Operational Experience of the ATLAS High Level Trigger with Single-Beam and Cosmic Rays

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***Abstract*—ATLAS is one of two general-purpose detectors at the LHC. Using fast reconstruction algorithms, the trigger system needs to efficiently reject a large rate of background events while keeping potentially interesting ones with high efficiency. The LHC start up and single-beam run periods in 2008 provided a "stress test" of the trigger system. Following this period, ATLAS continued to collect cosmic-ray events for detector alignment and calibration as well as for commissioning the trigger. These running periods allowed us to exercise the trigger system online, including its configuration and monitoring infrastructure, as well as reconstruction and selection algorithms. Several tracking, muon-finding, and calorimetry algorithms were commissioned under different running conditions. Frequent changes of the trigger configuration were required to cope with the parallel commissioning of the ATLAS sub-detectors. The experience gained while running the trigger system online was very valuable to design and implement an optimal strategy for the collision data taking period of 2009. This paper focuses on the operational experience gained in running the trigger in the fast-changing environment of the detector commissioning with cosmic rays and single beam runs.**

I. Introduction

At the LHC design luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, proton bunches will collide at a rate of 40 MHz with a center of mass energy of $\sqrt{s}$ = 14 TeV. About 25 overlapping inelastic pp interactions will occur during a bunch crossing. One of the most challenging components of the ATLAS experiment [1] is the trigger system, whose task is to reduce online the huge event rate of the LHC to around 200 Hz for permanent storage. The online event selection happens at three trigger levels: Level-1, Level-2 and the Event Filter (EF). The trigger strategy is largely based on the local reconstruction of interesting physics objects in an event, such as leptons or jets with high transverse momentum. The requirements on the trigger system in terms of speed and robustness are particularly demanding at Level-2, where the event rate is reduced from the Level-1 output rate of 75 kHz to about 3kHz. The EF reduces the event rate to about 200 Hz which is the input rate to the permanent storage.

The Level-1 trigger is implemented as a system of purpose-built hardware processors with a maximum processing latency of 2.5μs. It uses information from the calorimeters and the muon system to form trigger towers that are used to identify trigger objects. Level-2 and EF are collectively referred to as High-Level Trigger (HLT) [2]. They are software-based triggers that are run on a farm of commercial PCs. There are tight timing constraints on the Level-2 trigger, which on average processes an event in about 40 ms. At the EF the average event processing time is about 4 s, which allows to run offline-like algorithms at the EF.

During 2008 and 2009 all ATLAS major sub-detectors, including the HLT, have been commissioned with cosmic ray data taking runs. The aim of this article is to describe the operational experience of the HLT with cosmic ray runs and also with first LHC single beam events.

II. The High-Level trigger

The ATLAS trigger is based on the local identification of physical objects (muons, electrons/photons, hadrons/taus, jets) selected by the Level-1 calorimeter and muon triggers, labeled as so-called Region-of-Interests (RoIs). The Level-1 RoI contains information on the pseudorapidity and azimuthal angle (η, ϕ) and the E_T threshold satisfied. The concept of the RoIs is introduced in order to reduce the amount of data that needs to be transferred to the Level-2 trigger system.

At Level-2 a combination of feature extraction (FEX) algorithms and hypothesis algorithms is used to process the Level-1 RoI. Contrary to Level-1, the Level-2 has access to the detector data at the full granularity. Given the number of readout channels and an average processing time of 40 ms at Level-2, it is not possible to request the complete detector data at Level-2. Thanks to the RoI concept however, only a small fraction of the full detector data in a given window around the RoI position is needed.

Once an event is accepted by the Level-2 trigger, the event builder pulls out all data fragments from the readout system of detector and assembles the full event. The full event is then received by the EF, which runs algorithms adapted from the offline reconstruction.

