \times 5 \) region) and HCAL (a \( 1 \times 2 \) region). If this \( E_T \) is smaller than a given threshold the candidate is tagged as isolated, and as non-isolated otherwise. The threshold is a function of \( \eta \) and depends on an estimator for the number of pile-up interactions in the event. This pile-up estimator is the number of trigger towers in the event with \( E_T \) greater than a given value. The threshold values are tuned to have a 90% efficiency, constant with pile-up and with \( \eta \).

These algorithms are currently being implemented in firmware. A first version is being tested in the layer-2 cards.
4. Expected performance

The upgrade algorithms are being tested during their development and compared to the current algorithms. The expected performance obtained with an initial version are presented here.

The trigger efficiency is measured with electrons from $Z \rightarrow ee$ events, using a tag and probe method. The dataset is from the 6 fb$^{-1}$ of data collected in the last period of 2012. Both the tag and the probe electrons are required to pass tight identification criteria in order to reduce background contamination to a negligible level. The invariant mass of the dielectron system must be consistent with the $Z$ boson mass ($60 \text{ GeV} < M_{ee} < 120 \text{ GeV}$). The tag electron must trigger the event at L1 while the probe electron is used for efficiency studies. The trigger efficiency is given by the fraction of probes with an associated L1 cluster above a given trigger threshold, as a function of the offline reconstructed probe $E_T$. The efficiency curves for a trigger threshold of 20 GeV (L1_SingleEG20) obtained with the current and upgrade algorithms are shown in Fig. 3, for probe electrons in the EB and in the EE.

![Efficiency Curves](chart.png)

**Figure 3.** Electron trigger efficiency at L1 as a function of the offline reconstructed $E_T$, in the EB (left) and EE (right), for a threshold of 20 GeV. In both cases the efficiencies obtained with the upgrade and current algorithms are shown, without isolation criteria.

The curves corresponding to the upgrade algorithms are steeper, which is a direct consequence of the dynamic clustering. The energy deposited by electrons is better clustered and leads to a better energy measurement of about 30%. In the endcaps, the upgrade improvement comes from a more precise calibration of the upgrade clusters. The EB and EE turn-on curves are now closer to each other.

The better granularity available in the layer-2 of the upgrade L1 system (granularity of trigger towers), compared to the granularity of the current system (granularity of RCT regions), leads to improved spatial location of the L1 $e/\gamma$ candidates. The position measurement, based on the energy distribution in the cluster, is improved by more than a factor of four, as can be seen in Fig. 4 (left).

The new capability of the clustering algorithm to provide shape information, to discriminate between electron (or photon) clusters and jet clusters, reduces the rate of fake electrons and photons with negligible loss of signal efficiency. These rates can be reduced further, with a signal efficiency loss of about 10%, by requiring the candidates to be isolated. In this case a reduction of the rate by a factor of about two is obtained, with respect to the current algorithms,
for similar signal efficiencies. Figure 4 (right) shows the relative rates of triggered events as a function of the offline threshold at which the trigger reaches 95% of the plateau efficiency. The results for the current and upgrade algorithms are shown with and without isolation criteria.

![Graphs showing relative rates of triggered events](image)

**Figure 4.** (Left) The difference in pseudorapidity for L1 electrons with respect to the offline reconstructed pseudorapidity, for the current and upgrade algorithms. (Right) Relative rate of triggered events from 8 TeV minimum bias data for an average pile-up of 45, obtained with the current and the upgrade algorithms, both with and without their respective isolation requirements.

**Conclusion**
An upgrade calorimeter L1 trigger system is being developed for CMS. It will be commissioned in parallel with the current system at the beginning of the Run 2 in 2015, and will be used for physics starting from 2016. This new system is composed of cards based on latest generation FPGAs with high bandwidth optical links. Sophisticated algorithms are being implemented for the reconstruction and identification of electrons and photons at L1 that make use of the improved capabilities of the new system. An initial version of these algorithms brings substantial improvement. The position resolution is improved by more than a factor of four, and the energy resolution is improved by about 30%. A reduction of the trigger rate by a factor of two is obtained for isolated candidates, while maintaining a similar signal efficiency to that for the current isolated candidates.

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