

The ATLAS Level-1 Topological Trigger performance in Run 2

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Abstract. The Level-1 trigger is the first event rate reducing step in the ATLAS detector trigger system, with an output rate of up to 100 kHz and decision latency smaller than $2.5 \mu\text{s}$. During the LHC shutdown after Run 1, the Level-1 trigger system was upgraded at hardware, firmware and software levels. In particular, a new electronics sub-system was introduced in the real-time data processing path: the Level-1 Topological trigger system. It consists of a single electronics shelf equipped with two Level-1 Topological processor blades. They receive real-time information from the Level-1 calorimeter and muon triggers, which is processed to measure angles between trigger objects, invariant masses or other kinematic variables. Complementary to other requirements, these measurements are taken into account in the final Level-1 trigger decision. The system was installed and commissioning started in 2015 and continued during 2016. As part of the commissioning, the decisions from individual algorithms were simulated and compared with the hardware response. An overview of the Level-1 Topological trigger system design, commissioning process and impact on several event selections are illustrated.

1. Introduction

The ATLAS experiment [1] is a general purpose detector 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.

The Level-1 (L1) trigger system [2] is designed to reduce the output event rate from 10^9 proton-proton interactions per second produced by the LHC to a maximum of 100 kHz. It is implemented in fast custom electronics designed to decide in less than $2.5 \mu\text{s}$. It consists of three main systems: the Level-1 Calorimeter (L1Calo) trigger, the Level-1 Muon (L1Muon) trigger and the Central Trigger Processor (CTP). The L1Calo trigger makes use of reduced granularity information from the electromagnetic and hadronic calorimeters to search for electrons, photons, taus and jets, and to calculate the total and missing transverse energy (E_T^{miss}). The L1Muon system provides fast trigger signals from the Resistive Plate Chamber strips in the barrel and Thin Gap Chambers in the end-cap regions. The CTP is the system that receives all of this information and provides the final L1 acceptance signal.

In order to be able to cope with a higher event rate in Run 2 with respect to Run 1 due to the increase in LHC luminosity and collision center-of-mass energy, some parts of the ATLAS trigger hardware, firmware and software were upgraded. In the L1Calo system, new Multi-Chip Modules based on Field-Programmable Gate Array (FPGA) technology were installed to replace the modules with Application-Specific Integrated Circuits used in Run 1. This new hardware makes it possible to improve pile-up (simultaneous proton-proton collisions) suppression by applying new bunch-by-bunch dynamic pedestal corrections. To suppress muon fake triggers, the L1Muon end-cap trigger ($1.05 < |\eta| < 2.4$) was modified to require a coincidence with hits from the innermost muon chambers. Also, the main part of the CTP was replaced to increase the number of input and output L1 trigger decisions, thus increasing event selection flexibility.

2. The L1 Topological trigger system

With the Run 1 trigger system, the L1 output rate would be kept within the maximum allowed 100 kHz by requiring higher transverse momentum p_T or transverse energy E_T for the L1 trigger objects. To mitigate this increase a new hardware system was introduced in the L1 trigger path: the L1 Topological (L1Topo) trigger system. It performs real-time event selection based on geometric and kinematic relationships between Trigger Objects (TOBs), i.e. electrons/photons, muons, jets and taus, as well as on event-level quantities such as missing transverse energy.

2.1. Physics motivation

The L1Topo system [3] increases the physics potential of ATLAS while maintaining a manageable event output rate. One example that benefits from the new L1Topo selections is the analysis of $H \rightarrow \tau_{\text{had}} \tau_{\text{had}}$ event candidates. The non-topological selection requires two isolated tau TOBs with relatively high p_T . The requirement of nearby tau candidates in pseudorapidity (η) rejects minimum bias events while keeping most of the signal ones. The addition of this angular requirement to the presence of two taus makes it possible to reduce the minimum tau p_T thresholds. As a result, the signal efficiency is maintained while the event output rate is kept to a manageable level. Another example is the search for $ZH \rightarrow \nu\bar{\nu}b\bar{b}$ events. Events are selected by requiring two jets and E_T^{miss} above a given E_T threshold. The requirement of a minimum angular distance in ϕ between the jets and E_T^{miss} makes it possible to reduce the E_T^{miss} threshold, thus increasing event rejection while keeping good signal efficiency.

