Real Time Data Analysis With the ATLAS Trigger at the LHC in Run-2

Pierre-Hugues Beauchemin, on behalf of the ATLAS Collaboration

Abstract—The trigger selection capabilities of the ATLAS detector have been significantly enhanced for the Large Hadron Collider (LHC) Run-2 in order to cope with the higher event rates and with a large number of simultaneous interactions (pile-up) per proton–proton bunch crossing. A new hardware system, designed to analyze real-time event-topologies at level-1, came to full use in 2017. A hardware-based track reconstruction system, expected to be used real time in run-3, is designed to provide track information to the high-level software trigger at its full input rate. The high-level trigger (HLT) selections widely rely on off-line-like reconstruction techniques and in some cases multivariate analysis methods. Despite the sudden change in LHC operations during the second half of 2017, which caused an increase in pile-up and, therefore, also in CPU usage of the trigger algorithms, the set of triggers (so-called trigger menu) running online has undergone only minor modifications thanks to the robustness and redundancy of the trigger system and the use of a leveling luminosity scheme in agreement with LHC and other experiments. This article gives a brief yet comprehensive review of the real-time performance of the ATLAS trigger system in 2017. Considerations will be presented on the most relevant parameters of the trigger (efficiency to collect signal and output data rate) and details on some aspects of the algorithms which are run real time on the HLT CPU farm will be presented.

Index Terms—ATLAS, Large Hadron Collider (LHC), performance, Run-2, trigger, upgrade.

I. INTRODUCTION

ONE of the main objectives of the Large Hadron Collider (LHC) physics program in Run-2 is to discover new phenomena beyond the standard model (BSM) of particle physics. Following the tight constraints set on many BSM scenarios by the Run-1 LHC analyses, a large spectrum of still viable BSM models requires very exclusive final states in small regions of the phase space. Another central piece of the LHC physics program is the precision measurement of electroweak and quantum chromodynamics (QCD) processes and a complete mapping of the various Higgs boson couplings and parameters. In order to meet these research objectives, data samples with very high statistics must be used for the analysis of data collected by the detectors, the LHC is constantly increasing the luminosity delivered to the experiments. This constitutes a challenge for the trigger and data acquisition (TDAQ) system of the LHC experiments because of the limited CPU and storage available.

During Run-1, the ATLAS trigger system operated efficiently primarily at center-of-mass energies of 7 and 8 TeV and at instantaneous luminosities of up to $8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.\(^1\) In Run-2, the center-of-mass energy increased to 13 TeV, enhancing the total proton–proton (pp) cross section by more than a factor of two, therefore, increasing the trigger rate by more than 100%. In addition, changes in the LHC beam parameters resulted in an increase of the instantaneous luminosity up to a factor 3, with up to 80 pp-interactions per bunch-crossing (in-time pile-up) in 2017. Finally, a reduction of the bunch spacing from 50 to 25 ns added interactions from neighboring bunch-spacing (out-of-time pile-up). These changes in the LHC operation, designed to allow for the experiments to take data samples with larger statistics, made the Run-1 trigger menu completely unsustainable. To preserve the physics program of the experiment, a significant upgrade of the ATLAS trigger system was needed for Run-2.

II. RUN-2 IMPROVEMENTS OF THE ATLAS TRIGGER SYSTEM

Improvements of the hardware, firmware, and software parts of the trigger system must aim at a better rate control and processing time per event, higher reconstruction and identification efficiencies with respect to off-line selections, and resolution effects closer to off-line measurements. A detailed description of the upgrade of the trigger system is presented in [2].

A. Level 1 Trigger Improvements

From the hardware perspective, the fourth layer of resistive plate chambers (RPCs) was added, before Run-1, to the muon spectrometer in order to recover acceptance lost at the first trigger level (L1) near detector feet and elevator shafts. These chambers were, however, only equipped with electronics during the long shutdown following Run-1. A net increase of 3.6% in the muon L1 trigger efficiency resulted from this hardware addition while reducing the trigger rate by 60%, thanks to its impact on the suppression of particles not originating from the interaction point.

