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COMMISSIONING AND VALIDATION OF THE ATLAS LEVEL-1 TOPOLOGICAL TRIGGER

A.T. Aukerman*†, T.M. Hong*, University of Pittsburgh, Pittsburgh PA, USA

Abstract

The ATLAS experiment has recently commissioned a new hardware component of its first-level trigger: the topological processor (L1Topo). This innovative system, using state-of-the-art FPGA processors, selects events by applying kinematic and topological requirements on candidate objects (energy clusters, jets, and muons) measured by calorimeters and muon sub-detectors. Since the first-level trigger is a synchronous pipelined system, such requirements are applied within a latency of 200 ns. We will present the first results from data recorded using the L1Topo trigger; these demonstrate a significantly improved background event rejection, thus allowing for a rate reduction without efficiency loss. This improvement has been shown for several physics processes leading to low-p_{T} leptons, including $H \rightarrow \tau\tau$ and $J/\Psi \rightarrow \mu\mu$. In addition, we will discuss the use of an accurate L1Topo simulation as a powerful tool to validate and optimize the performance of this new trigger system. To reach the required accuracy, the simulation must take into account the limited precision that can be achieved with kinematic calculations implemented in firmware.

INTRODUCTION

The ATLAS experiment at CERN is one of the multipurpose experiments operating at the Large Hadron Collider (LHC) at the European Center of Nuclear Research in Switzerland [1]. At design specifications, the LHC provides proton-proton (*pp*) collisions at a center of mass energy of $\sqrt{s} = 14$ TeV and an instantaneous luminosity of $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1} [1]. These protons collide at a rate of 40 MHz; however, bandwidth constraints impose limits on the number of events per second that can be recorded, and the majority of these events contain only *pp* scattering events. This motivates the need for an online trigger system that identifies certain signatures, including but not limited to, missing transverse momentum, lepton production, and high p_{T} jets [2].

The ATLAS experiment includes an online Trigger and Data Acquisition (TDAQ) system that selects events that will be saved to offline storage for later physics analysis. This system is comprised of two levels, the first being a hardware based, low-granularity level-1 (L1) system with a design latency of 2.5 µs [3]. This system constructs Regions-of-Interest seeding the software based algorithms used in the subsequent high level trigger (HLT) system, reconstructing the event with full detector read-out granularity. The L1 system is further divided into three subcomponents, the Calorimeter Trigger (L1Calo), the Muon Trigger (L1Muon) and the Central Trigger Processor (CTP). The L1 system reduces the 40 MHz collision rate to 100 MHz, and the HLT trigger reduces the rate further to 3-4 kHz [3].

The level-1 topological trigger system is a new element deployed to impose topological constraints to L1 triggers [4]. The goal of this system is to purify L1 event selection by imposing kinematic requirements motivated by the event topology of certain processes. These new electronic boards compute angular and kinematic quantities between various L1 Trigger Objects (TOBs) [4]. Its role in the L1 trigger is shown in the flowchart included in Fig. 1. The system is designed to receive and process up to 6Tb/s of real time data [4]. In 2016 the L1Topo system was first deployed online. This proceedings contribution details its commissioning and validation.

MOTIVATION

As higher luminosities are reached at the LHC, the production rate for physics signatures increase [5]. To cope with the increase in trigger rate, two solutions are traditionally employed: to record one out of N events, i.e. to prescale the trigger; and to tighten the selection criteria, e.g., to increase the transverse momentum threshold. Both approaches cause some loss of interesting data. For example, the $B^0 \rightarrow J/\psi\ \varphi$ analysis was approaching bandwidth limits for triggering on low p_{T} muons [6]. The B-physics program would benefit from improved purity in L1 event selection as proposed by L1Topo [6]. A non-exhaustive table is given in Table 1 to illustrate some physics applications for given topological quantities. As a concrete example, consider the following two variables implicated in di-muon pairs: the angular separation ΔR and the di-muon mass $M_{\mu\mu}$ as defined in equations (1) and (2). The application of these quantities is illustrated in Fig. 2.

