Performance of the ATLAS Calorimeter Trigger with 7 TeV Collision Data

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Abstract. Since the start of the LHC physics programme earlier this year, the ATLAS detector has been collecting proton-proton collisions at a 7 TeV center of mass energy. As the LHC luminosity rises the ATLAS trigger system must become increasingly selective to reduce the event rate from a design bunch crossing rate of 40 MHz to 200 Hz to be recorded for offline analysis. To achieve this goal, the trigger algorithms must meet challenging requirements in terms of speed and selectivity.

The ATLAS trigger is hardware based at level-1 and uses software algorithms running on a farm of commercial processors at the next two trigger levels. The calorimeter-based software algorithms perform the selection of electrons, photons, jets, taus and also events with missing transverse energy. We present the physics performance achieved during 2010 data taking, highlighting the achievements of the different signatures. Event features reconstructed by the Trigger are compared with offline reconstruction and with expectations from MC simulations. Rate stability, processing time and data access performance during different periods of data-taking are also discussed. The results presented demonstrate that the calorimeter based trigger is effective in selecting data for the ATLAS physics programme.

1. Introduction

After more than a decade of careful studies, assembling and commissioning, the ATLAS detector in the Large Hadron Collider (LHC) beam line started to record the first 7 TeV center-of-mass proton-proton collisions. Detector performance analysis [1] before restricted to Monte Carlo (MC) simulations can now be performed with real data, focusing on understanding the behavior of the detector with respect to known Standard Model observables before moving into the new discovery territory provided by the LHC luminosity and energy. Comparisons between expected performance from the simulations and real data as well as the evaluation of the experimental detector ultimate resolution are the most important steps to be accomplished at this early stage of the experiment.

The accelerator complex managed to raise the luminosity continuously during this first data taking period, surpassing the initial goal of reaching a delivered instantaneous luminosity of \(10^{32} \text{cm}^{-2}\text{s}^{-1}\) by a factor of 2. The luminosity raised, in this period, 5 orders of magnitude, imposing an increasing demand in the ATLAS Trigger System which initially operated in (close-to) zero bias mode accepting all events with any signal in the detector[2] to a mode in which trigger selection is active and only a small fraction of the collision events is recorded. High efficiencies for meaningful physics and strong rejection for the large background produced by the LHC are the key factors for a successful physics exploitation of the detector. The ATLAS trigger
Figure 1. ATLAS Calorimeter subdetectors (left) and the trigger system (right) depicted as data flow components distributed in 3 trigger levels used for selection.

system was activated in steps as soon as the rate of each physics channel became unsustainable by the data acquisition system and that enough data was collected to validate the selection for that channel. Our focus will be on the results obtained by the ATLAS software trigger for calorimeter based selections.

In the next section, we briefly introduce the ATLAS calorimeter and trigger systems emphasizing only the aspects that are relevant for the comprehension of the software trigger algorithms described later. In the following section, the results for events with electrons, taus, jets and missing transverse energy are presented. Since processing time improvements may have an important impact in the physics available for the research, we discuss in the fourth section a technique used for quick network data retrieval we are presently using. The last section brings out conclusions and discusses the next steps being taken.

2. ATLAS Calorimeter and Trigger System

In order to cover the ambitious requirements of the ATLAS scientific program, the ATLAS calorimeters[3, 4] use different technologies to achieve the necessary performance. The first calorimeter section, closer to the beam pipe, is the electromagnetic (EM) calorimeter composed of lead absorbers immersed in liquid argon which acts as sampling material. This layer has a very fine granularity helping to perform isolation to sort electron and photon candidates from jets. For hadronic calorimetry, in the central region up to a pseudorapidity ($\eta$) of 1.7, iron absorbers and scintillating plates as sampling material are used. At higher $\eta$, copper plates and liquid argon are used. These calorimeters provide an excellent performance in terms of jet resolution. In the very forward region, close to the beam pipe, tungsten rods immersed in liquid argon complete the detector coverage (up to $\eta = 5$) and take part on the forward jets and global transverse energy measurements. Details can be seen in Figure 1. The readout electronics, installed in the detector provide the analogue pulses for each cell as well as samples of this signal (sampled at bunch crossing rate). Such digital samples are processed at the Readout Driver (RODs) units to extract the energy in each cell through an optimal filtering algorithm.

The ATLAS level 1 trigger (L1) uses the analogue sums of the pulses of all cells in regions of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ called Trigger Towers, to form a coarse picture of the calorimeter for each event. This provides input to a hardware (FPGA) based trigger system with has a very short latency (2.5$\mu$s). This restricted time budget is achieved with the cost of an important drop of
particle identification performance specially in the EM section where a total of 60 cells form a single Trigger Tower. Despite that, the L1 can reduce drastically the input rate with some simple isolation and energy thresholds criteria. It also provides the detector coordinates of the active regions (called Regions of Interest - RoIs) in the calorimeter of each event that it accepts.