2.2. Technical description

The L1Topo system is a single shelf (crate) equipped with two identical AdvancedTCA-compliant L1Topo modules, of the format shown in figure 1. It receives TOB data from the L1Calo and L1Muon systems through parallel-optical ribbon fibers in the backplane and front panel respectively. The optical signals are then converted to electrical ones. The electrical high-speed signals are routed into two large Virtex-7 FPGAs per module, each with up to 80 Multi-Gigabit Transceivers. The two FPGAs process the data in parallel. High bandwidth, low latency parallel data paths allow real-time communication between the two processors. After processing the data, the L1Topo system sends the selection results to the CTP via electrical and optical transmission. In addition to the two L1Topo modules, dedicated boards were built and included in the system to convert the input muon data to the required format.

2.3. Functionality description

The L1Topo system installed in Run 2 is able to provide up to 128 decisions based on topological information, i.e. 32 decisions per FPGA. Each FPGA processes independently the data from the L1Calo and L1Muon systems through several algorithms, which are configurable through an ethernet interface, and calculates event kinematic quantities. These calculations can be assigned

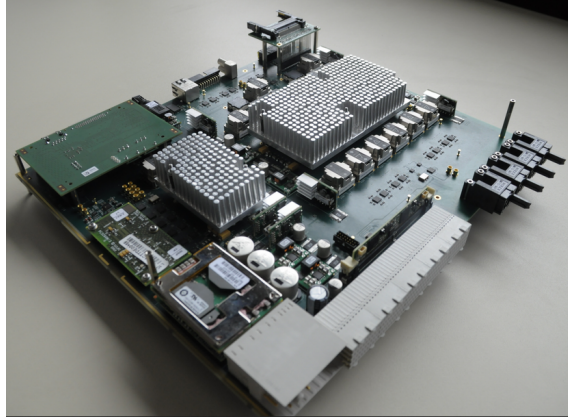


Figure 1: L1Topo module with no front panel or fiber assembly.

to three different categories, as detailed in table 1: angular separation between TOBs (in η , ϕ or radius R), invariant mass or transverse mass, and hardness of interaction (the scalar sum of p_T of jets, H_T). Conditions on these topological calculations are required in addition to multiplicity and a minimum p_T or E_T to TOBs in order to reject background events while keeping interesting ones for physics analyses.

Table 1: Examples of L1Topo selections implemented in the ATLAS trigger system in 2016.

Type	Name	Details
Angular Separation	$\Delta\phi$	$\Delta\phi(\text{TOB}_1, \text{TOB}_2)$
	$\Delta\eta$	$\Delta\eta(\text{TOB}_1, \text{TOB}_2)$
	ΔR	$\sqrt{\Delta\phi^2 + \Delta\eta^2}$
Invariant Mass	M	$\sqrt{E_T^1 E_T^2 (\cosh\Delta\eta - \cos\Delta\phi)}$
Transverse Mass	M_T	$\sqrt{E_T E_T^{\text{miss}} (1 - \cos\Delta\phi)}$
Interaction hardness	H_T	$\Sigma p_T(\text{jets})$

3. Commissioning and validation process

Around 100 variations of topological selections were programmed in VHDL and implemented in the trigger in 2016. They are based on the algorithms described in table 1 in addition to several other ones. All topological output decisions are provided to the CTP.

The validation of the topological decisions taken by the hardware was done at various levels. The firmware is simulated in VHDL and basic checks are performed standalone. Well-defined input data are processed through the hardware via a playback mechanism and the decisions are examined.

When the experiment does not receive proton collisions from the LHC, hot towers in pre-defined regions of the sub-detectors can be generated and the L1Topo output decisions cross-checked. The timing of the arrival of the decisions is also checked to ensure they are all well aligned with the triggered events.

All L1Topo algorithms were simulated and run in real-time for all L1 accepted events. A comparison of the L1Topo hardware selections against the simulated ones was performed. Both statistical and event-by-event differences were displayed in various histograms for online

monitoring. Some small differences are to be expected as simulations do not include an exact bit-wise implementation of the topological trigger algorithms in the hardware. Furthermore, L1Topo hardware trigger decisions take into account overflow conditions while they are not simulated. It was checked however that overflows did not happen very frequently.

In addition to the normal trigger output data path, a sample of events selected by L1Calo, L1Muon or L1Topo triggers was sent to a special output data stream. Events in this stream contain detailed information about the individual CTP decisions, L1Topo decisions and energy and position of the TOBs received by the L1Topo system. Using standalone programs, this stream was reprocessed and the L1Topo decisions re-simulated using the L1Calo and L1Muon information, or the L1Topo TOBs information directly.