$$\Delta\mathrm{R} = \sqrt{\Delta\phi^2 + \Delta\eta^2} \quad (1)$$

$$\mathrm{M}_{\mu\mu}^2 = p_{\mathrm{T}}^{\mu 1} p_{\mathrm{T}}^{\mu 2} \cdot \left(\cosh\left(\Delta\eta_{\mu\mu}^{12}\right) - \cos\left(\Delta\phi_{\mu\mu}^{12}\right)\right) \quad (2)$$

Table 1: Physics use Cases for Some Topological Quantities. The L1Topo Firmware Accepts a Multitude of Parameters such that Each Physics Use case can be Optimally Tuned

Topological Quantity	Physics Use Case
Dijet mass	Vector Boson Fusion / Scattering
Jet, Et-Miss $\Delta\phi$	Exotics, SUSY
Di-muon mass, radius	B-physics
Di-tau opening angle	Higgs

* On behalf of the ATLAS Collaboration
† ata28@pitt.edu

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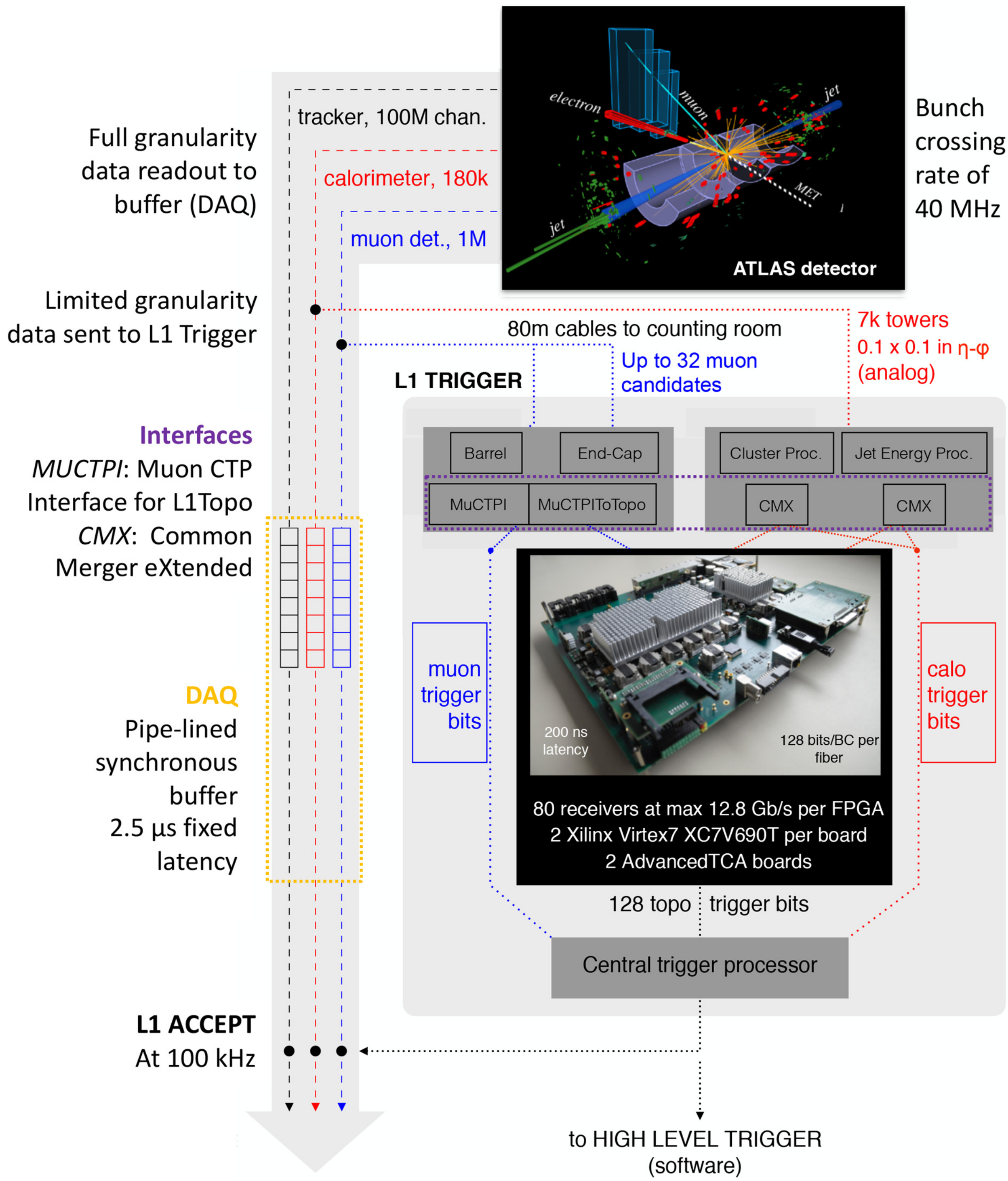

