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PERFORMANCE OF THE ATLAS MUON TRIGGER IN RUN 2

M.M. Morgenstern

On behalf of the ATLAS collaboration

Nikhef, National institute for subatomic physics, Amsterdam, The Netherlands

E-mail: [a] marcus.matthias.morgenstern@cern.ch

The ATLAS trigger system is essential for fulfilling the physics program of the ATLAS experiment. It consists of two steps, a hardware-based Level-1 trigger and a software-based high-level trigger to select events of interest at a suitable recording rate. Both stages underwent upgrades to cope with the challenges of LHC Run 2 data-taking at a centre-of-mass energy of 13 TeV and instantaneous luminosities up to 2×10^{34} $cm^{-2}s^{-1}$. The design of the ATLAS muon trigger and its performance in proton-proton collisions at 13 TeV are presented.

Keywords: ATLAS, LHC, Trigger, Muon, TDAQ

1. Introduction

The trigger system of the ATLAS experiment [1] is an essential component of it and is designed to efficiently select events of high interest for physics analyses. Prompt muons are of crucial importance in many physics analyses at the LHC, ranging from precise Standard Model measurements and top physics to Higgs physics and searches for new particles. Thus an efficient muon trigger is essential to provide the necessary inputs for the analyses.

The ATLAS trigger system consists of a hardware-based Level-1 (L1) trigger and a software-based High-Level trigger (HLT). The Level-1 trigger decision is formed by the central trigger processor (CTP) based on the inputs provided by the L1 muon and calorimeter triggers as well as from several other subsystems. Events accepted at L1 are passed to the HLT, which runs algorithms close to the offline reconstruction and takes the final acceptance decision.

The increased rate of collision data at the higher instantaneous luminosities achieved at the LHC and the increased center-of-mass energy provide enormous physics potential, but set new challenges for the trigger system. To cope with these challenges the muon trigger system was upgraded.

An overview of the trigger design and recent upgrades to the muon trigger as well as its performance measured in 2017 proton-proton collision data will be outlined.

2. The ATLAS muon trigger

Muon triggers are based on the information provided by the muon spectrometer (MS) and the inner detector (ID) of the ATLAS detector. The muon spectrometer is based on three large air-core superconducting toroids. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. Several detector technologies are used to provide fast response for triggering purposes as well as precision tracking. In the central region ($|\eta| < 1.05$) three layers of resistive plate chambers (RPCs) and in the end-cap regions ($1.05 < |\eta| < 2.4$) three layers of thin gap chambers (TGCs) are installed. To detect the deflection of the muon trajectory in the toroid magnetic field three layers of monitored drift tube chambers (MDTs) are installed covering $|\eta| < 2$. In the region $2.0 < |\eta| < 2.7$ two layers of MDTs are combined with one layer of cathode strip chambers (CSCs). The ID provides track measurements based on hits in the pixel, semiconductor tracker (SCT) and transition radiation tracker (TRT), arranged in successive layers, with the pixel detector closest to the interaction point, surrounded by a 2T magnetic field provided by a solenoid. It covers a fiducial region up to $|\eta| = 2.5$.

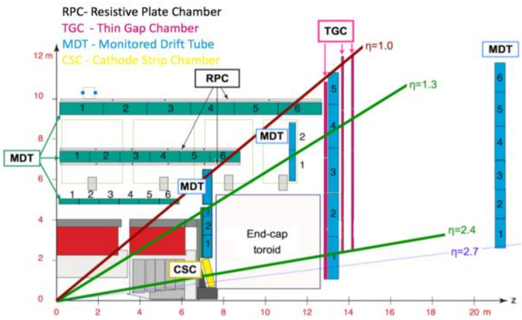

Figure 1. Schematic drawing of one quarter cross-section of the muon system of the ATLAS detector [2]

3. Level-1 muon trigger

At Level-1 muons are identified by spatial and temporal coincidence requirements on the hits provided by the RPCs or TGCs. To estimate the p_T of the muons, the degree of deviation from the hit pattern of an infinite momentum assumption is used to define six L1 thresholds. Information on Regions of Interest (RoIs) is provided by the central trigger based on the

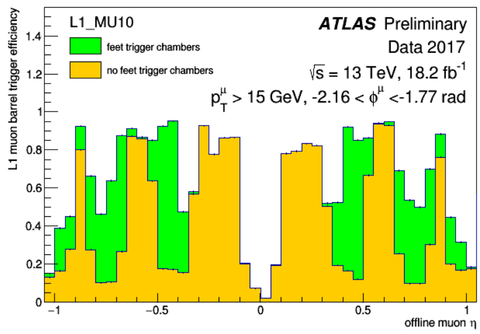

Figure 2. L1 muon trigger efficiency in one ϕ slice as a function of the muon candidate pseudo-rapidity η [3]

L1 decision, and passed to the HLT. The typical size of a RoI in ΔηxΔϕ is 0.1 x 0.1 (0.03 x 0.03) in the barrel (end-cap) region. In the barrel region for the three highest p_T thresholds hits in all three layers are required, while for the remaining lower p_T thresholds the hit requirement is loosened to two coincidence hits. In the end-cap regions the coincidence in three layers is required for all thresholds. To increase the coverage, additional RPC chambers have been installed in 2015 in the regions close to the feet that support the ATLAS detector. Figure 2 shows the L1 muon trigger efficiency in one slice of the azimuthal angle with the new chambers versus η. In green the effect of the additional RPC chambers can be seen.

