Performance of the ATLAS Trigger with Proton Collisions at the LHC

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Abstract. The ATLAS trigger has been used very successfully to collect collision data during 2009 and 2010 LHC running at center-of-mass energies of 900 GeV, 2.36 TeV and 7 TeV. It is designed to reduce the event rate, from the design bunch crossing rate of 40 MHz, to a maximum recording rate of about 200 Hz. To achieve this it is composed of three levels. Level-1 uses custom electronics to reject most background collisions, in less than 2.5 µs, using information from the calorimeter, muon and minimum bias detectors. The upper two trigger levels, known collectively as the High Level Trigger (HLT), are software-based and run on farms of commodity processors. The Level-2 trigger uses mostly custom algorithms while the Event Filter is based on offline tools. In order to achieve average processing times of 40 ms at Level-2 and 4 s at the Event Filter, most HLT processing is performed on partial event data corresponding to Regions of Interest identified by the Level-1 trigger. The trigger selection is based on global event features, such as missing transverse energy, and identifies candidate muons, electrons, photons, tau mesons and jets. We present the results from detailed studies of trigger performance during collision running. We give distributions of key quantities calculated online, compared with the same quantities calculated offline and expectations from Monte Carlo simulation. These studies show that the trigger is performing well and is efficiently collecting the data needed for the ATLAS physics program.

1. Introduction
The ATLAS experiment [1] is a general purpose detector, currently taking data, which is designed to exploit the full potential of proton-proton and heavy ion collisions at the Large Hadron Collider (LHC). The goal of the ATLAS experiment is to explore the fundamental nature of matter and the basic forces that shape our universe. Its overall design is the result of the requirements for high precision muon momentum measurements, efficient tracking, large acceptance and very good calorimetry for electron, photon, tau and jet identification and measurements.

With the LHC design parameters of a bunch crossing rate of 40 MHz and about 23 interactions per bunch crossing, a highly selective trigger system is required to reduce the expected $10^9$ interactions per second to an acceptable rate of a few hundred Hz. To achieve this, the ATLAS trigger is designed in three levels of online selection: Level-1 (L1), Level-2 (L2) and Event Filter (EF). The L1 trigger is implemented in fast custom electronics designed to reduce the rate to a maximum of 75 kHz in less than 2.5 µs. The second and third level triggers, together known as the High Level Trigger (HLT), are software based and implemented on farms of commodity
processors connected by fast dedicated networks. The L2 and EF are designed to reduce the event rate to about 3 kHz and 200 Hz in an average time of 40 ms and 4 s respectively. The final system will consist of about 500 L2 nodes and 1800 EF nodes about half of which were installed in 2010.

The L1 decision is based on data from the calorimeters, muon trigger detectors and minimum-bias scintillators. The L1 identifies small localized regions in pseudo-rapidity and azimuthal angle (known as Region of Interest, RoI) centered on L1 features, which are to be investigated at the HLT. Each RoI corresponds to only 2-4% of the full event data. On a L1 accept, detector data are transferred to the Readout Buffers (RoBs) that store events pending the L2 decision. Following a L2 accept, the Event Builder assembles event fragments from the RoBs providing the full event to the EF. On a EF accept, the event is written to storage at a maximum average output rate of 200 Hz, determined by available offline resources.

The trigger selection is configured via a trigger menu that defines trigger chains. A trigger chain defines a sequence of reconstruction and selection algorithms starting from a specific L1 trigger which leads to a specific trigger signature \[2\]. There are between 200 and 500 chains defined in the current trigger menus. Events are recorded if one or more trigger signatures are satisfied. Flexibility to adapt menus to different conditions is provided by the possibility of applying prescale factors to both L1 triggers and HLT chains. Different prescale sets are available for a range of luminosities.

