Performance of the ATLAS trigger system

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Abstract. The ATLAS trigger has been used very successfully to collect collision data during 2009-2011 LHC running at centre of mass energies between 900 GeV and 7 TeV. The three-level trigger system reduces the event rate from the design bunch-crossing rate of 40 MHz to an average recording rate of about 300 Hz. The first level uses custom electronics to reject most background events, in less than 2.5 µs, using information from the calorimeter and muon detectors. The upper two trigger levels are software-based triggers. The trigger system selects events by identifying signatures of muon, electron, photon, tau lepton, jet, and B meson candidates, as well as using global event signatures, such as missing transverse energy. We give an overview of the performance of these trigger selections based on extensive online running during the 2011 LHC run and discuss issues encountered during 2011 operations. We describe how the trigger has evolved with increasing LHC luminosity coping with pile-up conditions close to LHC design luminosity.

1. Introduction
The ATLAS detector [1] successfully operated during the 2009–2011 LHC running at centre of mass energies between 900 GeV and 7 TeV. The very high live time of the trigger and data acquisition system [2,3] allowed 4.49 fb⁻¹ of collision data to be recorded from a total of 4.78 fb⁻¹ delivered luminosity in 2011. This paper summarizes the performance of the ATLAS triggers in 2011 (2010 performance are reviewed in [4]) and the changes which have been applied for 2012.

The ATLAS trigger is a three-level system in which the first-level (L1) logic is implemented with custom electronics that takes the decision in less than 2.5 µs, using information from the different subdetectors, whereas the second-level (L2) and third-level (or Event Filter, EF) are software-based. Together, the L2 and EF are collectively called the High Level Trigger (HLT). At the L1, the input rate is given by the nominal LHC bunch crossing rate of 40 MHz, while the output rate in 2011 was about 60 kHz. The detector acceptance is split into several “regions of interest” (ROIs) of limited size in pseudorapidity and azimuthal angle, and the information from the calorimeters and the muon spectrometer belonging to different ROIs is processed in parallel at the L1. Events are rejected unless some interesting “signature” is detected in at least a single ROI, in which case the event is passed to the L2, where high-granularity data belonging to the ROI are processed. The output of the L2 was 4–5 kHz in 2011. In case of L2 acceptance, the information coming from the whole detector is made available at the EF, whose output rate was 300–400 Hz.

The LHC instantaneous luminosity increased steadily in 2011, with a number of in-time proton-proton collisions ranging from about 5 to 17 int/BC (average interactions per bunch crossing). The detector is not able to separate the contributions of each individual collision, hence the multiple events occurring in the same bunch crossing “pile-up” and can only be
distinguished (to a limited degree) during the offline analysis. In addition, the energy deposited in different bunch crossings (separated by 50 ns) in the same “train” may also create difficulties in the analysis because it may affect the calorimeter measurement. This “out-of-time pile-up” has a measurable effect because of the integration time of the calorimeter signals (∼ 0.5 µs). In 2012, the proton beams have higher energy than in 2011 (4 TeV compared to 3.5 TeV) with pile-up of about 30 int/BC, still with 50 ns bunch separation. The trigger configuration needs to be adjusted to cope with the pile-up increase, in order to keep the rates under control while maintaining a high signal efficiency.

2. Trigger signature groups

The trigger system selects events by identifying signatures of muon, electron, photon, tau, jet, and B-meson candidates, as well as using global event signatures, such as missing transverse-energy (MET). Jet, photon, and MET triggers are based on calorimeter information, whereas electron, and tau triggers also use tracking information. The signatures based on muons make use of the information coming from the muon spectrometer, the tracking detectors, and possibly calorimeters. Other useful triggers are produced by random sampling of collision events to provide zero-bias selections, or by selecting forward objects. The choice of keeping almost a constant output bandwidth for each family of signatures, with increasing pile-up, implied a number of adjustments as explained below.

2.1. Jet and missing transverse-energy triggers

The pile-up increase has important effects on the triggers which only use calorimeter information. The biggest rate increases are due to the larger amount of energy deposited in the forward calorimeters, hence 2011 data have been used to find new sets of energy thresholds for higher pile-up periods which, compared to lower luminosity settings, apply a stronger noise suppression, especially in the forward regions. The new noise suppression scheme improved the trigger performance in 2011 and is now crucial to operate jet and MET triggers in 2012, in addition to several other improvements discussed below.

Other significant improvements were made possible by the changes of the data acquisition system applied before the beginning of the 2011 LHC operation, allowing the HLT to access the L1 calorimeter trigger-towers (analog sum of all cells aligned along the same direction, with respect to the nominal interaction point) and the summary information coming from the front-end electronics of all calorimeters (which includes the sums over the x, y components of the transverse energy and the scalar sum over all connected channels to each front-end board). The tests carried on during the early 2011 data taking also allowed to validate new algorithms which improve the performance of the jet and MET triggers by exploiting the improvements of the data acquisition system.