4. L1Topo triggers performance

During the commissioning process, modifications to the firmware and to the simulation in order to understand the differences were needed. Reprocessing of selected data and re-simulating the algorithms proved to be very useful in this process. Various validation tools were developed in order to help to quickly identify the source of discrepancies. In the end, a very good agreement for several topological triggers was reached. Figure 2a shows the relative differences (hardware false negatives and hardware false positives according to the simulation) for various H_T triggers. When no discrepancy is found, the histogram is not filled while the filled (blue) bins show a discrepancy smaller than 0.5%. These triggers calculate the scalar sum of jet p_T by using various lists of jet TOBs: jets with p_T above 15 or 20 GeV and with $|\eta| < 2.1, 3.1$ or 4.9. H_T is required to be above 20, 150 or 190 GeV. The efficiencies with respect to the offline-calculated H_T value of two of these H_T triggers are shown in figure 2b. Relatively sharp efficiency turn-on curves can be observed.

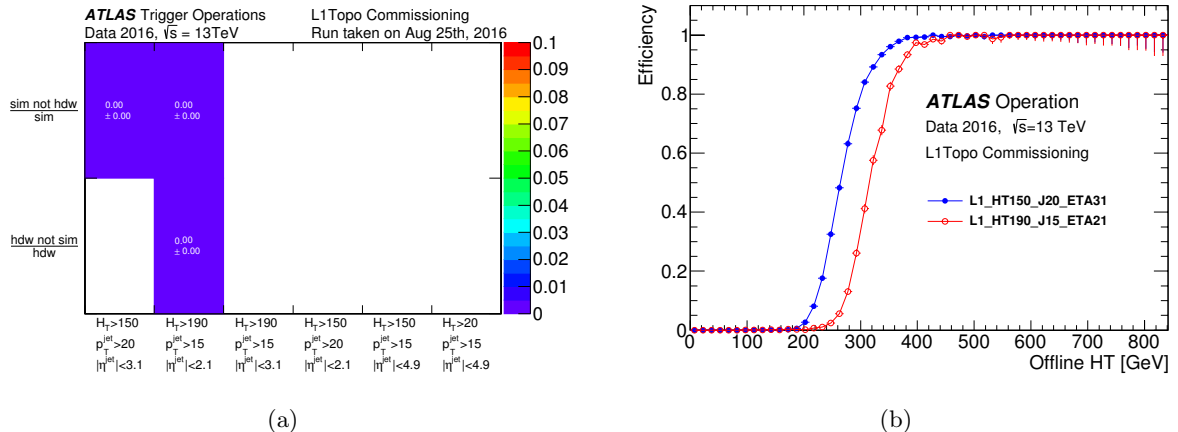


Figure 2: Relative differences between hardware and simulated trigger decisions for various H_T triggers [4] (a) and efficiency of two H_T topological triggers with respect to the offline-calculated H_T variable [5] (b).

As described in Section 2.1, the ditau triggers can benefit from a topological selection. This is shown in figure 3a where the event rate corresponding to various L1 ditau triggers is displayed versus the instantaneous luminosity. The ditau trigger with the requirement of one additional jet (black circles) has a higher event rate than triggers using topological requirements. The requirement of a radial distance ΔR between the two leading L1 tau TOBs below 2.9, reduces by about 0.5 kHz the event rate with respect to the ditau plus one jet trigger. By requiring an

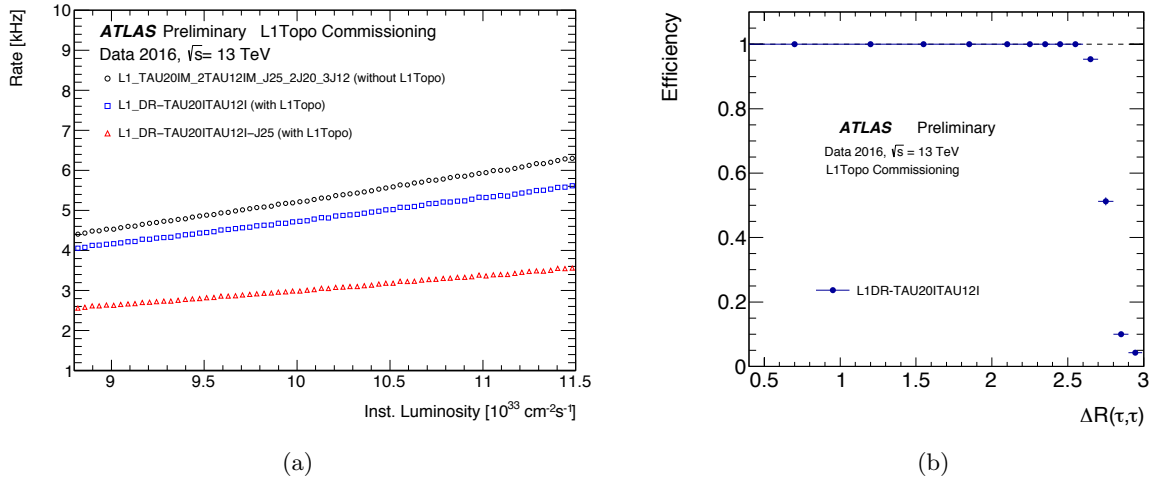


Figure 3: Event rate versus instantaneous luminosity of various L1 ditau triggers with and without topological requirements (a) and efficiency of the topological ditau trigger with respect to the radial distance between two offline-reconstructed taus matching tau TOBs (b) [5].