Multiple changes have also been brought to the hardware and firmware L1 trigger system. A new fast-tracking (FTK)
reconstruction system has been developed [3] and will become fully operational in Run-3. The FTK system provides global inner detector (ID) track reconstruction at L1, using lookup tables in associative memory chips for pattern recognition. This FPGA-based track fitter performs a fast linear fit and the tracks are made available to the high-level trigger (HLT) system. The FTK allows for the use of tracks at much higher event rates in the HLT than is affordable using CPU systems, improving, among others, the tau and the B-meson physics (B-physics) trigger performances.

In order to refine the muon and calorimeter-based object kinematic calculations and to make more sophisticated event selections at L1 (e.g., invariant mass cuts, the angular distance between jets, and so on), two FPGA-based processor modules (L1-Topo) have been added to the L1 trigger system and became fully operational in 2017. Consequently, changes to the central trigger processor (CTP) were required (see [2] for details). The improvements made to the CTP and other L1 components allowed for a bunch-by-bunch pedestal subtraction that significantly reduced the rate of L1 jets and missing transverse energy ($E_T^{miss}$) triggers. It also linearized the L1 trigger rate as a function of the luminosity and the position of bunches in a train and improved the bunch-crossing identification. Finally, the CTP upgrades allowed to double the number of L1 trigger signatures and bunch-group selections providing more sophisticated trigger chains for very exclusive event topologies. The improvements brought to the entire L1 trigger system allowed for an L1 accept rate of 100 kHz, which constitutes approximately a 30% increase with respect to the corresponding rate in Run-1. It also made it possible to keep a similar L1 trigger composition as in Run-1 despite the dramatic increase in the luminosity and pile-up.

B. High-Level Trigger Improvements

The entire HLT architecture has been changed after Run-1. The level 2 and event filter farms have been merged to allow for more flexibility, to simplify the hardware and the software, and to remove rate limitations between fast and precision processing by using the resources more efficiently. To deal with the increase in the readout rate due to a higher L1 accept rate, but to also increase the output rate of the TDAQ system, the read-out system has also been upgraded. Thanks to these improvements, data have been stored at a rate of 1.1 kHz in Run-2, almost a factor of 3 increase with respect to Run-1 [2].

The output rate is, however, not the only limiting factor; the HLT processing time is also limited by the number of CPU cores available at HLT. The time taken to process one event at the LHC is determined by both the trigger menu and by the number of pile-up interactions which are continuously increasing with time, as can be seen in Fig. 1. At an instantaneous luminosity of $5.2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ and an average pile-up of $\langle \mu \rangle = 15$, the average HLT processing time is 230 ms, which is well within the 2–3 s time available before time-out. However, as was reported in [2], the average processing time increases with luminosity and pile-up, and the distribution of HLT processing time has a tail that goes well above the time-out threshold. Part of these long-processing events can be recovered thanks to the data stream procedure (debug stream), but there is an imperative need for HLT algorithms to cleverly deal with pile-up to avoid a significant decrease in the triggering performance.

Many improvements have been brought to the online ID and muon spectrometer tracking [2]. For example, to limit CPU usage, multiple stage track reconstruction was implemented, thanks to the redesign of the HLT architecture in Run-2. It allows, among other things, to use larger region of interest around L1 objects, to see hadronic taus or b-quark jets (b-jets) reconstruct for example, before precision tracking exploits aspects of off-line tracking to improve resolution and reduce the rate at no cost in efficiency, as can be seen in Figs. 2 and 3.

The signal output from the calorimeter readout is also processed to produce cells or clusters that are then used to reconstruct physics objects, such as electrons, photons, taus,
jets, and $E_T^{miss}$. The cells and the clusters are also used in the determination of the shower shape and isolation characteristics of these particles to enhance the purity of their identification. Two different clustering algorithms are used to reconstruct the clusters of energy deposition in the calorimeter: the sliding-window algorithm [5] and the topo-clustering algorithm [6]. The first stage of their reconstruction consists of unpacking the data from the calorimeter. With the very high amount of pile-up events produced in Run-2, the possibility to reconstruct topcusters for the full calorimeter on each event was compromised. However, with a new memory caching mechanism allowing for a very fast unpacking of the data and with the development of off-line-like clustering algorithms for HLT, the mean processing time for topcustering has been kept to 82 ms, making topcusters available to tau, jets, and $E_T^{miss}$ algorithms on every events. An energy correction based on the bunch-crossing identification in a train and the average pile-up contribution for such bunch-crossing is applied to the topcusters to reduce the out-of-time pile-up distortion of their energy measurement. As a consequence, the energy resolution of the topcusters reconstructed online is comparable to what is achieved offline.