Figure 1: Flowchart of the L1 trigger scheme. Shown is the role that L1Topo plays in considering both L1Muon and L1Calo information. The MUCTPIToTopo and CMX modules specifically prepare input to L1Topo. The L1Topo output bits must be propagated to the CTP such that a decision can be made within the 2.5 microsecond buffer.

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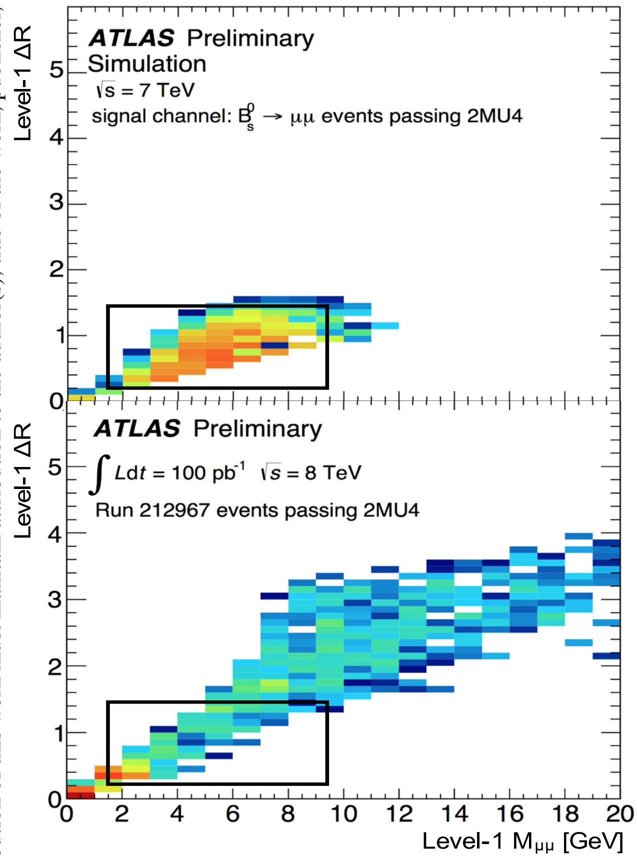

Figure 2: Plot showing the angular separation and invariant di-muon mass distributions for $B^0 \to \mu\mu$ (above) and for the minimum bias background (below). Highlighted is an area of discrimination where a topological cut can improve L1 trigger purity [6].

L1 TOPO ALGORITHM EXECUTION

Data Collection from the L1Muon Subsystems

In Run 1, the MUCTPI (Muon CTP Interface) extracted only muon multiplicity and momentum quantities to be sent to the CTP for use in the L1 muon decision [2]. With the planned implementation of L1Topo, additional kinematic and angular cuts could be performed [4]. Thus, for Run 2, the MUCTPI was upgraded to also extract coarse-grained topological information for the L1Topo module [7].

The MUCTPI system includes 16 Muon Octant (MIOCT) modules, one for each octant in each half of the detector. These cards originally operated at 40 MHz; overclocking would be necessary to reach a throughput sufficient to provide good $\eta - \phi$ resolution. An overclock by a factor of 8 would permit 8 bits per muon, and with DDR transmission a total of two muon candidates per octant module [7].

