PROCEEDINGS OF SCIENCE

# The ATLAS Trigger System

**D. O. Damazio on behalf of the ATLAS Collaboration**[a,*]

[a] *Brookhaven National Laboratory,*
*Physics Department, Bldg 510A, Upton, NY 11973, USA*

*E-mail:* Denis.Oliveira.Damazio@cern.ch

The ATLAS experiment in the LHC Run 3 uses a two-level trigger system to select events of interest to reduce the 40 MHz bunch crossing rate to a recorded rate of up to 3 kHz of fully-built physics events. The trigger system is composed of a hardware based Level-1 trigger and a software based High Level Trigger. The selection of events by the High Level Trigger is based on a wide variety of reconstructed objects, including leptons, photons, jets, b-jets, missing transverse energy, and B-hadrons to cover the full range of the ATLAS physics programme. We will present an overview of improvements in the reconstruction, calibration, and performance of the different trigger objects, as well as computational performance of the High Level Trigger system.

*42nd International Conference on High Energy Physics (ICHEP2024)*
*18-24 July 2024*
*Prague, Czech Republic*

*Speaker



https://pos.sissa.it/

PoS(ICHEP2024)879

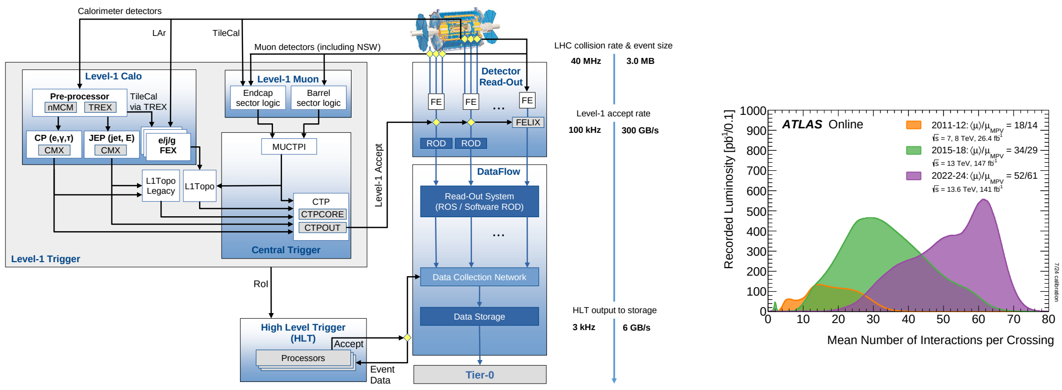


**Figure 1:** The ATLAS Trigger System for Run 3 and luminosity profile of the three LHC runs.

## 1. Introduction

The present work describes the ATLAS trigger system with emphasis on the changes that were implemented between the end of the LHC Run 2 data taking period (2015-2019) and Run 3 (2022-). ATLAS [1] is an ensemble of particle physics detectors exploring the collisions provided by the Large Hadron Collider (LHC) at CERN, Switzerland. The LHC provides proton-proton (Heavy Ions) collisions at 13.6 (5.36) TeV in the centre of the detector and the emerging particles cross the tracking systems (Pixel, SCT, TRT), the EM and Hadronic calorimeters and the large Muon Spectrometer measuring the properties of the different types of particles. A solenoidal and a toroidal magnetic systems help to measure their charge and momentum.

The LHC nominally provides 40 MHz of bunch crossings with 27.5 independent proton collisions in each one, a number referred to as $<\mu>$. During different LHC data taking periods (see Fig. 1 right), Run 1, 2 and the present Run 3, the LHC is constantly increasing such number, reaching $<\mu>$ values above 64. High levels of pileup affect all of the trigger systems and require new techniques to maintain or improve upon the physics performance required by analyses teams whilst keeping the rate of selected events below 3 kHz.

## 2. The Trigger System and ATLAS Upgrades

The ATLAS Trigger [2, 3] is a complex staged system (see Fig. 1 left) starting from coarse granularity information in the calorimeter and muon systems to identify larger energy deposits in the calorimeters (Level-1 Calo) as well as high $p_T$ tracks in the muon chambers (Level-1 Muon). Final decisions at this hardware step are taken by the Central Trigger Processor (CTP). Combinations of items are also possible, for instance calculating the invariant mass of pairs of objects with the L1 Topo processor. This hardware system reduces the input rate to less than 100 kHz while also providing pointers to the identified Regions of Interest (RoI's) in the detector. The next processing step is a farm of computers, called the ATLAS High-Level Trigger (HLT), which reaches a final decision on keeping or rejecting the event by exploring with full detector granularity either within the RoIs or within the whole detector volume, referred to as Full Scan (FS).

