The role of the CMS electron and photon trigger in the study of the Higgs boson and high mass searches

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Abstract. The Compact Muon Solenoid (CMS) experiment implements a sophisticated two-level triggering system composed of the Level-1, instrumented by custom-design hardware boards, and a software High-Level-Trigger. A new Level-1 trigger architecture with improved performance is now being used to maintain the thresholds used in LHC Run I for the more challenging conditions experienced during Run II. We present the performance of the upgraded CMS electron and photon trigger in the context of Higgs boson decays into final states with photons and electrons. The calorimeter trigger system plays a central role in achieving the ambitious physics program of Run II. The upgraded trigger uses the full granularity of the calorimeters to optimally reconstruct and calibrate the electromagnetic trigger objects. It also implements combinations of calorimeter objects to provide new Level-1 quantities such as invariant mass. Optimized software selection techniques have been developed and advanced algorithms to mitigate the impact of event pileup have been implemented. The selection techniques used to trigger efficiently on these benchmark analyses will be presented, along with the strategies employed to guarantee efficient triggering for new resonances and other new physics signals involving electron/photon final states.

1. Introduction
In LHC experiments, a trigger system is mandatory to select events on the fly and reduce the 40 MHz collision rate to a level sustainable by the data acquisition system, typically on the order of 1 kHz. The development of an efficient triggering system represents a real challenge for the LHC Run II in CMS, as its physics program includes a wide variety of processes, from precision physics at the electroweak scale to the search for new physics at very high energy. Due to the high hadronic activity in proton collisions, leptons and photons provide ideal candidates to trigger on. For the trigger system of the CMS experiment, a two-layer implementation has been adopted:

- The Level-1 trigger bases its decision directly on coarse granularity detector readout. Its implementation is hardware-based and its operation is synchronous. Its decision time is 4 μs and the L1 accept rate is kept below 100 kHz.
- The High-Level Trigger (HLT) benefits from full detector readout and full granularity. Its implementation is software-based and very close to the offline reconstruction. Its average decision time is about 200 ms and it produces on average 1 kHz of physics data.

1 On behalf of the CMS Collaboration
The electron and photon reconstruction, offline as online, is based on information from the electromagnetic calorimeter (ECAL) and from the tracker. The CMS ECAL [1] is made of 75848 lead tungstate crystals, arranged between the barrel and two endcaps. Lead tungstate has the advantages of being relatively dense, containing 80% of the energy of an electron or photon within a single crystal, while also having a fast scintillation time. The CMS tracker is made of silicon pixels and strips and is used to reconstruct the tracks from charged particles. For the LHC Run II, the offline electron and photon reconstruction has been fully integrated within the CMS Global Event Description (also called Particle-Flow). This algorithm optimally combines the information produced by each of the CMS subdetectors, which are used to produce different blocks. For the electrons and photons, those blocks correspond to tracks and superclusters built from the energy deposits in the ECAL. Those individual blocks are then linked together to reconstruct individual particles, which leads to a final unique event interpretation. However, as this algorithm is time-consuming, it is not possible to use it directly for the trigger decision. Alternative selection techniques have therefore been developed to be used for the online selection of electrons and photons.

2. The Level-1 electron-photon trigger in CMS

The CMS Level-1 trigger has undergone a major change of architecture to cope with the challenges arising from the increase in luminosity and pileup. The Level-1 electron-photon (L1 EG) trigger has been completely renewed and improved thanks to this upgrade. In the Level-1 trigger, only the calorimetric information is used to reconstruct electron and photon candidates, which are built from clusters of trigger towers (corresponding to 5x5 sets of ECAL crystals). A new dynamic clustering has been developed, which better collects potential Bremsstrahlung radiation along the $\phi$ direction. The better granularity of the new system also leads to a large improvement in position resolution. Together, these improvements will allow us to develop efficient invariant mass triggers at Level-1. The improvement in terms of triggering efficiency with respect to the algorithm used in Run I is presented in Fig. 1, where the efficiency has been measured from 2012 data using a tag-and-probe method [3].

To reduce as much as possible the level of background and thus the rate of the L1 EG trigger, different features are used:

- the fine-grain, corresponding to the energy distribution within the seed trigger tower of the L1 EG candidates, which is required to be compatible with an electromagnetic object
- the ratio between the energy deposit in the hadronic and electromagnetic calorimeter
- the shape of the clusters, for which the large ones more compatible with jets are rejected or trimmed

In addition, a possible isolation requirement can be used, based on the calorimetric energy deposit around the candidates. The isolation threshold is tuned to keep a constant efficiency as a function of pile-up, using an event-by-event estimate of the level of pile-up. All these configurable features lead to a sizable reduction of the rate with respect to the L1 EG algorithm used during Run I.