A feasibility study in which a high resolution phase scan was performed on data received from the overclocked MIOCT modules showed that there exists an optimal sampling point for DDR data transmission, with a bit error rate lower than 10^{-15} at 95% confidence level [7]. This demonstrates that the MUCTPI trigger outputs can reliably transmit data to L1Topo. The total aggregated rate of the MUCTPI system is 10.24 Gb/s [7].

Commissioning tests of this system specifically include use of a high-level software simulation to generate input vectors and calculation of expected results [7]. No errors appeared in a sample of snapshot memory from 10^{10} bunches. The parallel output from the MUCTPI must also be encoded into optical output for the L1Topo modules. This is implemented in a dedicated MUCTPIToTopo board, which includes a Xilinx VC707 development kit and two FMC cards. Overnight integration tests showed zero errors out of $2.6 \cdot 10^6$ test bunches. Cross-checksums are implemented within the board to ensure error free serialization [7].

Data Collection from the L1Calo Subsystems

The L1Calo common merger modules (CMMs), which interface with the CTP, had to be replaced in order to function with the proposed L1Topo module. The CMM modules, in the same vein as the MIOCT modules, collect information from the calorimeter specific to its crate number [8]. The proposed upgrade of these crate modules to CMX (Common Merger eXtended) models would allow transmission of the 400 backplane inputs from a crate to be sent to L1Topo [8]. The serialization of these crate data is handled by an FPGA which drives two Avago MiniPOD optical transmitters [8].

Performance of L1Topo

The L1Topo module includes two FPGAs receiving serial data on 80 links at 6.4 Gbit/s with 8b/10b encoding [9]. These modules operate within a clock domain of 160MHz, and each event is contained in 128 bit words [9]. The algorithms are executed in sync with the 25 ns LHC clock. The first stage sorts the input TOBs, and the next stage applies the topo algorithms to these truncated lists. A visual representation of this process is shown in Fig. 3. This result is output to the CTP for use in the L1 trigger decision.

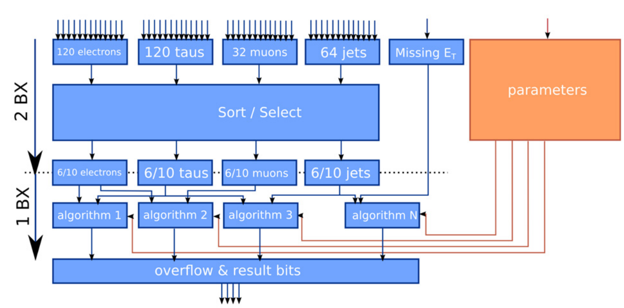

Figure 3: Block diagram of L1Topo execution. The input TOBs are sorted and truncated to reduce the combinatorial load put on the algorithms. Exactly 2 bunch group spacings (BX) of 25 ns are allocated to the sorting procedure.

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COMMISSIONING

The aforementioned goal of L1Topo is to improve the purity of L1 trigger selection by imposing kinematic and angular constraints. This is manifested as a rate reduction when the rate for a L1 trigger including a topological requirement is compared with the one for the same multiplicity and energy thresholds, but without the topological requirement. An example of this rate reduction is shown in Fig. 4. This rate reduction however does not cause any significant reduction in the selection efficiency [4].

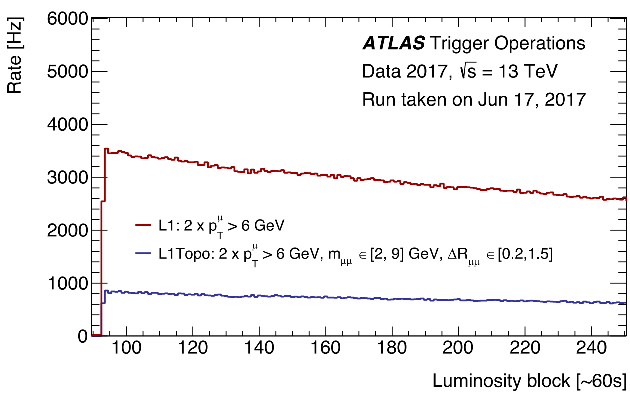

Figure 4: The rate vs. time of two triggers selecting two muons with transverse momentum larger than 6 GeV. One trigger (blue) includes the topological requirement that the two L1 muons form an invariant mass 2 GeV < Mμμ < 9 GeV and have angular separation 0.2<ΔR<1.5, while the other (red) does not [5].