Building on these various improvements, the trigger menu composition and the lowest transverse energy/momentum thresholds used by the different trigger objects for selecting events without random rejection (i.e., without prescale), has been designed to comply with the requirement of the LHC physics program. In 2015, it was even more inclusive than it was in Run-1. To maximize the output of the experiment relevant to the complete set of physics analyses to be carried during Run-2, the trigger menu is optimized for several luminosity ranges, changing even during a fill to use all available resources while the instantaneous luminosity and the average pile-up drop during a fill. An example of the bandwidth usage of the various triggering objects is presented in Fig. 4. Finally, the streaming strategy has been simplified: rather than using different data collection tags (streams) for events with muons (muon stream), electrons and photons (egamma stream), and jets, taus, and $E_T^{miss}$ objects (JetTauETmiss stream), only one single main physics stream has been used to channel all of the events to be used in most physics analyses. This change reduced event duplication, thus reducing storage and CPU resources required for online reconstruction by roughly 10%. In addition, a new streaming strategy, based on partial event storage of only HLT reconstructed objects sacrificing the ATLAS detector data needed for off-line reconstruction, has been developed in Run-2. Such streams are used for calibration purpose and to carry trigger-level analyses (TLA) [7]. Such analyses are particularly useful for physics studies where the phase space probed is at kinematics lower than what is provided by the lowest unprescaled triggers. For example, more than one order of magnitude of dijet low $p_T$ events can be recovered by the TLA compared with what standard offline analyses can afford [2]. This is another example of how creativity on real-time analysis serves the physics objective of the experiment.

III. EXAMPLES OF REAL-TIME DATA ANALYSES

ID, muon spectrometer tracks, and calorimeter cells and clusters are not directly used to select events at trigger level but are used as ingredients to reconstruct electrons, muons, taus, jets, b-jets, and $E_T^{miss}$ objects. In turn, these objects can be used to select multiple particle events, such as the triggers dedicated to B-physics, for example. The reconstruction and

2Note that some special triggers do not rely at all on the reconstruction of tracks or clusters, such as the random trigger, the minimum bias triggers, or the empty bunches triggers. These are not discussed here.
identification of these particles are critical for selecting as many events containing W bosons, Z bosons, H bosons, and top-quarks as possible, on which most of the LHC precision measurements bare. The particles reconstructed at trigger level are also used to signal new phenomena. Inefficiencies in their reconstruction or too high kinematic thresholds could compromise a BSM discovery or the precision of the SM parameters and cross sections to be obtained from these data. The task of the trigger is, therefore, to control rates in a compromise a BSM discovery or the precision of the SM measurements bare. The particles reconstructed at trigger level can be kept very close to the corresponding threshold at L1. This is impressive because the L1 accept rate is about 100× larger than the HLT output. In Fig. 7, we can see that the HLT efficiency turn-on curve is steeper than the L1 one. The cost for keeping such a low HLT threshold is, however, that 100% efficiency is never reached by the HLT L1 one. The cost for keeping such a low HLT threshold is, however, that 100% efficiency is never reached by the HLT L1 one. The cost for keeping such a low HLT threshold is, however, that 100% efficiency is never reached by the HLT identification algorithm compared with offline. Comparing the top and bottom panel of Fig. 8 shows that the tighter is the identification working point, the larger is the signal efficiency lost. However, increasing the $p_T$ threshold well beyond 30 GeV would compromise the precision measurements of many important physics parameters, such as the W mass [8].