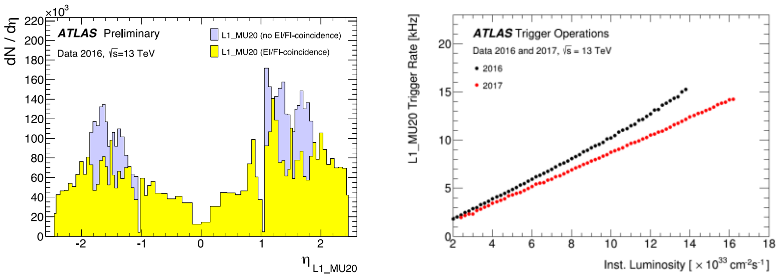

Figure 3. Left: The pseudo-rapidity (η) distributions of the L1 muon trigger with the p_T threshold of 20 GeV (L1_MU20) and the rate reduction effect by a coincidence with small-wheel TGCs in end-cap inner (EI) and forward inner (FI) chambers. Right: L1_MU20 trigger rate as a function of instantaneous luminosity in 2016 (black) and 2017 (red) data-taking [4]

For the end-cap regions an additional coincidence of the small-wheel TGCs in the forward inner (FI) and end-cap inner (EI) chambers is required to reduce fake muon contributions from particles not originating from the interaction point. As shown in Figure 3 (left) fake muons can be significantly suppressed. In 2017, the overlap region at the barrel feet region and look-up table in the end-cap region have been optimized using 2016 data, the resulting rate reduction is presented in Figure 3 (right).

4. High-Level muon trigger

The muon reconstruction at the HLT is split into a fast and a precision reconstruction stage. In the fast reconstruction stage the MDT precision hits are used to refine the muon candidate provided by the L1. First, MS-only muon candidates are built by performing a track fit based on the precision measurement of drift times and positions in the MDT chambers. The transverse momentum is assigned via look-up tables. Subsequently, the MS track is back-extrapolated to the interaction point and combined with tracks reconstructed in the inner detector, forming combined muon candidates with refined track parameters. In the regions equipped with CSC chambers, an additional measurement outside the magnetic field is used to back-extrapolate to hits in the CSC layer to improve p_T resolution (see Figure 4). Selection criteria defined for each muon trigger chain are applied to these muon candidates to allow early rejection of fake muons.

If the fast reconstruction step is passed successfully, the muon candidate enters the precision stage. Starting from the refined RoI provided by the fast reconstruction, segment and track reconstruction exploiting the information from all MS detectors is performed. As for the fast stage, MS-only muon candidates are built first and are subsequently combined with ID tracks to form combined muons. In addition to the back-extrapolation from the MS to the ID (inside-out), there exists another algorithm that extrapolates ID tracks to the MS in case the

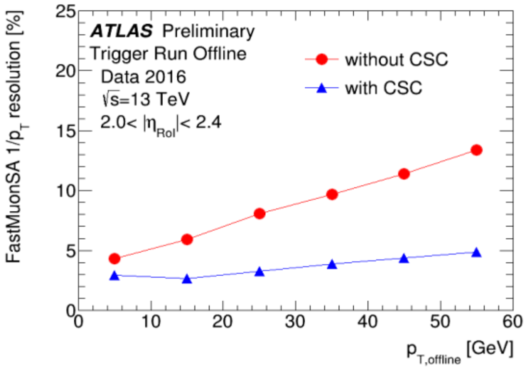

Figure 4. Impact of the CSC hit measurement on the transverse momentum resolution of the fast muon reconstruction as a function of the p_T of the reconstructed muon [4]

former fails (outside-in). This recovers about 1-5% of muons at low p_T.

These baseline algorithms run only for the RoIs provided initially by the L1 trigger. To recover efficiency losses from the L1 trigger, another algorithm searches for muon candidates in the full detector (full-scan). As this is very costly in terms of CPU consumption, it is typically considered for multi-muon triggers where one muon passed the baseline sequence and the second muon is searched for in the full detector. The full-scan procedure first builds muon candidate tracks in the MS followed by track reconstruction in the full ID. Subsequently a combined fit is executed.

MS-*only* triggers are also available. In this case the muon reconstruction is only run in the MS. While combined muons are suitable for the majority of physics analyses, MS-only triggers are crucial as well, e.g. in searches for long-lived particles, which do not leave a full trajectory in the ID due to their displaced decay.