2. Performance of the trigger selections

The ATLAS trigger was commissioned in several steps during 2010. Initially, no HLT algorithms were running online and the selection was made by L1. During this period, the HLT was exercised extensively by running it offline on data recorded few hours earlier. After a few weeks, the HLT algorithms were enabled online in monitoring mode where they were running but not rejecting. This allowed validation of the selection algorithms such that rejection could be progressively enabled as required. The HLT was fully active from August 2010 when the luminosity reached \(2 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}\). Throughout 2010, the ATLAS trigger coped very successfully with an increase in LHC instantaneous luminosity by more than five orders of magnitude, reaching a maximum of \(2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}\) in October. Fig. 1 shows the average L2 processing time, which includes both data collection and event processing time, for data taken at 7 TeV center-of-mass energy. The average processing time for L2 and EF have been measured to be \(\sim 40\) and \(\sim 270\) ms respectively, satisfying the design time constraints.

Initially, it was possible to record all collisions triggered by the minimum bias trigger. It is based on the Minimum Bias Trigger Scintillators (MBTS) installed in each calorimeter end-cap covering a region in pseudorapidity \(\eta\) of \(2.1 < |\eta| < 3.8\). The time difference between the signals from either end-cap provides good discriminator between proton-proton collisions and beam-background events. As shown in Fig. 2, a trigger based on a single MBTS count in either end-cap (MBTS\(_{1}\)) has an efficiency of more than 97% for events with at least two reconstructed tracks with more than 100 MeV. Data taken with this trigger was used to produce the first ATLAS charged-particle multiplicity measurements \[3\]. As luminosity increased, the MBTS trigger was prescaled and other L1 triggers became the main ones for physics.

2.1. Electron, photon and tau trigger selections

Electrons and photons triggers are important for many physics studies, including Z and W-boson production and searches for new physics such as Super Symmetry or the Higgs boson. They are selected at L1 using the analogue sums of calorimeter cells in regions of \(0.1 \times 0.1 \text{ in } \Delta \eta \times \Delta \phi\), called Trigger Towers. Fig. 3 shows a good agreement between data and Monte Carlo (MC) for the L1 trigger efficiency as a function of the uncalibrated transverse energy \(E_T\) of the offline cluster. Full efficiency is reached above the threshold. The HLT refines this selection by applying cuts
on the shape of the energy deposits and on the leakage into the hadronic calorimeter. Narrow showers with all the energy contained inside the electromagnetic (EM) calorimeter are expected for real electrons. The high granularity in $\eta$ of the first sampling of the calorimeter provides a high rejection power against QCD background. In addition, the Inner Detector information is used to reconstruct tracks which are then matched to calorimeter clusters to form trigger electron candidates. Fig. 4 shows the distribution of the shower shape variable $R_\eta$ calculated at EF. $R_\eta$ is calculated by the ratio of the energy deposited in 3×7 cells over 7×7 cells in the second EM layer. It is peaked towards one for electrons. The shape of the distribution is well modelled by MC simulation. HLT rejection was enabled when the rate of L1 EM calorimeter triggers with a 2 GeV threshold reached more than 200 Hz. This happened with a LHC instantaneous luminosity of $1.5 \times 10^{29}$ cm$^{-2}$s$^{-1}$.

In order to increase the sensitivity of searches for new physics, a dedicated tau trigger has been designed to select events where a tau lepton decays into one or more hadrons and has been commissioned during 2010. The L1 tau trigger uses a cone of 0.2×0.2 in $\eta \times \phi$ to sum energy in the EM and hadronic calorimeters and calculate the energy in core and isolation regions. In the HLT a tau candidate is identified as a well collimated calorimeter cluster with a small number of associated tracks. The number of associated L2 tracks is shown in Fig. 5, demonstrating a good agreement between data and simulation. Isolation requirements can be imposed at L1 for both the electron/photon and tau triggers, but were not used in 2010 running.