A. Electron Trigger

Like any other object, the objective of HLT electron reconstruction algorithms is to reject events as fast as possible, while identifying electrons and reconstructing their kinematics almost as efficiently and accurately as what can be done offline. Because of the Run-2 improvements to the ATLAS TDAQ system, especially of the better CPU time management at the HLT, multivariate techniques are now being used online to: 1) calibrate the energy of the clusters used to reconstruct electrons and photons and 2) implement the likelihood discriminant developed offline to identify electrons with a better purity versus efficiency figure of merit. Three working points are used at HLT: loose, medium, and tight. The composition of the likelihood is the same as offline, with the exception of the momentum loss due to bremsstrahlung that is not accounted for in the online algorithm. This approach has a better rejection for the same efficiency as the simple cut-base approach that was used in Run-1, or, conversely, better efficiency for the same rate, as is demonstrated in Fig. 6 with simulation. Because of the high rejection rate of these electron identification algorithms, the lowest unprescaled $p_T$ threshold at the HLT can be kept very close to the corresponding threshold at L1. This is impressive because the L1 accept rate is about 100× larger than the HLT output. In Fig. 7, we can see that the HLT efficiency turn-on curve is steeper than the L1 one. The cost for keeping such a low HLT threshold is, however, that 100% efficiency is never reached by the HLT identification algorithm compared with offline. Comparing the top and bottom panel of Fig. 8 shows that the tighter is the identification working point, the larger is the signal efficiency lost. However, increasing the $p_T$ threshold well beyond 30 GeV would compromise the precision measurements of many important physics parameters, such as the W mass [8].

It is, therefore, better to sacrifice a few percent efficiencies for all $p_T$, to keep the bulk of the electron $p_T$ distribution.

The dielectron trigger rate with even lower $p_T$ is attributed to the lowest unprescaled single lepton (electron, muon, and tau) triggers. This is shown in Fig. 5 that gives an example of the single-electron trigger rate compared with the di-electron trigger rate with even lower $p_T$ threshold on each electron (top), and an estimate of the physics processes contributing to the lowest unprescaled single-electron trigger used in 2016 (bottom). Similar patterns apply to muons. Jets are, however, more tricky. Because the LHC is a hadron collider, the realm of the strong interaction, the production rate of dijet and multijet events is so large that the jet thresholds have to be very high to keep rates manageable. For example, the lowest unprescaled single-jet trigger has a threshold of 360 GeV, more than one order of magnitude larger than for the corresponding electron and muon triggers. Similar arguments apply to tau and $E_T^{miss}$. That was already the case in Run-1. However, in Run-2, these triggers had also to develop strategies to stay robust against pile-up in order to keep the thresholds relatively stable with respect to what they were in Run-1. Improvements in the different object reconstruction algorithms, building on the improvements of the overall trigger system presented in Section II, succeeded in meeting the objective of keeping high efficiency at comparable kinematic thresholds as in Run-1 for all particles [electrons (e), muons (μ), taus (τ), and so on]. Some of these successes are summarized in the following.

### A. Electron Trigger

Like any other object, the objective of HLT electron reconstruction algorithms is to reject events as fast as possible, while identifying electrons and reconstructing their kinematics almost as efficiently and accurately as what can be done offline. Because of the Run-2 improvements to the ATLAS TDAQ system, especially of the better CPU time management at the HLT, multivariate techniques are now being used online to: 1) calibrate the energy of the clusters used to reconstruct electrons and photons and 2) implement the likelihood discriminant developed offline to identify electrons with a better purity versus efficiency figure of merit. Three working points are used at HLT: loose, medium, and tight. The composition of the likelihood is the same as offline, with the exception of the momentum loss due to bremsstrahlung that is not accounted for in the online algorithm. This approach has a better rejection for the same efficiency as the simple cut-base approach that was used in Run-1, or, conversely, better efficiency for the same rate, as is demonstrated in Fig. 6 with simulation. Because of the high rejection rate of these electron identification algorithms, the lowest unprescaled $p_T$ threshold at the HLT can be kept very close to the corresponding threshold at L1. This is impressive because the L1 accept rate is about 100× larger than the HLT output. In Fig. 7, we can see that the HLT efficiency turn-on curve is steeper than the L1 one. The cost for keeping such a low HLT threshold is, however, that 100% efficiency is never reached by the HLT identification algorithm compared with offline. Comparing the top and bottom panel of Fig. 8 shows that the tighter is the identification working point, the larger is the signal efficiency lost. However, increasing the $p_T$ threshold well beyond 30 GeV would compromise the precision measurements of many important physics parameters, such as the W mass [8].
Fig. 6. Comparison of the likelihood-base and the cut-base HLT electron triggers efficiency as a function of the off-line electron candidate’s transverse energy $E_T$ with respect to true reconstructed electrons in $Z \rightarrow ee$ simulation. The HLT$_{e24 \_ medium \_ iloose \_ L1EM18VH}$ trigger is the Run-1 algorithm requiring an electron candidate with $E_T > 24 \text{ GeV}$ satisfying the cut-based medium identification, while HLT$_{e24 \_ lhmedium \_ iloose \_ L1EM18VH}$ corresponds to the Run-2 algorithm using the likelihood-based lhmedium electron identification. Both trigger chains also require the same track isolation selection and are seeded by the same level-1 trigger (L1$_{\text{EM18VH}}$) [4].