The processing of an event in the HLT is based on the execution of chains of FEX and hypothesis algorithms. Chain execution can be stopped after each step, if the hypothesis being tested is not satisfied, leading to an early rejection as possible in the processing chain. An HLT processing chain is build from a sequence of FEX and hypothesis algorithms that is seeded by the Level-1 RoI. The collection of trigger chains is set in the trigger menu. The full configuration of the trigger menu is stored in a relational database, which preserves the history of trigger menu changes and does not allow duplications of records. The user interface to the trigger database is a java based application, which allows quick update of configuration changes to the menu and the prescales [3].

In the final configuration the HLT will consist of about 500 Level-2 and 1600 EF machines. Currently about 35% of the final system is commissioned, as planned for early LHC beam. Each HLT node consists of two quad-core 2.5 GHz CPUs with 16 GByte memory (2 GB per core) and two 1 Gbit/s network interfaces. The operating system is Scientific Linux CERN 5. The HLT software environment is based on the offline software framework Athena [4]. Some machines can be easily interchanged between Level-2 and EF application, as needed.

The deployment of up to one terabyte configuration data (trigger configuration, detector conditions) from a single server to the HLT farm in a fast and reliable way is a challenging task. The ATLAS Trigger system uses database access caching processes arranged in a tree structure that shields the database server from the large number of clients. Each node in the tree reduces the configuration traffic and the number of connections through caching and multiplexing. This allows to configure the HLT farm in the order of tens of seconds, as was demonstrated and measured during cosmic data taking.

Another challenge is the monitoring of the many applications that are running on the HLT nodes and are updated every minute. Therefore a data quality monitoring framework has been developed within the monitoring system, that provides automated checks. It provides a number of basic operations on histograms, such as histogram comparison or fitting, whose result are presented in terms of a status flag [5].

Besides the automated tests, there exist other tools, such as the Online Histogram Presenter (OHP) [6], which is highly configurable. It can either show a predefined set of histograms in a series of tabs or it can be used to browse through all the produced histograms.

III. HLT EXPERIENCE WITH SINGLE BEAM EVENTS

During the single beam coasts of the LHC in 2008 high occupancy events were produced by colliding the beam with closed the collimators, located 140 meters from the ATLAS interaction point. These so-called splash events produced a flood of secondary particles traversing the detector. Low occupancy events were recorded from beam-halo interactions.

Extensive use was made of the beam pickup devices (BPTX) to synchronize the Level-1 triggers. The BPTX is located at 175 m from the nominal interaction point on both sides of ATLAS and is used as a stable time reference with respect to the LHC beam circulating through ATLAS. After only two days the relative timing between the BPTX and the minimum bias trigger scintillators (MBTS) was excellent, as can be seen in Fig. 1.

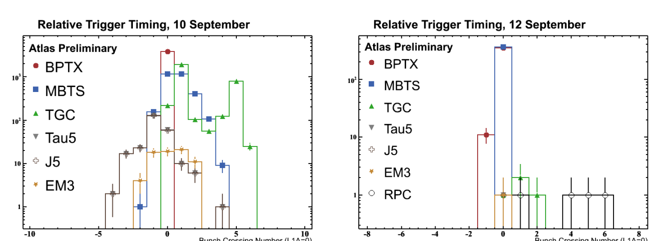

Fig. 1. Timing distribution of Level 1 triggers from September 10, the first day of single-beam data. Events were triggered with the BPTX, providing a stable time reference at bunch crossing (BC) = 0 with respect to the LHC. Timing distribution of Level 1 triggers from September 12, the third day of single-beam data. Events were triggered here with the MBTS at BC 0.

During the few days of LHC beam the HLT was not actively used for rate reduction, but solely for assigning events to the corresponding data stream. After the LHC incident on September 19th 2008, ATLAS moved back to cosmic data taking mode.

