PROCEEDINGS OF SCIENCE

Phase-1 ATLAS Level-1 Trigger in Run-3

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The ATLAS Level-1 Trigger, crucial for the selection of LHC events at CERN, has been upgraded for Run-3 with state-of-the-art processors and electronic devices, extensively using optical links to enhance performance. The Calorimeter Trigger system, utilizing 10-fold higher granularity, enhances object identification alongside a redesigned Topological Processor for detailed angular analysis. Notably, the Muon Trigger system, with input from the newly installed muon sub-detector (New Small Wheel), improves Level-1 Trigger background rejection. Trigger Decision and Clock distribution were enhanced with new single-board modules. The Central Trigger system includes a System-on-Chip for the new Muon Interface, running control and monitoring applications directly on the hardware. This overview highlights the impact on the performance of the upgraded system, particularly under Run-3 high-intensity conditions.

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1. Introduction

The ATLAS detector has entered the third period of the LHC operation (Run 3) with an upgraded Level-1 (L1) Trigger in the frame of the overall ATLAS Phase-1 upgrade [1]. The L1 Trigger is the first stage of the ATLAS Trigger system reducing the collision event rate of 40 MHz to around 100 kHz. This can be achieved thanks to a tailor-made electronics system made of state-of-the-art electronic devices. This hardware-based part is followed by the second purely software Trigger stage, called High Level Trigger, that reduces the event rate further to the target frequency of about 3 kHz. The trigger system is complemented by the data acquisition system handling the detector readout and storage of the selected data at the CERN Data Center. The signal collision events are selected based on both the L1 and HLT accept decision consecutively.

The L1 Trigger system in Run 3 can be divided into three logical blocks [2]:

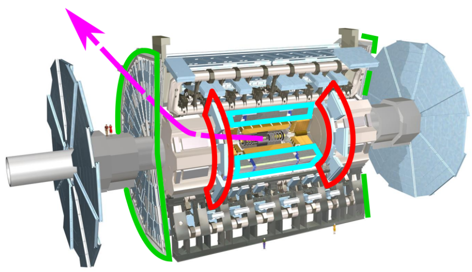
- L1 Muon Trigger (L1Muon), collecting data from the fast muon sub-detectors based on Resistive Plate Chamber (RPC), Thin Gap Chamber (TGC), its improved successors small-strip TGC (sTGC), and finally Micro-mesh Gaseous Structure (MicroMegas) technologies;
- L1 Calorimeter Trigger (L1Calo), processing reduced granularity information from the Liquid Argon (LAr) and Solid scintillator (Tile) based calorimeters; and
- L1 Central Trigger (L1CT), gathering all trigger inputs to issue the L1 Accept decision and providing the clock to all ATLAS sub-detectors.

Overall, the trigger system was updated with electronics capable of high-speed high-bandwidth optical connections. It enables the transfer of large amounts of trigger data using more compact cables. The upgrade of each system will be detailed in the following sections.

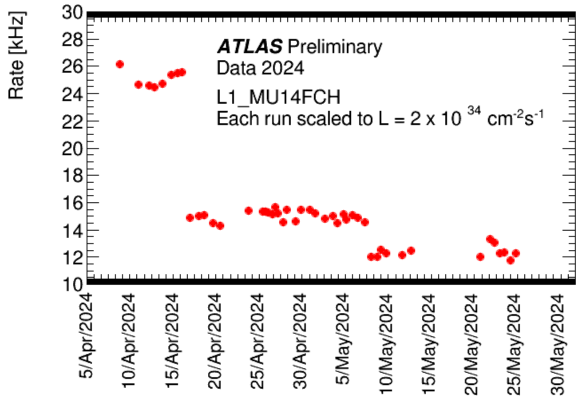
2. Level-1 Muon Trigger

The most significant change to the L1 Muon Trigger comes from the installation of the New Small Wheel (NSW), a new muon sub-detector placed in the end-cap region just between the barrel region and the toroid magnet. The important purpose of the NSW is the rejection of beam induced background particles, producing a number of fake muons detected in the muon end-caps. The fake muons are rejected thanks to the coincidence system between the NSW and Big Wheel (BW) end-caps. A signal muon from the collision has large enough energy to pass through the magnet with minimal bent (see Figure 1a), while the background muons bent significantly, so they are not likely to be detected in both endcaps. The NSW covers the coincidence in the range from 1.3 to 2.4 η, while the Tile calorimeter coincidence covers the range between 1.03 and 1.3 η. The system was designed to transmit the trigger information coming from the detector to the L1CT using optical links, thanks to which the cable volume to L1CT was reduced. The links transfer information on the position, momentum, and multiplicity of muons as well as their charge, magnetic field quality, coincidence with other layers of TGC and the coincidence with the already mentioned NSW and Tile.