Fig. 7. Efficiency of the L1 EM20VHI trigger (circles) and the combined L1$_{\text{EM20VHI}}$ and HLT$_{e24 \_ hlight \_ nod0 \_ ivarloose}$ trigger (blue triangles) as a function of the off-line electron candidate’s transverse energy ($E_T$) of the tab and probe method on a sample of 2017 ATLAS data and on a $Z \rightarrow ee$ Monte Carlo sample [4]. The data-to-MC agreement is very good. The efficiency is calculated for two different trigger chains: an electron candidate with $E_T > 24 \text{ GeV}$ satisfying the likelihood-based very loose identification and seeded by a 20-GeV electron L1 trigger (Top); and an electron candidate with $E_T > 26 \text{ GeV}$ satisfying the likelihood-based tight identification and seeded by a 22-GeV electron L1 trigger (Bottom).

These hard decisions have to be taken while designing the trigger menu, by the whole ATLAS community, but the high performance of the trigger makes this decision easier. Note, as we can see in Fig. 8, that the data to Monte Carlo agreement are excellent, showing that we have a good understanding of the behavior of this trigger.

### B. Muon Trigger

For the muon triggers, the largest challenge is not so much the large background reduction, but the efficiency lost at L1 due to limited instrumentation coverage. As can be seen in Fig. 9, there are significant variations of the L1 muon trigger efficiency as a function of the azimuth angle $\phi$ because of the limited RPC coverage for central rapidity ($|\eta| < 1.05$) due to the detector feet, elevator shafts, and toroid magnets. We can see that the HLT adds almost no inefficiency in selecting muons that can be reconstructed offline compared with the L1 trigger as HLT and off-line both use the same detector signal. Fig. 10 presents the muon trigger efficiency with respect to off-line as a function of the transverse momentum of the off-line muons. We can see on the top panel that the L1 inefficiency due to the lack of coverage of the RPC chambers amounts to about 30%. The problem is, however, about three times smaller for the region covered by the TGC detector, as can be seen on the bottom panel of Fig. 10. In both cases, we can see that the HLT-only muon trigger algorithm is performing very similarly than the off-line muon reconstruction and identification algorithm: the HLT turn-on curve with respect to L1 is very close to being a step function. Note that despite this limit of acceptance, the trigger and off-line reconstruction algorithm are very precise and the background usually well understood, such that measurements in the muon channel are often the most precise.

### C. Jet Trigger

Besides the rate difficulties discussed earlier, the main challenges for jet triggers at the HLT are to perform an
Fig. 9. Absolute efficiency of level 1 (L1) MU20 trigger and absolute and relative efficiencies of the OR of mu26_ivarmedium with mu50 HLT plotted as a function of $\phi$ of off-line muon candidates in the barrel detector region. The efficiency is computed with respect to off-line isolated muon candidates which are reconstructed using standard ATLAS software and are required to pass “medium” quality requirement. The selection is restricted to the plateau region with $p_T > 27$ GeV [4]*.

Fig. 10. Absolute efficiency of level 1 (L1) MU20 trigger and absolute and relative efficiencies of the OR of mu26_ivarmedium with mu50 HLT plotted as a function of $p_T$ of off-line muon candidates in the barrel detector region (Top), and the endcap detector region (Bottom) [4]*. The efficiency is computed exactly as described in the caption of Fig. 9.