additional jet with p_T above 25 GeV the event rate is reduced by about a factor of two. The efficiency with respect to the ΔR between two offline-reconstructed taus matching tau TOBs of the ditau trigger including the topological ΔR requirement is shown in figure 3b. Full efficiency is found through all ΔR values up to very close to the required trigger threshold, making it a very suitable trigger candidate for physics analyses.

Not only analyses of events with two hadronic tau leptons in the final state can profit from topological trigger selections but also analyses of events with b -hadrons. The trigger selection of events for B -physics analyses is primarily based on the identification of b -hadrons through decays including a muon pair in the final state. The dimuon triggers generally suffer from a high event rate and, in order to keep it within the allowed range, an increase of the required minimum p_T of the muon TOBs would be needed if no additional requirement could be applied at L1. Topological requirements on ΔR and invariant mass between the two muon TOBs are added to the dimuon trigger while the p_T muon trigger thresholds are kept reasonably low. Figure 4a shows the event rate for two L1 dimuon triggers with respect to time in minutes. A rate reduction of about a factor of 3 with respect to the L1 non-topological dimuon trigger is achieved if, in addition, the invariant mass between the two muon TOBs is required to be between 2 and 9 GeV and its radial distance between 0.2 and 1.5. The distributions of the offline-reconstructed dimuon invariant mass corresponding to events selected by HLT and L1 non-topological (red triangles) or L1 topological (blue circles) triggers are shown in figure 4b. Apart from an overall event rate reduction, the L1 topological trigger does not significantly affect the dimuon invariant mass in the range between 4 and 7 TeV. It can therefore be used by B -physics analyses as a similar range is required by the selections.

5. Conclusions

The ATLAS L1 trigger system was upgraded during the LHC shutdown after Run 1 with the inclusion of a new custom-made system called the L1 Topological trigger. It allows the system to select or reject events based on the calculation of variables based on event topology. The system was installed and commissioned during 2015 and 2016. Simulation and validation tools were written to reprocess events and understand initial hardware and simulated decision discrepancies.

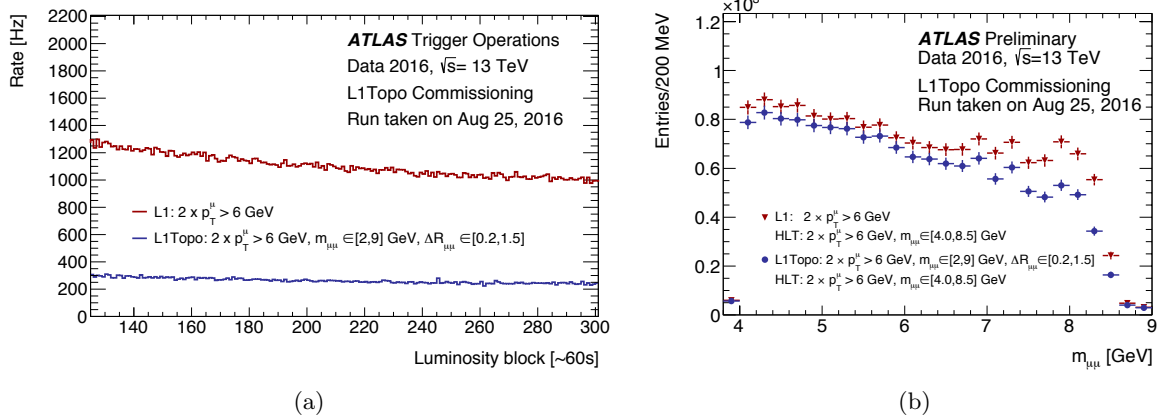


Figure 4: Event rate versus time in minutes of two L1 dimuon triggers with and without topological requirements (a) and distribution of the offline-reconstructed dimuon invariant mass for events triggered by HLT and L1 with or without topological requirements (b) [5].

As a result, several L1 topological triggers have been validated including selections based on ditau and dimuon triggers. Physics analyses interested in these final-state signatures are exploring the possibility of using them in 2016. This paves the way for commissioning and validating new topological selections foreseen for 2017.

References

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