At the L2, the jet reconstruction algorithm initially running in 2011 used a cone algorithm with cell-level input, limited to the ROI selected at the L1. With the larger number of jet ROIs in 2012 due to the higher pile-up compared to 2011, this algorithm would have taken too much time. Hence in 2012 it has been replaced by the anti-$k_T$ algorithm [4], running through the collection of all L1 trigger-towers. For multi-jet triggers this is the only L2 selection, followed at the EF by the same algorithm running over all (not just those belonging to the ROI) topological clusters (sets of adjacent calorimeter cells built starting from seed cells whose energy is above 4 noise RMS, taking neighboring cells above 2 noise RMS, and all adjacent cells). On the other hand, for inclusive jet triggers the L2 selection requires two steps: first the anti-$k_T$ algorithm performs a full scan of all L1 trigger-towers (as for the multi-jet triggers), then the same algorithm is run only over all cells belonging to the ROI defined by the previous step, to refine the selection. The final decision, as for multi-jet triggers, is taken by the EF full scan of all topological clusters.
This EF algorithm was also used online during the 2011 heavy-ion runs, where it proved to have a sharp efficiency turn-on, independent of the centrality of the event (figure 1).

MET triggers select events based on global quantities as the magnitude of the vector (MET) and scalar (SumET) sums of all transverse-energies \(\epsilon\). In addition, since 2011, events can also be selected based on a combination of these two quantities, called “MET significance” because it asymptotically approaches the statistical significance of the magnitude of the vector sum in the hypothesis of negligible missing transverse-momentum. The MET significance is defined as the (dimensionless) ratio between the magnitude of the vector sum and its resolution, the latter being a linear function of the square root of the scalar sum with parameters determined by looking at zero-bias or minimum-bias events (figure 2).

The input to the MET trigger algorithms are the trigger-towers at the L1 and the calorimeter cells at the EF. Until 2011, it was impossible to compute the vector and scalar sums at the L2, because the L2 had been designed such that only data from a subset of the entire detector were accessible. The early 2011 upgrade in the data acquisition system (which now allows accessing summary data coming from all calorimeters), together with the changes in the output from all calorimeters (providing summary information in a compact way), allows to compute those global quantities also at the L2. This has been tested in passive mode in 2011 and is actively rejecting events in 2012, providing a solution to the L2 bottleneck which prevented to run such triggers with high rate. Given the large MET rates increase due to the higher pile-up of 2012, the new L2 algorithm is vital to keep such triggers active with high instantaneous luminosity.

Thanks to the rate reduction applied at L2 by this new MET algorithm, the input rate to EF is low enough to be able to run more complex algorithms, with respect to the single loop over all calorimeter cells with energy above 3 noise RMS which operated at EF until the end of 2011. Since the beginning of 2012, the EF algorithm applies a 2-sided cut by requiring the absolute value of the cell energy to exceed 2 noise RMS, with a protection at \(-5\) noise RMS to avoid rate spikes due to large negative energy values coming from hardware problems. In addition, the vector and scalar sums are computed by looping over all topological clusters, obtaining a steeper efficiency turn-on.

2.2. Photon, electron and tau triggers

Electron and photon triggers evolved in 2011 to maintain high efficiency with low pile-up dependence. Higher thresholds have been progressively applied for inclusive triggers, together with tighter selection criteria. Single electron triggers moved from the initial thresholds of 14

![Figure 1. Efficiency turn-on of an inclusive jet trigger with final threshold of 75 GeV during 2011 p-p collisions (left panel), and efficiency of the EF-only jet trigger with threshold at 20 GeV for different event centralities, during 2011 Pb-Pb collisions (right panel).](image)
GeV (L1) and 20 GeV (EF) to 16 GeV (L1) and 22 GeV (EF). In addition, a new requirement on the hadronic leakage has been added at L1, together with a coarse-granularity dead-material correction. Finally, a refined HLT identification scheme has been applied allowing to keep the rates within the allowed limits while maintaining the efficiency for the selection of signal events.

Photon triggers remained stable for most of 2011, with an increase from 60 to 80 GeV of the EF threshold for inclusive triggers in the summer, when the instantaneous luminosity exceeded $1 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. On the other hand, the di-photon trigger (essential for the Higgs search) remained stable for the entire year, with a requirement of 20 GeV minimum $p_T$ on both photons and an efficiency higher than 98%. More details on photon and electron triggers can be found in [7].

Unlike the electron triggers, which require no energy deposition in the hadronic calorimeter behind the energy cluster in the electromagnetic calorimeter associated with a trigger electron object, tau triggers include also the hadronic calorimeters in the energy measurement. In addition, the tracking information available at the HLT is used differently by electron and tau triggers: the first ones require a single isolated track matching the energy deposition, whereas the tau triggers require one, two or three tracks associated to the calorimeter cluster. Tau triggers select charged pions originating from a hadronic tau decay: in the “1-prong” case a single charged pion is present, corresponding to a single track in the inner detector, while in the “3-prong” case there are three charged pions. At the trigger level, both to increase the signal efficiency and to allow for background studies, events with two tracks are also selected.