The muon coincidence was added to the L1 Muon Trigger system gradually sector by sector throughout the year 2024 sector by sector as can be seen in Figure 1b. The addition of the coincidence helped to reduce the muon rate from around 25 kHz to 12 kHz and further tuning of



(a) Muon coincidence example [1]



(b) Muon rate reduction through Spring of 2024 [3]

Figure 1: Figure on the left: Description of the muon coincidence between BW (green) and NSW (red) or Tile calorimeter (cyan). An example of a signal muon is displayed as the magenta arrow. Figure on the right: The muon rate was significantly reduced thanks to the coincidence mechanism by the addition of muon sectors of NSW to the L1 Trigger system. 65 % of the sTGC sectors were added in the middle of April, then another 27 % were added on the 7th of May and then the rest, together with all MicroMegas sectors, after the 28th of May.

the whole system reduced the rate to 11 kHz. Thanks to the large muon trigger rate reduction, the ATLAS detector could afford to increase the acceptable average pileup of p-p collisions per bunch-crossing by three up to 64.

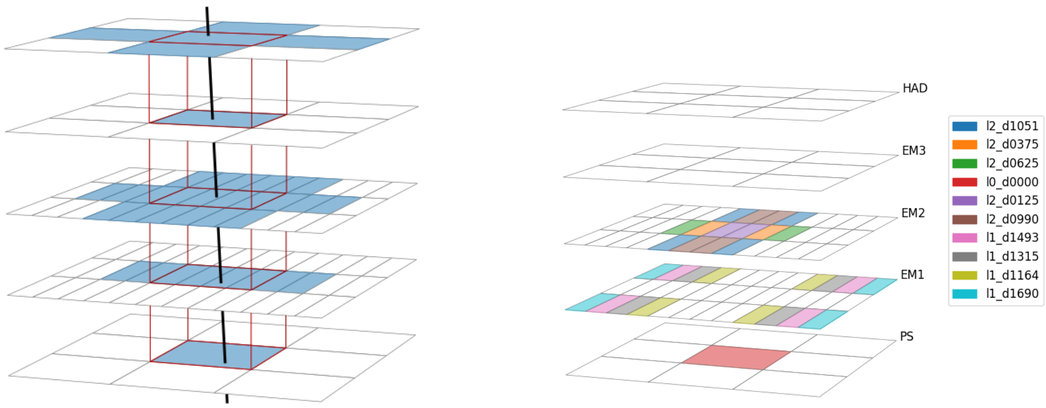
3. Level-1 Calorimeter Trigger

The L1Calo system was completely redesigned for Run 3. Digital signal Pre-processor and the Cluster and Jet/Energy Processors were replaced by a new modular system of Feature Extractors (FEXs). The FEX system now accomodates three different types of modules:

- eFEX (electron), for identification of electron, gamma, and tau objects;
- jFEX (jet), for reconstruction of jet, tau (three-prong), and missing transverse energy objects, and identification of the forward electrons; and
- gFEX (global), for processing of large-jets and missing transverse energy objects.

The double coverage of some physical objects is due to the use of different algorithms in different modules. The algorithms can have higher efficiency in specific cases and their eventual combination can improve the performance. The modular approach of the system enables easy addition of new FEXs dedicated to other physical objects or a particular region of the detector.

The new L1Calo system includes a completely redesigned L1 Topological processor (L1Topo) in the form of a multi-board system. The device gathers information from all FEXs and the L1Muon system and calculates angular features and mass of higher-level objects, for example, di-jet or di-leptons. In contrast to the legacy system, the L1Topo serves as the only connection point with the L1CT system (no direct connection with the FEXs).



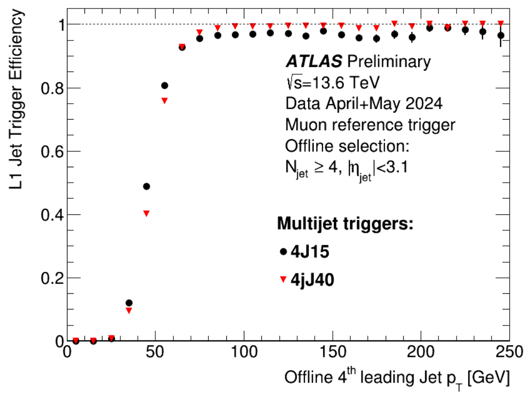
(a) Phase-1 L1Calo trigger tower highlighted in red **(b)** Individual cells as the input variables for the BDT

Figure 2: A sketch of the calorimeter cells employed in the L1Calo [4]. The cells are distributed across 5 layers: one pre-sampler, three electromagnetic, and one hadronic layer (on the left), in total, eleven cells per tower or a super-cell. Symmetrical distribution of individual cells around a seed tower across the calorimeter layers are utilized in the machine learning tau particle identification (on the right). The number of the label represents the distance from the center of the seed cell. The energy deposited in the cells with the same color serves as the BDT input (on both sides).