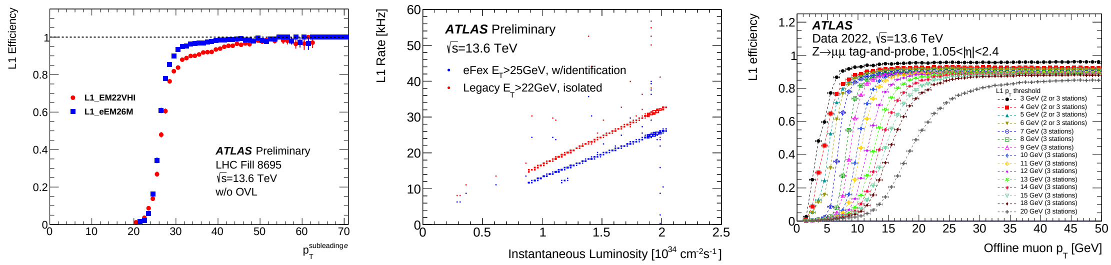


**Figure 2:** Efficiency (left) and acceptance rate (center) of electron trigger comparing legacy (red) and new Super-Cell based (blue) systems. The new muon system efficiencies for newly available thresholds (right).

Between Run2 and Run3, ATLAS undertook a number of major upgrades. The Level-1 Calo system primitives used in Runs 1 and 2, were based on the concept of Trigger Towers (TT - regions with granularity of $\delta\eta \times \delta\phi = 0.1 \times 0.1$ in the calorimeter) to define candidates such as electrons, photons, taus (eFex) or jets (jFex, gFex). The experience in Runs 1 and 2, demonstrated that this was too coarse a granularity and that an intermediate level between the TTs and the full calorimeter cell granularity could be explored. Hence the concept of Super-Cell was adopted, subdividing the EM component of each TT into 10 Super-Cells. These Super-Cells are used as inputs to FEature eXtractor boards, based on FPGAs that reconstruct electrons, photons, taus, jets candidates or calculate missing $E_T$ at the event level[4]. Furthermore, the Muon spectrometer was upgraded with two New Small Wheels (NSW) covering the endcap regions of the detector. This, together with some modifications on the hardware of the Level-1 Muon, brought the possibility of reducing output rates by adding more Muon transverse momentum thresholds (15 instead of 6) and the flexibility to add up to four quality requirement flags. Finally, the HLT software was completely rewritten to operate in multithread mode with important impact in the throughput obtained as will be further discussed.

## 3. Trigger Performance results

The concept of Super-Cells was particularly useful for detecting smaller objects in the calorimeter such as electron or photons as cluster confinement variables are calculated by the eFex. This reduces the acceptance of jets faking electrons whilst increasing detection efficiency (see Figs. 2 left and center). Stability of the trigger with respect to $<\mu>$ was improved.

Furthermore, we could measure the excellent performance of multiple new muon trigger thresholds (see Fig 2 right) that we could now implement with the installation of the NSW and the corresponding new L1-Muon. Thanks to this implementation, an overall output rate reduction of around 14kHz could be achieved. The overall L1+HLT efficiency is clearly well mapped in MC/data comparisons used later for Trigger performance analysis.

The HLT Calorimeter code unpacks information from this detectors either in RoI mode (for electron/photon/tau triggers) or in FS mode for jets and Missing Transverse Energy (MET) in an optimal way by keeping in memory all the cells of the detector per event processing slot. A memory map such as this speeds up cell-level reconstruction. Multiple clustering techniques are

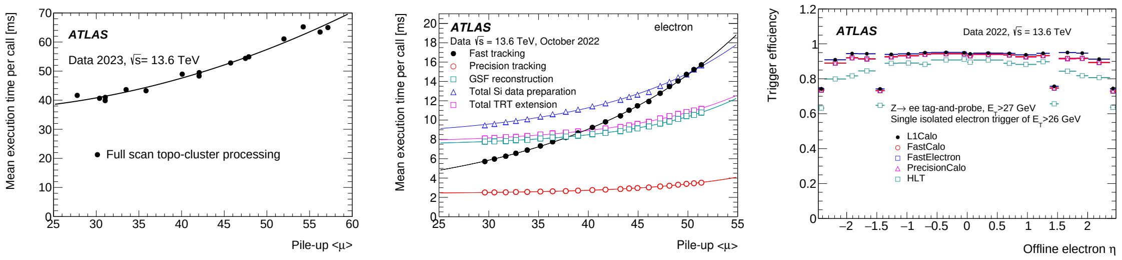


**Figure 3:** FS topo cluster algorithm processing time (left) and different tracking algorithmic steps (center) demonstrating dependency with <$\mu$>. Evaluation of the Electron Efficiency in steps (right).