The triggers used to select events with tau leptons changed during 2011 to keep the bandwidth relatively constant. At any given time, in addition to single tau triggers with high threshold and tight identification requirements, combined triggers were also active in which a looser tau selection was applied together with a requirement of a different lepton (electron or muon) or of significant MET in the event.

Several improvements have been applied in 2012 at the HLT for the electron, photon and tau triggers, being necessary due to the pile-up increase. For the electrons and photons, these include an isolation requirement on the lower-threshold single-electron trigger and a further reoptimisation of the electron and photon selection criteria. For the tau triggers [8], they include a reduced cone size for calorimeter-based variables, a tighter track selection, and the introduction of a boosted decision tree algorithm at the EF, which combines the information coming from the calorimeters and the tracking system.
2.3. Muon, b-jet and B-meson triggers

Single-muon triggers kept the EF $p_T$ threshold fixed at 18 GeV for the entire 2011, however the increase in the instantaneous luminosity required a gradual adjustment of the selections at both L1 and L2, in order to keep the rates under control while guaranteeing a good efficiency. The most significant change was the requirement of a 3-stations coincidence (matching hits in all layers) at the L1 for the triggers requiring a $p_T$ threshold of 10 GeV (a 2-stations coincidence was sufficient at the beginning of 2011, with 75 ns bunch separation).

In 2011, the thresholds of di-muon triggers remained the same for the entire year, at 10 GeV on both muon objects. In summer, the rate was reduced by applying additional checks at L1 and L2 aiming at suppressing the fake di-muon triggers happening at the chamber boundaries. The most significant difference in 2012 is the requirement of muon isolation, which is necessary in the high pile-up environment but was not used in 2011. More details in [9].

There are two main categories of b-jets triggers: lifetime triggers relying on tracking and vertex reconstruction to tag jets as defined at L1 (2011) and HLT (2012), and muon+jet triggers, mainly for calibration studies. At high luminosity, starting from September 2011, the HLT jets were required to accept the event as prerequisite. In 2012, several refinements have been applied to provide good performance with acceptable rates. Among them, a refinement in the primary vertexing and the adoption of the new L2 jet algorithms mentioned above. In addition to inclusive b-jet triggers, they are also used in combination with MET or another lepton. More details in [10].

B-physics triggers are low $p_T$ di-muon triggers with additional mass cuts to select specific signatures (e.g. $J/\psi, \psi'(2S), \Upsilon$). Because of the increase of the instantaneous luminosity, the L1 lowest threshold was re-optimized in September 2011 to allow unprescaled running while keeping high efficiency. Figure 3 shows the number of events collected in 2011 by single-muon trigger with 20 GeV $p_T$ EF threshold (the bottom gray distribution) and by specific B-physics triggers (shown with different colors), as a function of the di-muon invariant mass. Events accepted by multiple triggers are counted multiple times in this plot. The B-physics triggers require two muons (above 4 GeV at the EF in 2011; above 4 and 6 GeV in the first 2012 runs, and both above 6 GeV later), plus a requirement on the invariant mass window which is tuned to match $J/\psi$ (2.5–4.3 GeV), $B_s$ (4–8.5 GeV) and $\Upsilon$ (8–12 GeV), or the combined range of all three (1.5–14 GeV for the “DiMu” trigger in figure 3), as calculated using the trigger objects.

The EF threshold remained the same in 2011 but was increased in 2012 from 4 to 6 GeV for both muons, reducing somewhat the efficiency for $J/\psi$ (25%), $B_s$ (17%), and $\Upsilon$ (12%). In addition, in 2012 new L1 di-muon triggers have been introduced requiring at least one muon or both muons in the barrel, to recover some efficiency for low thresholds (4–6 GeV).
3. Summary
The ATLAS trigger is operating with LHC collisions since 2009 with very high live time (> 99%), with a continuous increase in the instantaneous luminosity. In order to follow the LHC evolution in 2011, several adjustments were applied in the configuration of most physics triggers. Electron triggers had to apply progressively higher thresholds and tighten the identification requirements. The threshold of single-photon triggers was also increased, although di-photon triggers remained stable for the whole 2011 year. On the other hand the changes in the muon triggers had a minimal impact on the selection efficiency.

The luminosity increase in 2011 had more important effects for tau, b-jet and B-physics triggers, for which significantly tighter selections needed to be applied at the end of the summer. However, the most important effects of the pile-up increase are found in jet and MET triggers, whose rates increased very quickly (and more than linearly with respect to the instantaneous luminosity). In both cases the calorimeter information from the whole detector is used, which represents a significant bottleneck. Hence the data acquisition system was upgraded in 2011 to allow new jet and MET triggers to run at the L2, providing additional rejection.

In 2012 the centre of mass energy is 8 TeV and the number of proton-proton collisions in the same bunch crossing can exceed 30 int/BC, hence all trigger signatures need to cope with the increased luminosity. All triggers are applying significantly tighter selection criteria than in 2011, and jet and MET triggers are running new algorithms which have been made possible by the improvements in the data acquisition system performed and tested in 2011.

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