The level 2 (L2) starts by requesting data only around the L1 pointed RoIs as they allow to process an event at the L2 based on a reduced set of all detector data. This data, from the RODs, with energy calculated per cell, is stored in the read-out buffers (ROBs). Data is spread in more than 700 ROBs and a few tens is requested per event. The first task of the L2 is usually to confirm and increase the isolation precision of the L1. In the case of calorimeter algorithms, clusters and shower shapes are calculated to evaluate different particle candidates. It is also possible at this level to combine calorimeter information with tracks from the ATLAS inner detector and muon systems. The average L2 latency is expected to be below 40 ms. Events accepted at this stage have all their data sent to the Event Building. Offline-like clustering or jet algorithms are run over the full event in the Event Filter (EF) farm which is expected to reduce the recording rate to 200Hz using a 4s maximum latency. Both L2 and EF run on off-the-shelf computers and are together referred to as the High-Level Trigger (HLT).

The HLT calorimeter algorithms cover a wide range of physics channels, such as electrons, photons, taus, jets, missing transverse energy and also work on muon isolation requirements. All these algorithms use a common, highly optimized, data preparation layer. These software tools request data from the different parts of the calorimeter, hiding detector specific details and preparing a list of cells with geometry and energy information to be used by the feature extraction algorithms involved in clustering, shower shape calculation or jet reconstruction.

3. Physics Performance

The electron-gamma calorimeter based algorithms at the L2 and EF contribute to identify some of the Standard Model processes such as Z decaying into an electron-positron pair. Despite the initial selection performed by the L1, a huge amount of jets coming from the strong LHC QCD background can fake electron or photon candidates demanding further criteria for the selection of real candidates of these particles.

At the L2, the first step is to improve the position resolution obtained from the L1. This is performed by fetching data from the deepest layer of the EM calorimeter, which contains most of the energy of a photon or an electron. The position of the cell with highest energy, is used as a pre-seed, being the center of a 3x7 cell grid from which many of the shower shape properties
are calculated. The final cluster position is improved by averaging the grid cells positions with their energies. Isolation can be explored at cluster level by dividing the energy in the 3x7 grid by the energy in the 7x7 cluster centered in the same cell. Candidates surviving the cuts at the L2 calorimeter and track matching are sent to the EF, where a more robust against noisy cells cluster finding algorithm can be performed thanks to the longer processing time budget available. At this stage a sliding window algorithm can be run to detect higher energy clusters instead of single hot cells. This also increases compatibility with the offline algorithms.

In Figure 2 (left), the L2 transverse energy profile as obtained directly from ATLAS monitoring system during a physics run at 7 TeV (circles) is shown. During the normal operation, many events are caused by cosmic particles or detector noise when no collision really happened. By requiring coincidence with collisions, the plot with triangles is obtained. The histogram agrees much better with the MC simulations, as expected. This result is a very important demonstration of the reliability of these algorithms. Figure 2 (right) shows the isolation variable (ratio of the energy in the 3x7 cluster by the energy in the 7x7 cluster) for the EF. Here the comparison with MC presents some deviations. These were later understood as caused by imperfections in the electronics simulation and further comparisons will be done when a new MC production is available.

The L2 tau algorithm has a similar high energy cell finding algorithm as well as a cell energy-weighted average cluster position finding. The main difference is that, since taus may produce an important hadronic fraction in their decays, the search for the highest energy cell is not limited to a single layer in the EM calorimeter but can come from any layer of the detector within the RoI. Also, the RoI size is larger ($\Delta\eta \times \Delta\phi = 0.6 \times 0.6$). At the EF, the clustering technique used is called topological clustering. In this case, a seed cell is declared in the RoI if its energy is above a few $\sigma$ (eg: 4) of the noise expected for that cell. Any cell, touching this initial one, and still above some other noise threshold (eg: 2$\sigma$) will be added to the cluster. So, in principle, topological clusters do not have a defined shape and grow as much as necessary to keep all energetic cells involved.

Up to now, most of the signals found do not involve any real taus, so, we are much more interested in evaluating the rejection power of the algorithms. Figure 3 (left) shows the acceptance for background events selected by a relatively loose L1 trigger for tau candidates. As can be seen, above 40 GeV, the L1 accepts most of the candidates of this loose tau trigger. However, the more refined analysis performed at the L2 and EF can reject almost 70% of these events. We also see a good agreement between MC and data, showing that the algorithm is
performing as expected.