The Xmon Online Rate Monitoring System

The Xmon rate monitoring system stands as one of the tools available to both trigger shifters and online trigger experts. Xmon provides real-time, luminosity scaled rate predictions based upon both offline and online trigger cross-section regressions [10].

Each individual trigger can be written in terms of cross-section by considering the current rate of the trigger and the instantaneous luminosity. Given a rate R, and a luminosity $\mathcal{L}$, division and adjustment for the trigger prescale PS, and number of bunches N, returns the trigger's observed cross section. This function is parametrized in time [10] and regression algorithms are performed in reference to the average interaction rate.

$$\sigma_{pp\to x}(t) = \frac{PS \cdot R_{pp\to x}(t)}{N_{bunches} \cdot \mathcal{L}(t)}$$

For L1Topo, the Xmon functionality was expanded to monitor the ratio between trigger rates. Specifically, the ratio of L1Topo items with their L1 equivalent without topological requirements. This in turn provides generalized real-time monitoring of the MUCTPI, CMX modules, CTP link, and the L1Topo modules themselves. Issues that involve systematic and widespread failure would immediately be visible if they involved the new L1Topo components. An example showing the ratio between the L1Topo rate and L1 rate for muons is shown in Fig. 5. This ratio is now monitored along with the L1 and HLT rate prediction quantities.

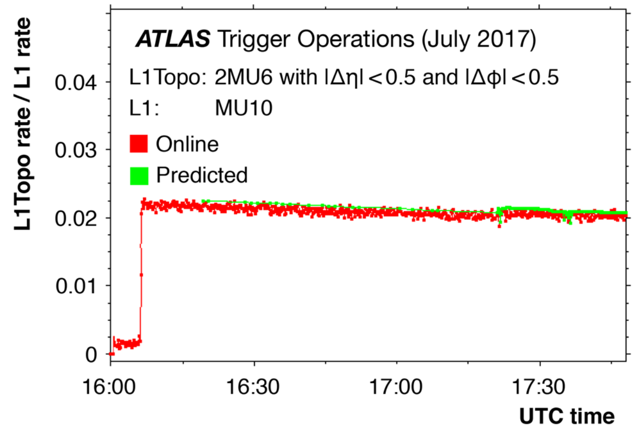

Figure 5: The ratio of a first level topological trigger (L1Topo) item rate and the associated first level trigger (L1) item rate. This measurement (red curve) is compared with predictions based on a linear pileup regression (green curve) for DY-BOX-2MU6/MU10 [5]. This plot shows excellent agreement between observed and predicted values.

VALIDATION

Hardware and Firmware Validation

Validation of the physical modules is of great importance; for L1Topo this was achieved in two ways. One such test was to analyze bitwise agreement in the board output given the same specified input vector. This can be performed only offline, using a specialized test rig. Results show great consistency, with a bit error rate set at an upper limit of 10^{-19}.

The second test was performed within the actual trigger environment at the experiment site and involved validation of the calculated angular separation, $\Delta\eta$. This was achieved by forcing specific trigger towers in the electromagnetic (EM) calorimeter with a $|\Delta\eta| > 3.0$ to "go hot." This angular separation is expected to be reflected in any L1Topo output that involves an angular cuts imposed upon EM TOBs.