explored and their resolution with respect to the offline extracted variables is constantly evaluated. Some cell energy corrections are not feasible at the trigger run time, limiting the efforts for HLT/offline harmonization. The most computing resources demanding calorimeter algorithm is the FS Topological Cluster builder, which reconstructs clusters based on each cells signal-to-noise ratio and the cell's neighboring cell relations. The algorithm execution time is dependent on detector occupancy related to <$\mu$> as expected and depicted in Fig. 3 (left).

This is also the case for the tracking reconstruction algorithms. As shown in Fig. 3 (center), the initial tracking (Fast Tracking reconstruction) is also dependent on the detector occupancy as more combinations of space-points must be explored in the search for tracks. The following algorithms performing precise track fitting and extrapolation are more resilient to <$\mu$>, but must be seeded by this Fast Tracking. The tracking code was also updated to handle Large Radius Tracking for Long Lived Particles (LLPs). Furthermore, the code can handle multiple RoIs at once, avoiding duplicated reconstruction in overlapping zones by building Super-RoIs. For Electron tracks, the Gaussian Sum Filter approach was used to compensate for possible Bremsstrahlung losses in the track path[5].

The ATLAS Electron Trigger uses the concept of ringers of cells in the Calorimeter RoIs to extract new features from the particle deposition shower shape. This information is sent to a Neural Network (NN) code that eliminates efficiently fake candidates for the signal of interest. This reduces the need to run the tracking code in a large number of RoIs. The rest of the electron and photon chains (the same as the electron chains without tracking) is similar to the offline reconstruction code, usually with a different tunings for some of the selection parameters. The efficiency performance at the different selection stages is shown in Fig. 3 (right).

The Tau reconstruction also uses Machine Learning (ML) techniques combining tracking and calorimeter information. Its efficiency is quite inclusive to a loose transverse energy cut. A reasonable rate for combined items (electron-tau, muon-tau, di-tau) is obtained. Jet triggers added a new Particle Flow stage and are studied given their importance for resonances, H->bb and other physics topics. Multiple jet signatures are also checked.

Multiple MET algorithms are used in the ATLAS trigger. Simpler algorithms perform a vectorial energy/position sum of all reconstructed objects (calorimeter cells or topological clusters). During Run 3, algorithms taking as input particle-flow-objects reconstructed via FS tracking were also introduced. The performance of these approaches is presented in Fig. 4 (left). All these MET

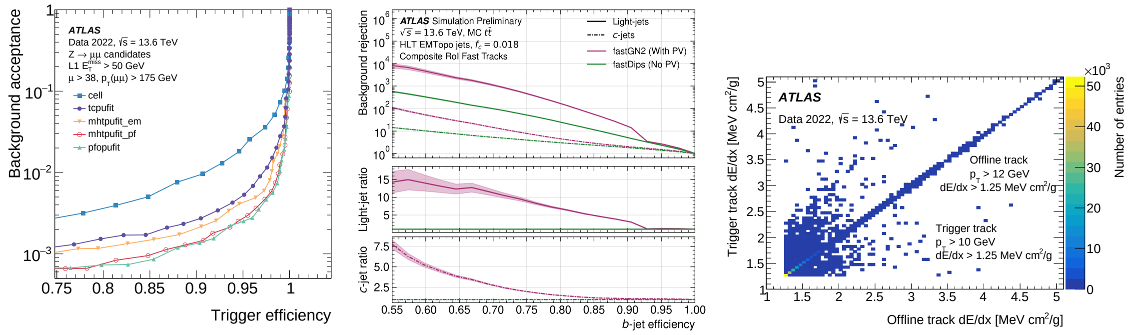


**Figure 4:** Relation between efficiency and background acceptance for MET Triggers (left), B-jet ML preselection performance (center) and LLP trigger/offline software comparison (right).

classifiers were subsequently combined via a neural network classifier (not shown).

Another important upgrade was the restructuring of the B-jet triggers using a pre-selection step that reconstructs tracks Super-RoIs. These are initially defined where calorimeter-only jets where reconstructed with a transverse momentum above 15 GeV/c. Features of these jets (their mass, vertex measurements and so on) are used in a fast Graph NN[6] algorithm to reduce lighter quark jets background. A large rate reduction is obtained with very high efficiency and a much small number of events are reconstructed with the computer intensive FS tracking and evaluated by the particle flow algorithm, providing a reasonable rate of recorded events as visible in Fig. 4 (center).