3. The High Level Trigger selection for electrons and photons

For LHC Run II, the electron and photon reconstruction at HLT has been made closer to the offline Particle-Flow reconstruction. In particular, thanks to a new superclustering algorithm, combined with regression-based energy corrections, the HLT energy resolution has been significantly improved. The use of the Gaussian Sum Filter algorithm [4] in the track reconstruction, which better accommodates deviations due to Bremsstrahlung radiation than the previous Kalman Filter [5], also improved the momentum resolution for electrons. The tracks also provide additional parameters to identify electrons, when combined with calorimetric
Figure 1. Level-1 e/gamma trigger efficiency as a function of the electron supercluster transverse energy ($E_T$) for electrons in the barrel (left) and in the endcaps (right) in 2012 data. The performance of the Run II upgraded trigger (red) are compared with those of the Run I system (black) [6].

information: the distance between the track and the calorimetric supercluster in $\Delta\eta$ and $\Delta\phi$ together with the difference between the inverse of the energy $1/E$, measured with the ECAL, and the inverse of the momentum $1/p$, measured with the tracker, are used to reject fake electrons from the QCD background.

Electrons and photons can be further discriminated from hadronic processes using isolation criteria. The Run II HLT isolation has also been modified with respect to Run I to use the same input blocks (calorimeter clusters and tracks) as the offline Particle-Flow algorithm, which resulted in a sizable improvement of the selection efficiency for a given level of background contamination. This new isolation also makes use of pile-up subtraction techniques based on the average energy density measured in the event, which results in a selection efficiency that is relatively robust with respect to the pile-up conditions.

4. Impact of the electron and photon trigger on physics analyses

Data taken with the electron and photon trigger are used in a wide range of CMS analyses. This is for instance the case of diphoton analyses, like $H \rightarrow \gamma\gamma$ [7] or the search for high-mass diphoton resonances [8], which rely on double photon triggers. As the $p_T$ spectrum of the photons is relatively hard due to the high mass of the resonances, the acceptance of those analyses is not directly limited by the trigger thresholds. However, the expected number of signal events being relatively low, the triggers used must have efficiencies consistent with 1 for high $p_T$ photons, which is indeed the case.

The electron triggers are also used for $H \rightarrow ZZ^* \rightarrow 4\ell$ studies [9]. Although this final state provides a clean signature in the hadronic environment of proton-proton collisions, the number of expected signal events with four reconstructed leptons is still relatively low. Moreover, the $p_T$ of the trailing lepton can be very low, because of the presence of an intermediary off-shell $Z^*$ boson. To accommodate for that effect, the offline selections must be as low as $p_T > 7$ GeV for electrons. On the other hand, triggering on those low $p_T$ leptons is very challenging because of
the high rates at low trigger thresholds. This issue can be mitigated by requiring the presence of multiple electrons in the event, which enables us to reduce the trigger thresholds with respect to single electron triggers. To maximize the trigger acceptance, a combination of different single, double and triple electrons (together with muon) triggers are then used, leading to a trigger efficiency above 99%.

Finally, it is worth mentioning that the electron and photon triggers are not only used to target Higgs decay modes with electrons or photons in the final state but also for $H \rightarrow b \bar{b}$ searches. Indeed, because of the large QCD background, only associated production modes (like the $VH$ [10] or $t\bar{t}H$ [11] production) have a sensitivity high enough to be observed at the LHC. The decay of the additional vector boson or top quarks can then produce electrons, which can be used to trigger on those events more efficiently than with hadronic triggers, since the electron trigger thresholds are lower.

Conclusion
Due to increases in luminosity and pile-up, maintaining highly efficient triggering on electrons and photons with low thresholds poses a significant challenge during LHC Run II. Maintaining a high trigger efficiency is a critical issue for many physics analyses, like the study of the properties of the Higgs boson and searches for new resonances. The L1 EG algorithm has largely benefited from the new Level-1 trigger system used in CMS, while the selection of electrons and photons in the High-Level Trigger has been improved thanks to techniques closer to the offline reconstruction. It has been possible for CMS to maintain a wide physics program for Run II thanks to the continuous improvements of the electron and photon trigger, which has already contributed to a large number of physics analyses at 13 TeV.

Acknowledgments
The work of the author of this paper has been partly funded by the P2IO LabEx (ANR-10-LABX-0038) in the framework "Investissements d’Avenir" (ANR-11-IDEX-0003-01) managed by the French National Research Agency (ANR).

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