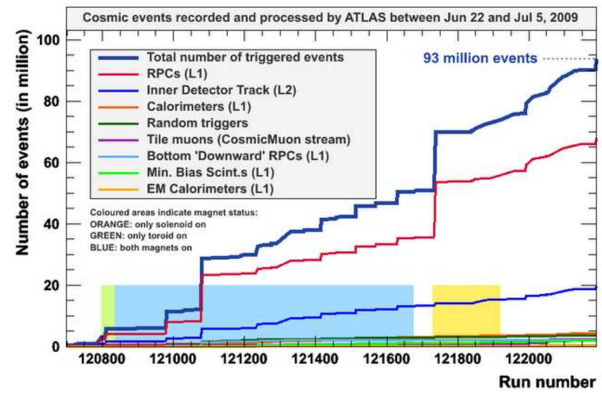

Fig. 2. Number of recorded events during the cosmic ray runs between June 22 and July 5 2009. The rate is broken down into the contributions of the different triggers

IV. COMMISSIONING THE HLT WITH COSMIC RAY EVENTS

Several goals were set for the trigger system from the cosmic ray runs.

- Test the infrastructure needed to run the HLT
- Test the algorithm performance (timing, memory leaks)
- Improve the relative L1 trigger timing
- Exercise trigger operations with a shift crew

ATLAS has started to take cosmic ray events with most of the subsystems combined in the data taking runs since 2007. During the 2008 and 2009 cosmic ray data taking periods more than 300M events have been recorded.

As shown in Fig. 2, several triggers contribute to the data recording rate. The recorded sample is dominated by the Resistive Plate Chambers (RPC) trigger, i.e. the Level-1 muon trigger signal, followed by the Level-2 tracking triggers. Calorimeter triggers and tile muon triggers contributed a smaller fraction of events, but nevertheless useful for several purposes as will be discussed in this section.

A. *Calorimeter triggers for cosmic ray events*

Since the identification of several physical objects requires calorimeter data all HLT triggers involving calorimeter data access were exercised during cosmic ray runs. Since there are several physics objects that require calorimeter data, a common interface for calorimeter data access was implemented and commissioned with cosmic rays events.

Cosmic-ray muons typically deposit only a small amount of energy in the calorimeter. This motivated running the calorimeter Level-1 trigger with a lower noise threshold than is foreseen for collisions. This operation mode made the Level-1 calorimeter triggers more sensitive to noise, which can result in high Level-1 output rates.

Monitoring tools for the calorimeter triggers were implemented in order to find sources of high rates due to noisy trigger towers or calorimeter cells. An example of such a monitoring histogram is shown in Fig. 3. The distribution in

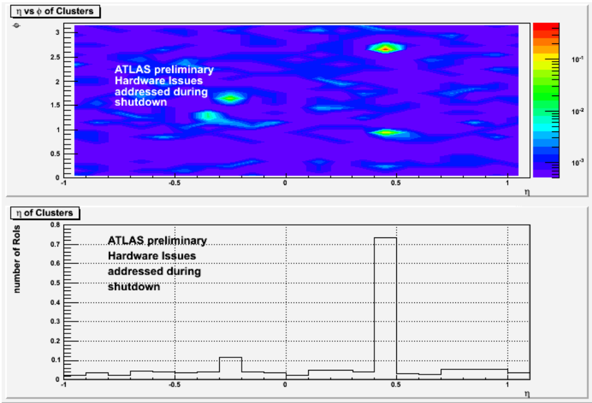

Fig. 3. The eta-phi map of calorimeter clusters reconstructed by the FEX algorithms at Level-2 (top) and the multiplicity of Level-1 trigger towers (bottom). The hot region at phi=2.7 and eta=0.45 is associated to a noisy trigger tower.

the top shows the position of calorimeter clusters reconstructed by Level-2 FEX algorithm in the eta-phi map. One can clearly see regions with large energy deposits at ϕ=2.7 and η=0.45. This can be correlated with the graph in the bottom, which shows the number of Level-1 calorimeter trigger towers. With the help of this monitoring it was found that only less than 1% of all LAr calorimeter cells were problematic and most of these problems are addressed directly in hardware during shutdown.