Other interesting triggers were implemented such as specific ones for LLPs. Massively charged particles could appear in the Inner Detector volume and their tracks are not necessarily projective from the interaction point. For models which produce such particles, the pixels touched by them stay longer above their firing threshold, resulting in an indirect measure of the objects' energy. This is explored offline and the trigger is validating a similar approach as depicted in Fig. 4 (right).

To profit from the multi-core processors in the market for the HLT farm, multiple trigger processes are run per computing unit. However, we could identify a high (order of 1.5 GB/process) increase in the memory footprint (see Fig. 5 left). To minimize this, a multi-threaded approach based on a significant rewrite of the HLT framework was adopted. A smaller occupancy (less than 200MB/thread) was reached but, given the locks included to avoid concurrent memory writing, some limits in the throughput can be seen (Fig. 5 center). The ATLAS HLT is now running in a hybrid mode with 16 processes with 4 threads each for each processing node.

The rate of saved data follows the LHC luminosity profile as depicted in Figure 5 (right). There are number of triggers for which only HLT-reconstructed physics objects are saved. This Trigger Level Analysis (TLA) is used to explore signatures for which the rates would be too high (e.g: lower $p_T$ resonances).

## 4. Conclusions

The ATLAS Trigger System is being adapted to the hardware upgrades presently installed in the detector and starts to include new algorithm techniques being explored in the offline analysis. The

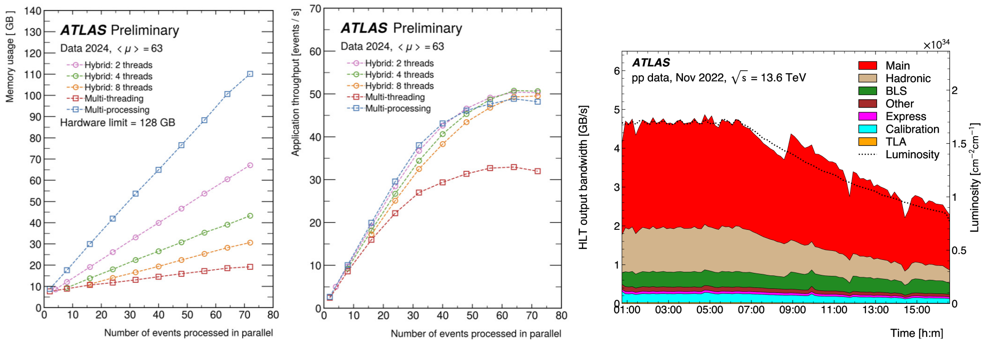


**Figure 5:** Memory occupancy (left) or Trigger throughput (center) for multiple processes or multiple threads, motivating the present operational point. Final storage of events (right) correlated to the Luminosity profile.

higher segmentation of the Level-1 Calorimeter primitives improved the initial detector selections as well as the available features from the NSW.

The system relies more on hardware designed algorithms in FPGAs and ML techniques are clearly benefiting the Trigger (and, globally, the ATLAS experience). The re-writing of the ATLAS code into multi-threaded mode, provided an extra handle to control the performance of the software trigger level and is exploring the limits of the available computing resources.

Overall, the ATLAS Trigger System is becoming a highly specialized ensemble of optimal trigger systems, controlling the bandwidth of accepted events for the hardware and software steps in the limits of what is possible to extract from the detector, whilst keeping a broad physics programme.

## References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* **3**(2008) 10.1088/1748-0221 [hep-ex/S08003].

[2] ATLAS Collaboration, *The ATLAS experiment at the CERN Large Hadron Collider: a description of the detector configuration for Run 3*, *JINST* **19**(2024)[P05063].

[3] ATLAS Collaboration, *The ATLAS trigger system for LHC Run 3 and trigger performance in 2022*, *JINST* **19**(2024) [P06029].

[4] ATLAS Collaboration, *Level-1 Calorimeter Trigger Public Results* https://twiki.cern.ch/twiki/bin/view/AtlasPublic/L1CaloTriggerPublicResults#ATLAS_Level_1_calorimeter_trigge (2024).

[5] ATLAS Collaboration, *Improved electron reconstruction in ATLAS using the Gaussian SumFilter-based model for bremsstrahlung*, **ATLAS-CONF-2012-047** https://cds.cern.ch/record/1449796 (2012).

[6] ATLAS Collaboration,*Public b-Jet Trigger Plots for Collision Data*. https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BJetTriggerPublicResults#2024_13_6_TeV (2024).