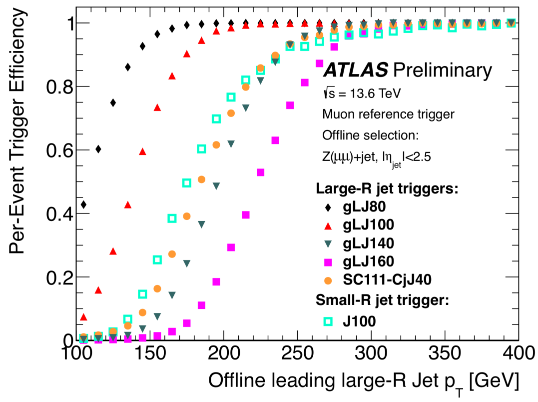
To keep up with the L1 input rate the L1Calo system processes the information from the LAr calorimeter at a lower granularity with respect the old L1Calo system. The Phase-1 upgrade also involves the addition of a new readout path called LAr Digital Trigger, which increases this granularity 10-fold in comparison with the legacy system. The new trigger tower of the system is depicted in Figure 2a. This and the state-of-the-art electronic of FEXs enable the employment of advanced object identification methods based on machine learning.

Variable thresholds for the energy deposit in the individual cells as well as increased number of cells across the layers provide enough information to feed machine learning methods for trigger object identification. The Boosted Decision Trees (BDTs) were chosen as an experimental method for the L1 tau trigger object identification of the eFEX. Summation of the cells around the tower (Figure 2a) and symmetrically placed surrounding cells (Figure 2b) serve as the input variables for the BDTs. These are calculated on the hardware level in the eFEX module employing fast FPGAs to be able to feed the trees and calculate the BDT score with very low latency. Commissioning of the machine learning based L1 tau triggers is in full swing and the first results can be expected in the late months of this year or in 2025.

This year is dedicated to the commissioning of jFEX and gFEX, while the primary triggers of eFEX were commissioned already in 2023 which resulted in the reduction of the electron trigger rate by around 20 % [4]. Finer cluster seeds and upgraded algorithms allow for better resolution of individual and close-by jets and therefore significantly improve the efficiency of the single jet as well as the multi-jet triggers as can be seen in the comparison with the legacy system in Figure 3a. The large-radius jet triggers also benefit from the upgrade, as demonstrated by the performance plot in Figure 3b.



(a) Multi-jet trigger turn-on curves [5]



(b) Large-radius jet trigger turn-on curves [4]

Figure 3: Performance plots of the L1 jet triggers. A set of large radius jet trigger turn-on curves for thresholds from 40 to 160 GeV (on the right). A comparison of the new (jJ40) and legacy (J15) multi-jet trigger turn-on curves (on the left).

4. Level-1 Central Trigger

The Level-1 (L1) Central Trigger is a critical component of the system, with the Central Trigger Processor (CTP) responsible for gathering inputs from various sources, including L1Muon, L1Calo, L1Topo, and Forward detectors. It issues the L1 Accept decision, featuring new optical inputs and a switch matrix for the accommodation of new inputs. Additionally, the system includes a redesigned Muon-to-CTP-interface (MUCTPI) board and a new board dedicated to the distribution of Trigger, Timing, and Control (TTC) signals, called ATLAS Local Trigger Interface (ALTI).

The ALTI board is meant as a TTC client for each sub-system, responsible for synchronizing the majority of the sub-detectors in ATLAS. It consolidates the functionality of three legacy boards into one, providing a "Mini CTP" feature that allows sub-systems to perform tests with the L1 Trigger in their own environment. ALTI offers locally programmable options, including random triggers, prescaling, deadtime, and a pattern generator, among other functions.

The MUCTPI has undergone a complete redesign, integrating 18 legacy boards into a single advanced board with optical connections, based on the ACTA standard. This upgrade allows for the processing of up to four Muon candidates per trigger sector in the end-cap TGC, compared to only two in the legacy system. It is natural to expect more muons and, in general, a busier environment in the forward region, therefore, the same upgrade was not aimed for the barrel region. It also enables overlap removal between muon sectors and provides full muon trigger information for L1Topo. A network-isolated System-on-Chip (SoC) is integrated into the board, running ATLAS Run Control software, a unique feature within ATLAS. The SoC includes advanced monitoring capabilities, with low-level software designed based on a high-level firmware description, and an XML-based register description. The board operates on a Linux OS, with a dedicated host computer acting as a gateway to the ATLAS technical network.

5. Conclusion

The commissioning of the Phase-1 ATLAS upgrade is nearing completion, with the widespread adoption of new technologies, including state-of-the-art processors, FPGAs, and optical connections. Redesigned electronics leverage the finer granularity of the calorimeters, with the LAr digital trigger providing a faster and more detailed readout. A modular approach has been implemented for the Feature Extractors of L1Calo, with electron triggers commissioned in 2023 and other primary triggers following in 2024. The integration of upgraded muon detectors, including all New Small Wheel sectors, has also been achieved in the ATLAS L1 Trigger system. Pioneering methods for controlling and monitoring electronic board operation, such as the use of SoC technology in the MUCTPI, gFEX, jFEX, and L1Topo, have been introduced. The system delivers high trigger efficiency while improving or maintaining turn-on curves and purity. Reduction of the muon and electron trigger rates enabled the ATLAS detector to increase the average pileup to 64 and even experiment with the amount of 65 during the 2024 data-taking year. Additionally, some of the hardware has been designed for easy adaptation or reuse in the upcoming Phase-2 upgrade [6].

References

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