B. Tracking triggers for cosmic ray events

The ATLAS tracking system consists of three detector elements: the pixel detector, the semiconductor tracking detectors (SCT) and the transition radiation tracker (TRT). Close to the beam pipe, semiconductor trackers provide precision measurements of charged tracks, using highly granular pixel detectors positioned nearest to the beam pipe. At larger radii from the beam pipe, silicon microstrip detectors are being used in the SCT. The outermost component is the TRT, which uses straw tube tracker and provides efficient tracking paired with electron identification capability.

In the HLT two algorithms based on hits in the silicon detectors (pixel and SCT) have been developed for tracking, SiTrack and IDSCAN [7].

In addition there is a tracking algorithm based only on hits in the TRT, the TRTSegfinder [7]. By design these tracking algorithms give the optimal efficiency for tracks with low transverse impact parameter within a few millimeters. For cosmic rays the algorithms had to be modified in order to reconstruct tracks that do not point to the nominal interaction point.

The algorithms configuration was modified to get tracks traversing the ATLAS detector from top to bottom with at least three silicon hits on the lower and on the upper halves of the detector. Either of the two arms can be reconstructed separately by the Level-2 tracking. Weaknesses in the tracking algorithms introduced by the relaxed pointing constraints were found and corrected, such as some sensitive to noise in the silicon detectors.

The modified Level-2 tracking chains were implemented in the cosmic runs configured to use any Level-1 signature as input.

In Fig. 4 the efficiency of the three Level-2 tracking algorithms with respect to offline is shown as a function of the transverse impact parameter d_0 and the transverse momentum p_T. It shows that in 99% of the events a track was found by any of the Level-2 tracking algorithms.

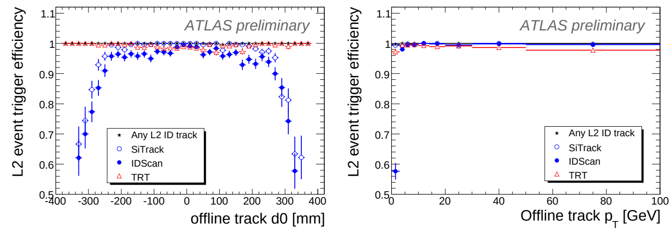

Fig. 4. The efficiency of the three Level-2 tracking algorithms with respect to the matched offline track and as a function of the offline track impact parameter (left) and transverse momentum p_{T}.

C. Cosmic muon triggers

The ATLAS muon spectrometer is equipped with trigger and precision chambers, that allow for both the fast Level-1 reconstruction and the more precise measurement of muon tracks in the HLT and offline. trigger and the p_{T} measurement of muon tracks. At Level-1, trigger RoIs are provided by the Resistive Plate Chambers (RPC) in the barrel region and by the Thin Gap Chambers (TGC) in the end-cap region. The precision chambers, the Monitored Drift Tube (MDT), are adjacent to the trigger chambers and are used by the Level-2 algorithm μFast to find hit clusters associated with trigger hits.

The reconstruction of the muon p_T with μFast [8] uses pre-calculated look-up tables, which are based on Monte Carlo data. These LUTs are derived from simulated collision data with muons pointing to the nominal interaction region of ATLAS. Therefore the estimation of the muon p_T was not possible and impeded the measurement of the physics performance of the HLT muon trigger.

The reconstruction of MDT clusters and the measurement of track bending power done by μFast was assessed with cosmic rays. Fig. IV-D shows the number of hits in the Level-1 RoI found by the TGC versus the distance between the track reconstructed by μFast and the hit clusters in the MDT. The muon track finding efficiency of μFast was found to be 93%, smaller than the design goal of 99%. The loss of efficiency is due to bad detector conditions. A 2% efficiency loss was found to be due to mis-calibrated tubes of the MDT, while another 5% was due to bad MDT readout elements.