The Jet algorithm at L2 uses a cone approach in which, starting from the cell with a larger energy, some iterative procedure tries to determine which cells in the vicinity of this initial one should be included in a cone of cells. The Jet RoI is much larger than the electron-gamma or tau RoIs ($\delta\eta \times \delta\phi = 1.0 \times 1.0$). After the cone is determined (basically by a flag associated to each cell in the RoI that states whether the cell belongs or not to the cone), some extra properties are calculated, like the fraction of the energy in the EM and Hadronic parts of the cone and the total $E_T$ of the jet. In Figure 3 (right), the efficiency of the L2 jet algorithm with respect to offline jets is presented. The plateau is reached around 40 GeV, being the L2 curve completely dominated by the L1 resolution at the lower end (the L2 algorithm by itself, follows the L1 efficiency). Also, as can be seen when comparing with the MC, this effect is modeled correctly in MC data.

The Missing Transverse Energy is calculated initially at L1 by summing up the total Transverse Energy of every Trigger Tower that compose the detector. The scalar energy sum is also calculated. At L2, the missing $E_T$ cannot be really calculated, as this would demand acquisition of data from the full detector which would be much more demanding in terms of bandwidth between the L2 and the ROBs. For events with significant L1 Missing $E_T$, the L2 algorithm only adds the signal from the muon detectors to the L1 MET. The events which are accepted at this stage are used at the EF where the major task is to unpack all the cells from the available data fragments in a very efficient way. The whole data is unpacked and the global cell granularity based missing $E_T$ can be calculated using less than 3% of the total available time at the EF due to the highly optimized data preparation tools and algorithm. Furthermore, the missing $E_T$ algorithm helps by caching the unpacking of the whole detector data fragments. Other EF algorithms run faster than when running purely standalone.

Figure 4 (left) shows the total missing $E_T$ as calculated by the EF algorithm. The agreement with the MC simulation validates the algorithm behavior. The resolution with respect to offline missing $E_T$ is also evaluated showing in a quite sharp turn on curve.

4. Improving Processing Time

Historically, the processing time of each single L2 algorithm used to need a large time budget to complete. Due to this, most of these algorithms were designed to request data per layer of the detector (up to 7 requests). The initial idea was that parts of the features to be extracted for a given cluster could already provide enough information to reject an event. So,
the algorithm would fulfill its task without really requiring full RoI data, saving some processing time. However, with the code optimization, most of the algorithms take a really small processing time to complete and most of the total algorithm time at the L2 is presently used to request and transfer data. For instance, for electron-gamma algorithms, 3.52 ms are spent on average on RoI data requests and 0.81 ms are actual processing time. Similarly, the L2 jet algorithm takes 3.76 ms in data request and 2.04 ms to process the RoI.

Carefully studying the ATLAS network model, it can be verified that when data is requested, a network transaction starts and most of the spent time is used only at the communication start up and not in the actual transfer. Furthermore, the amount of data requested has little relation to the total transference time when compared with this start up processing time. Consequently, it is more efficient to issue less requests with higher amount of data. A modification applied in the software responsible for selecting the ROBs to be accessed was made so that when the first request for a given layer of the detector is received, all the data from all the layers pertaining to that same RoI is retrieved at once.

The initial data request time was reduced from 3.76 ms for the jet algorithm to 3.03 ms. For the electron-gamma algorithm, a reduction of 3.52 ms to 1.84 ms could be obtained. Globally, a reduction from 39.8 ms to 30.7 ms was reached for the full L2 processing, as shown in Figure 4 (right). Since less requests are performed by event, the maximum ROB request limit (around 20KHz) is less likely to be reached, reducing chances of clogging the L2 data flow. This optimization will be used at the beginning of the next data taking period and we are presently studying an even stronger optimization by requesting data for all the RoIs at once, instead of requesting all data for each RoI separately.

5. Conclusions

The performance of different algorithms for particle identification was presented. Comparison with MC simulation or turn on curves with respect to offline software demonstrate that the ATLAS High Level Trigger calorimeter algorithms have the expected performance and can be used efficiently to select events for physics studies. During this first data taking period the described algorithms were used to discard background events as the LHC luminosity increased 5 orders of magnitude. The present peak luminosity is still 2 orders of magnitude below the final LHC design luminosity. For the next data taking period, the cuts based on the features extracted by such algorithms will be even tighter aiming at increasing the background rejection. Also, to account for increasing pile up effects, cell level noise suppression mechanisms are provided but not yet applied to the HLT.

Improved data requests helped to reduce global L2 processing time and reduce load in the Readout Buffers of the ATLAS data acquisition system. This will be further explored in the next data taking period.

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