2.2. Muon trigger selection
The L1 trigger [4] is based on dedicated detectors: Resistive Plate Chambers (RPC) in the barrel ($|\eta| < 1.05$) and Thin Gap Chambers (TGC) in the end-caps. The TGC trigger is about 95% efficient above threshold while the RPC trigger efficiency is limited to a maximum of ~80% by holes in the geometrical coverage due to support structures, etc. At L2, a fast pattern recognition algorithm using additional data from Monitored Drift Tubes is used to find muon tracks in the RoI found by the L1 muon trigger. At the EF, similar algorithms to offline reconstruction are used. Both L2 and EF have standalone and combined modes, where combined refers to the combination of muon segments and inner detector tracks. Fig. 6 shows the efficiency of the L2 muon standalone trigger with respect to the L1 muon trigger as a function of the muon transverse momentum $p_T$. This plot is for a muon $p_T$ threshold of 4 GeV. The standalone

Figure 1. L2 total time measured online during data taking at a 7 TeV center-of-mass energy. It includes both data collection and processing time.

Figure 2. Trigger efficiency of a single-sided minimum bias trigger as a function of offline selected track multiplicity for data taken in 2010.
Figure 3. L1 trigger efficiency for a 5 GeV EM cluster threshold as a function of the raw offline cluster transverse energy (E_{T,raw}). The turn-on is shown for data (black markers) and MC simulation (red line).

Figure 4. Comparison of the distributions of the shower shape R_\eta calculated at EF for data and simulation for EF clusters matched to an offline electron candidate. The shower shape is shown for data and MC simulation.

Figure 5. Comparison of the tau candidate number of tracks distribution at L2 for 7 TeV data (black dots) and MC simulation (red line).

Figure 6. L2 muon standalone trigger efficiency with respect to L1 as a function of the muon transverse momentum p_T for data (black) and MC (red).

L2 muon reconstruction efficiency is found to be above 98% and good agreement with MC simulation is observed.

2.3. Jet, Missing Et and Sum Et trigger selections
The L1 jet trigger is also based on Trigger Towers and sums energy in a cone of 0.8 \times 0.8 in \eta \times \phi. The lowest jet threshold is nominally 5 GeV (the cut applied to the uncalibrated EM scale L1 jet). If a L1 jet candidate is identified, the L2 jet trigger requests calorimeter data in a window of 1 \times 1 around the L1 jet RoI position and runs an iterative cone algorithm with a radius of 0.4. No EF selection was applied for jet triggers in 2010 running. The EF jet trigger will be activated when needed in 2011. Fig. 7 shows the efficiency for offline reconstructed anti-kT jets [5] (with
In addition to the RoI-based triggers, the trigger menu contains L1 triggers based on transverse missing energy (MET) and total transverse energy. These are based respectively on vector and scale sums of calorimeter cell energy over the entire calorimeter. At L2 the energies are corrected using muon information and at EF they are recalculated using information from both the calorimeter and muon detectors. Fig. 8 shows the correlation between the total transverse energies calculated at the EF and offline. A very good correlation can be observed. Up to an instantaneous luminosity of $10^{30} \text{ cm}^{-2} \text{s}^{-1}$ the 10 GeV MET trigger ran un-prescaled. The lowest un-prescaled threshold was raised to 30 GeV when the luminosity increased to $2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$.

In addition to single MET triggers, the menu contains combined triggers such as tau lepton plus MET, which is used, for example, as trigger for $W \rightarrow \tau \nu$ events selection.

3. Summary and outlook
The trigger has been successfully commissioned and used to deliver the data for the first ATLAS physics analysis. Good agreement has been observed between data and Monte Carlo simulation, both for the distributions of trigger selection variables and for trigger efficiency, demonstrating that the ATLAS trigger is behaving as expected. During this first year of data taking, the trigger menu has been progressively adapted to follow the increase in delivered LHC instantaneous luminosity, spanning more than five orders of magnitude during the 2010 data taking period. The trigger selection will continue to evolve making use of higher pre-scales, tighter selection cuts, application of isolation requirements and use of high multiplicity and multi-object triggers. We are confident that the ATLAS trigger is well prepared and ready to meet the new challenges it will face in 2011 and beyond.

4. References