accurate calibration of the jets and to trigger them in a high pile-up environment efficiently. As presented in Section II-B, topoclusters, very similar to the off-line ones, are used as input to the HLT jet algorithm. Jets are then calibrated in a two-step procedure similar to that adopted for off-line analyses: first, pile-up contribution is subtracted on an event-by-event basis using the calculated area of each jet and the measured energy density in the central part of the calorimeter; second, the response of the calorimeter is corrected using a series of $p_T$- and $\eta$-dependent calibration factors derived from simulation. The calibration strategy is continually improving, as can be seen in Fig. 11. Starting in 2017, the calibration also uses track information. The sharp HLT efficiency turn-on curves presented in Fig. 11 prove that there is a good agreement between the HLT and the off-line jet energy measurements. Note that on the contrary to electron and muon efficiency measurements, a bootstrap method [9] is used to obtain the jet trigger efficiency as is shown at the top panel of Fig. 12. Many physics analyses focus on events with heavily boosted massive particles decaying to multiple jets that are collimated. To avoid large efficiency lost due to jet reconstruction algorithm not adapted to this kind of event topologies, the jet reconstruction algorithm is fast enough to be run twice on an event in order to produce large size (large-R) jets from the output of the standard jet algorithm. Special jet trigger elements are then added to the menu to select such large-jet events efficiently. The performance of this jet algorithm is shown at the bottom panel of Fig. 12.

D. Tau Trigger

While data samples enriched in leptonically decaying tau particles are selected by electron and muon triggers, hadronically decaying taus require a dedicated trigger. These are, in essence, narrow jets. Keeping the tau trigger rates under control for $p_T$ thresholds low enough for the physics of interest is particularly challenging. To meet this objective, a three-step reconstruction algorithm is deployed at the HLT. In the first step, narrow calorimeter energy deposits are identified from the reconstructed topoclusters found in a cone of size $\Delta R = 0.2$ around the L1 object used to seed the HLT. In a second step, tau candidates are selected if there are a small number of reconstructed tracks pointing to the tau cluster, with the leading track central to it. Finally, a collection of variables built from the topoclusters and the tracks obtained by a precision tracking algorithm is used in a boosted decision tree (BDT) multivariate algorithm to produce a score with which the final tau identification is made. To maximize the correlation
Top: efficiencies for HLT single-jet triggers as a function of leading off-line jet $p_T$. Triggers denoted HLT_jX accept an event if a jet is reconstructed at HLT with $E_T > X$ GeV. The unprescaled trigger with the lowest threshold requires a jet with $E_T > 380$ GeV [4].

Bottom: efficiencies for HLT large-R single-jet triggers as a function of the leading off-line trimmed jet $p_T$. Blue circles represent a trimmed large-R jet trigger with a $p_T$ threshold of 420 GeV. Adding an additional 30-GeV cut on the jet mass of the selected trimmed trigger jet is shown in green triangles. The mass cut significantly suppresses the QCD di-jet background, allowing a lower $p_T$ threshold of 390 GeV, while retaining nearly all signal-like jets with a mass of above 50 GeV.

between online and off-line identifications, the BDT is trained using off-line inputs. To mitigate pile-up effects, all variables used in the BDT are corrected according to the expected average interaction per bunch-crossing. Measurements of the tau trigger efficiency as a function of the off-line tau $p_T$ have been obtained using the tag-and-probe technique on high purity samples. Results are presented in Fig. 13. As can be seen in Fig. 13, the tau trigger efficiency is well modeled by the Monte Carlo (top panel), and the HLT is only adding an extra marginal source of inefficiency compared with L1 (bottom panel).

### E. $E_T^{\text{miss}}$ Trigger

The largest challenges, however, probably come from the $E_T^{\text{miss}}$ triggers which require information about the entire detector, but which is also highly sensitive to pile-up. To benefit from the pile-up removal from jet energy measurements at the HLT, an off-line-like $E_T^{\text{miss}}$ was developed using trigger jets as input (MHT) rather than calorimeter cells or topoclusters. While such a reconstruction algorithm performed very well in 2015 and in early 2016, it rapidly became clear that this was not sufficient: the MHT algorithm is exponentially dependent on the pile-up increase. During the shutdown between Run-1 and Run-2, another algorithm was developed that was suppressing pile-up energy on an event-by-event basis beyond what is reconstructed in the jets. This algorithm uses topoclusters energy in regions of the calorimeter where the hadronic activity is less intense, and then performs a fit, under the assumption that the total pile-up does contribute to no net $E_T^{\text{miss}}$, to estimate the pile-up contribution to regions of the detector where the hadronic activity of the main process is likely to be situated [2]. As can be seen in Fig. 14, this algorithm (PuFit) succeeded in linearizing the $E_T^{\text{miss}}$ rate dependence on pile-up, allowing much lower thresholds than would be otherwise possible. As can be seen in Fig. 15, the PuFit algorithm is even a little bit more efficient than the MHT algorithm, despite being much more different than the off-line $E_T^{\text{miss}}$ reconstruction algorithm. Note that because of
Fig. 14. Trigger cross section as measured by using online rate and luminosity is compared for the main trigger $E_{\text{miss}}^{T}$ reconstruction algorithms used in 2016 ("mht") and 2017 ("pufit") as a function of the mean number of simultaneous interactions per pp bunch crossing averaged over all bunches circulating in the LHC [4].

