Triggers for New Physics at the LHC

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Abstract. This article gives an overview of the trigger system of the CMS experiment. The unprecedentedly high luminosity at the LHC and the expected complexity of the data produced in collisions represents a formidable challenge for the design of a trigger system. Here we outline the approach taken by the CMS experiment to meet the goals of high trigger efficiencies at reasonable processing time and cost. The challenges to detect physics beyond the standard model are highlighted as well as the strategies that have been developed to these challenges.

1. Introduction
The CMS experiment [1] at the LHC is now mostly complete and awaits first collisions in summer 2009. It is a general purpose detector with almost complete solid angle coverage and the ability to efficiently identify and precisely measure the properties of various types of objects, such as electrons, photons, muons and jets (including b- and tau-jets) over a large range of energies and topologies. Thus, the CMS experiment is ideally suited for the measurement of various standard model processes as well as possible new physics. The CMS trigger system [2; 3] is built to ensure the highly efficient selection of the events of interest while reducing the amount of data taken by several orders of magnitude down to manageable levels.

During nominal operation the LHC is expected to reach instantaneous luminosities of $\sim 10^{34} \text{cm}^{-2}\text{s}^{-1}$ at a center of mass energy of 14 TeV. Under these conditions the bunch crossing rate in the CMS experiment will be 40 MHz with each crossing producing on average $\sim$20 interactions. Considering that each bunch crossing produces $O(1)$ megabytes of data and the CMS data acquisition system can sustain a write speed of $O(1)$ gigabyte/s, it is evident that the trigger system has to reduce the amount of data taken by several orders of magnitude.

2. The CMS Trigger System
The CMS trigger system consists of two stages. The level 1 (L1) trigger [2] is built from highly configurable custom electronics and designed to reduce the number of events processed by a factor of $\sim$400. The second step of the trigger chain, the so called higher level trigger (HLT) [3], consists of a large cluster of commercially available processors, running a slightly modified version of the full CMS analysis software. The trigger system is operational since 2008 and the full trigger chain has been successfully exercised in the taking of cosmic ray data as well as the first (non-collision) beam induced data.

2.1. L1
The L1 trigger needs to process data from every bunch crossing and thus has to accept and process events at a rate of 40 MHz. The data from each collision is stored in one of about 160
buffers. This results in an overall time window of \( \sim 3 \, \mu s \) to transfer the data to the L1 electrons reach a decision and transfer the data to the HLT. Due to this stringent time limit, the L1 trigger can only read and process the data at coarse granularity. Information from the muon systems and the calorimeters is processed to produce a list of roughly identified candidates for physics objects (such as jets or muons). The central tracking system is not used in the L1 trigger due to the time constraints. The L1 trigger decision is reached by applying various selection criteria to these candidates aiming at an acceptance rate of \( \sim 100 \, \text{kHz} \), corresponding to a reduction factor of \( \sim 400 \).

2.2. HLT

Even after the reduction by the L1 trigger the data flow is expected to amount to a prodigious \( \sim 100 \, \text{gigabyte/s} \), requiring a sophisticated switching network between the L1 trigger electronics and the HLT processor farm. The computers of the HLT cluster run a (slightly modified) version of the full CMS reconstruction software so that at this stage in the trigger the full granularity and precision of the CMS detector, including the central tracker, can be used to reject background. The HLT will reduce the data flow by a factor of \( \sim 1000 \). The number of available processors in the HLT (\( \sim 1000 \)) limits the average event processing time to less than 100 ms. This speed cannot easily be achieved when processing the data produced by the entire CMS detector. Instead, the various sub-detectors are only read out and reconstructed in areas around candidates identified by the L1 trigger as regions of interest. This so called regional reconstruction allows to greatly reduce the necessary processing time while retaining high efficiency and background rejection power.

3. Trigger Criteria

In the HLT a sequence of reconstruction and selection steps is performed, where each such sequence is called a trigger path, which corresponds to a desired final state. Many such paths are executed for each event in parallel, forming the so called trigger menu. The CMS trigger menu as currently implemented contains various paths to select known standard model process and physics beyond the standard model as well as paths to extract more technical information for data quality management. Most of the paths can be associated with one of the three following categories:

**Inclusive** These trigger paths select events by examining global properties, such as total deposited energy or missing transverse energy.

**Single Object** All paths requiring one identified object, such as an electron, muon or jet, above a certain transverse energy threshold fall in this category.

**Multi Object** It is possible to require arbitrary combinations of the objects otherwise used in single object trigger paths. While this complicates the determination of trigger efficiencies and acceptance corrections, it allows the setting of lower thresholds or looser identification criteria while still retaining high background rejection.

3.1. Standard Signatures

The inclusive triggers are typically not specific enough to effectively select physics processes of interest and are mainly used to gather technical information for detector studies. Most physics studies are planned to rely on single object triggers, particularly in early running, when trigger and reconstruction efficiencies are not yet well understood. The single object triggers are highly efficient for the expected standard model process, such as electroweak boson production, which will be studied with single lepton triggers. These triggers are also suitable for a wide variety particles predicted by theories beyond the standard model. In many of these theories, the predicted new particles will decay into standard model particles, which will be picked up by
the appropriate standard model trigger criteria. Thus the CMS trigger is expected to efficiently select events originating from a large variety of models.

3.2. Exotic Signatures
Nevertheless, some models predict particles that behave noticeably differently than standard model particles and these pose a considerable challenge to the trigger system. One particular challenge is associated with long lived particles ($\tau > 1\text{ ns}$), which appear for example in some hidden valley models [4]. The decay of such particles is likely to happen outside of the beam-pipe within the main tracker volume. While these far displaced vertices cause little problems in offline reconstruction it is a considerable challenge to reconstruct them within challenge to reconstruct and identify them with a single 25 ns bunch crossing. For even longer lived particles, for example R-hadrons in some SUSY models [5], it is possible to be stopped in the dense parts of the CMS experiments, typically the calorimetry or flux return yoke. They would then decay at a random later time. While they cannot be easily identified during running, a decay of a massive particle stopped in the calorimeter can be easily detected in times where no beam circulates in the LHC. A special trigger to select this off-beam activity has been incorporated into the CMS trigger and is accumulating data for background studies since summer 2008. Long lived particles of high mass may also pose a different problem: If the mass of such a particle is comparable to its momentum, it will have a speed considerably lower than the speed of light. This is likely to result in problems with the synchronization of signals caused by the slow moving particle in different detector parts.

4. Conclusion
The trigger system of the CMS experiment at the LHC has been build to efficiently select the most interesting of the 40 million collisions occurring every second during nominal running. The trigger reduces this rate to $\sim 100\text{ Hz}$ in two steps: the L1 trigger, build from custom electronics, and the HLT, a large cluster of commercial processors. Special care has been taken to have the trigger select not only standard model processes, but also the largest possible variety of exotic processes. The complete trigger chain has been successfully tested with cosmic ray data as well as the first (non-collision) beam induced data.

References
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