D. Complementary trigger tests

While cosmic rays provide a reliable data source for commissioning the HLT and other parts of the detector, they don't push the HLT in terms of performance and data throughput. To this end tests using Monte Carlo (MC) data were carried it out with the HLT farm, in which data was preloaded in the readout system and data was requested by the HLT processes. During these tests peak rates of about 4 kHz at Level-2 and of about 250 Hz at the EF were achieved.

In addition, trigger rate studies based on MC data with collisions at $\sqrt{s} = 10$ TeV and a luminosity of $\mathcal{L} = 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ predict a rate of about 9 kHz at Level-1, 1 kHz at Level-2 and 120 Hz at EF.

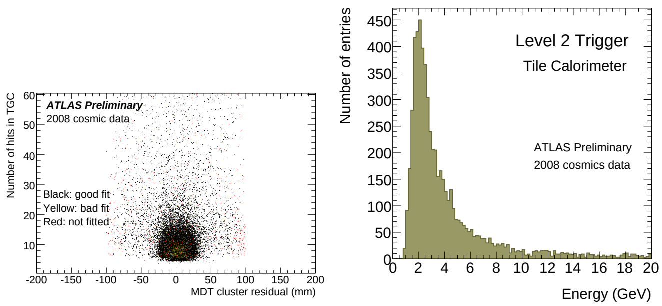

Fig. 5. μFast [8] performance in the end-caps with cosmic events.

E. Operational developments during 2009 cosmic ray runs

During cosmic ray data taking many operational developments have been implemented and exercised during 2008 and 2009.

In order to react quickly to sudden rate increase of a trigger chain in the HLT, it is now possible to update the prescales during a run, without introducing dead time to the data taking.

Another new feature that was commissioned with cosmic ray runs, was the so-called partial event building. Unlike physics events, calibration events for a specific sub-detector do not require the full event information, but only a fraction of the nominal 1.5 MB per event. Partial event building is a new feature that handles efficiently the assembly and logging of such calibration events based on a list of selected detector elements. This functionality allows to record calibration events at a higher rate while staying with minimal impact on the bandwidth available to the data acquisition system Events for sub-detector calibration purposes are selected by HLT algorithms, which create a list of identifiers and flag the event as a calibration event. The list of identifiers can be filled either in a static or a dynamic manner, based on the RoI information, and is passed to the event builder, which pulls the requested data fragments from the readout system. Partial event building has been used during cosmic ray data taking in 2009 by the pixel detector, tile calorimeter, the inner detector and LAr calorimeters

Another important feature that has been implemented is the ability of the HLT algorithms to access the detector conditions at the beginning of a run. This is important to be able to update to the latest detector conditions without the need to re-configure the HLT.

V. Conclusions

During the cosmic ray data taking runs in 2008 and 2009 the HLT was fully operational and many of the trigger algorithms have been exercised. The few days in 2008 during which the LHC delivered beam, were extremely useful to improve the relative timing of the Level-1 triggers. During that time the HLT was used to assign events to the corresponding data stream. The trigger and data acquisition systems were running and performing as expected and no problems occurred during the single beam coasts.

Besides exercising the existing system, new features were commissioned in 2009, such as the update of the HLT prescales during a run, the partial event building for calibration event, the update of the detector conditions in the HLT at the start of a run.

The ATLAS experiment has resumed cosmic data taking in October 2009 and is getting ready for LHC single beam and collision events expected at the end of 2009. The trigger strategy foreseen for the coming LHC beam events is similar to what was followed in the 2008 single beam runs. Namely, use the BPTX as initial timing reference for the other Level-1 triggers and start using MBTS and Level-1 muon and calorimeters.

In a first step the HLT is not going to be used for event selection, but only for streaming of the events to the several data streams. In a next step a well defined set of HLT algorithms, are going to be enabled online, but without rejecting events. After this first validation step of the HLT with LHC beams, the HLT selection will be activated as required by the event rate.

The tests with MC data along with the stable operation of the HLT during 2008 and 2009 with single beam and cosmic data, proves that the HLT is prepared to sustain the event rates that are going to be delivered by the LHC at the end of 2009 and in 2010.

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