Use of Offline Simulation

Proper validation requires accurate software modelling of the L1Topo system [9]. This expected decision from the software is then compared with the observed hardware decision. The results from a specific study involving the HT trigger algorithm, which imposes a cut to the E_T as calculated from jets with $p_T > 20$ GeV and $|\eta| < 3.1$, is shown in Fig. 6.

The excellent agreement between the expected and observed rates as a function of luminosity demonstrates the validity of the algorithm execution in the hardware components in terms of overall observed rate.

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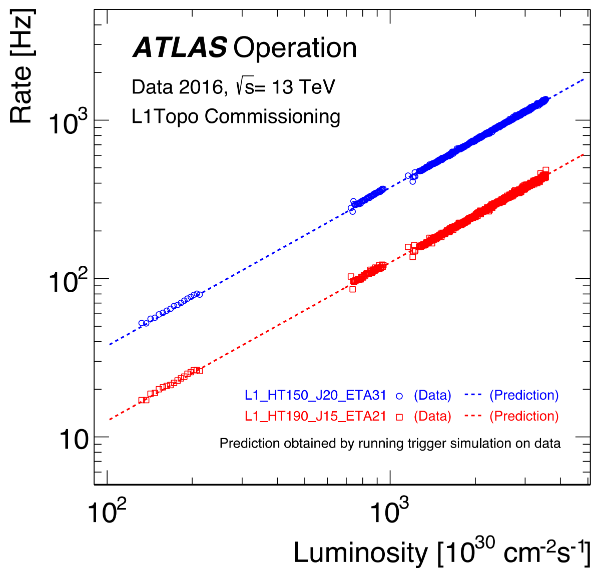

Figure 6: Trigger rates as a function of the instantaneous luminosity of two L1Topo triggers based on the H algorithm. The online trigger rates are compared to the prediction obtained by running the trigger simulation on an un-biased data sample [5].

Trigger rates provide a comprehensive overview of the algorithm performance. Consideration of hardware vs. simulation agreement on an event-by-event level provides additional and specific insights into the validity of the algorithm execution. Consideration of the bit-wise resolution of the trigger TOBs further improve this agreement. The data as shown in Fig. 7 show near 0% mismatch rate for both false positives and false negatives.

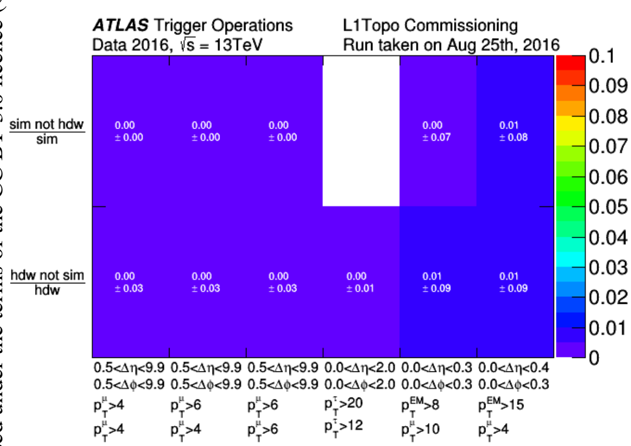

Figure 7: Event-by-event mismatches between hardware and simulation. O(1%) rates are shown for false positives (top) and false negatives (bottom) for L1Topo algorithms requiring angular separation for various TOB types and thresholds [5].

CONCLUSION

Following the thorough commissioning and successful validation of L1Topo, it has become clear that even with stringent bandwidth, latency, and hardware constraints, topological information can be extracted and utilized as part of a complex control scheme for data acquisition in the ATLAS detector. It is ultimately the TDAQ system that selects the events recorded, and this has great impact on the specific physics analyses performed with this data. With the implementation of L1Topo, greater purity and specificity of this data can be achieved at the high luminosity at which the LHC now operates.

The demands placed on the L1Topo subsystem, such as being low latency, high throughput, and free from angular and kinematic computation errors, are well met. Excellent bitwise agreement, extensive monitoring, and offline software and online firmware validation all show successful operation of the Level-1 topological trigger today, and this in turn opens the doors for the exciting physics analysis of tomorrow.

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