Fig. 15. Combined L1 and HLT efficiency of the missing transverse energy triggers HLT_xe110_pufit_L1XE50 and HLT_xe110_mht_L1XE50 and the efficiency of the corresponding L1 trigger (L1_XE50) are shown as a function of the reconstructed $E_{\text{miss}}^{T}$ (modified to count muons as invisible) [4]. The events shown are taken from data with a $W \rightarrow \mu\nu$ selection to provide a sample enriched in real $E_{\text{miss}}^{T}$.

L1 improvements presented earlier, the L1 threshold is kept so low (50 GeV) that the only source of inefficiency with respect to offline comes from the much more precise HLT algorithms.

IV. CONCLUSION

Large statistic data samples constitute one of the key ingredients for exploring new physics and performing high-precision measurements. To do this, the LHC luminosity is continually increased. This constitutes a challenge for data-taking. To cope with the high luminosity and pile-up conditions of LHC in Run-2, the ATLAS TDAQ system went through a series of hardware, firmware, and software upgrades. At L1, these improvements led to a 30% bandwidth increase and in the capacity to efficiently select events with a broader range of topologies. At the HLT, they allowed for the development of more performant algorithms deployed on all events, such as the multistage track reconstruction, and the full calorimeter scan topocluster formation with powerful pile-up mitigation. Information from tracks and calorimeter clusters are then used to efficiently select events with electrons, muons, taus, jets, and $E_{\text{miss}}^{T}$, often even exploiting multivariate techniques. Stronger correlations in the energy measurements of objects reconstructed online and offline have been observed compared to Run-1. Thanks to all these improvements, ATLAS succeeded in selecting with high performance the events needed for the success of its Run-2 physics program. New challenges are now awaiting for Run-3!

* From ATL-DAQ-PROC-2018-005. Published with permission by CERN.

REFERENCES

[1] G. Aad et al., “The ATLAS experiment at the CERN large hadron collider,” J. Instrum., vol. 3, Aug. 2008, Art. no. S08003.
[2] M. Aaboud et al., “Performance of the ATLAS trigger system in 2015,” Eur. Phys. J. C, vol. 77, p. 317, May 2017.
[3] G. Aad et al., “Technical design report fast tracker (FTK),” ATLAS Collaboration, Geneva, Switzerland, Tech. Rep. ATLAS-TDR-021, Jun. 2013.
[4] ATLAS Trigger Public Plots not Published in a Paper can be Obtained. Assessed: Jun. 1, 2018. [Online]. Available: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults
[5] G. Aad et al., “Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data,” Eur. Phys. J. C, vol. 72, p. 1909, Mar. 2012.
[6] G. Aad et al., “Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1,” Eur. Phys. J. C, vol. 77, p. 490, Jul. 2017.
[7] G. Aad et al., “Trigger-object Level Analysis with the ATLAS detector at the Large Hadron Collider: Summary and perspectives,” ATLAS Collaboration, CERN, Geneva, Switzerland, Tech. Rep. ATLDAQ-PUB-2017-003, 2017.
[8] J. A. Aguilar-Saavedra et al., “Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” Eur. Phys. J. C, vol. 78, p. 110, Feb. 2018.
[9] G. Aad et al., “The performance of the jet trigger for the ATLAS detector during 2011 data taking,” Eur. Phys. J. C, vol. 76, p. 526, Sep. 2016.
[10] M. Aaboud et al., “Determination of jet calibration and energy resolution in proton-proton collisions at $\sqrt{s} = 8$ TeB using the ATLAS detector,” ATLAS Collaboration, CERN, Geneva, Switzerland, Tech. Rep. CERN-EP-2019-057, 2019.
[11] D. Krohn, J. Thaler, and L.-T. Wang, “Jet trimming,” J. High Energy Phys., vol. 2, p. 84, Feb. 2010.