To cope with the rate limitations, additional selections are applied on the muon candidates built at the HLT stage. First they are required to pass certain p_T thresholds. As just applying p_T cuts is not sufficient to get sustainable rates at low p_T, additional isolation criteria are required. Isolation enforces that there is only little activity in the detector around the muon candidate by cutting on the relative track-p_T sum in a cone around the muon candidate with respect to the candidate's p_T. To reflect the boosted topology of high p_T jets, the isolation cone varies as a function of the muon p_T. Applying isolation discards mainly non-prompt muons from heavy flavor, pion and kaon decays, while accepting nearly 100% prompt muons from Z-boson decays.

Dedicated triggers for di- or multi-muon signatures as well as combinations with other physics objects, like electrons or hadronically decaying taus are provided as well. In total several hundred muon chains are included in the trigger menu, while the majority runs prescaled[1].

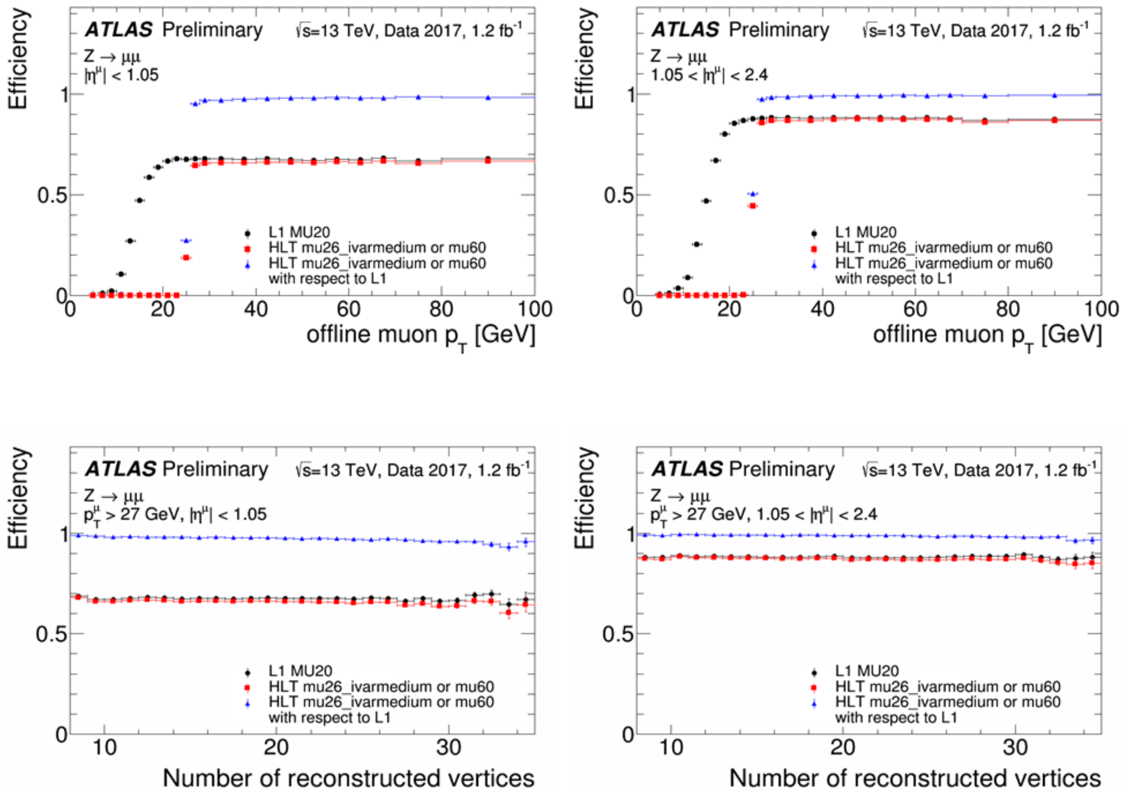

Figure 5. L1 and HLT muon trigger efficiency measured in $Z \to \mu\mu$ events as a function of the offline muon p_T (top) and number of reconstructed vertices (bottom). Left: Barrel region. Right: End-cap region. The black dots represent the L1_MU20 efficiency. In red the combination of the HLT triggers with 60 GeV p_T threshold as well as the isolated trigger with 26 GeV p_T requirement is shown. The blue curve shows the HLT efficiency with respect to the L1 efficiency, i.e. the pure HLT efficiency [4]

[1] A prescale of X means that only one out of X accepted events is recorded and the others are discarded.

5. Efficiency measurement

The performance of the muon triggers is continuously evaluated exploiting a tag-and-probe method using $Z \rightarrow \mu\mu$ events, which provide a clean signature. Selected events are required to contain two muons with opposite charge and their invariant mass to be within 10 GeV around the Z mass.

The tag muon is required to be a combined offline reconstructed muon within the fiducial region of the detector and to pass medium identification, as described in detail in [5]. This selects an unbiased sample of probe muon candidates used to measure the efficiency, defined as the fraction of offline reconstructed muon candidates passing several stages of the trigger. Single trigger efficiencies are shown in Figure 5. In the two plots at the top the efficiency as a function of the transverse momentum of the offline muon is shown, while in the two plots at the bottom the dependence on the number of reconstructed vertices, a measure of the amount of pile-up, is shown. Given the different technologies and acceptances of the MS detectors, efficiencies are evaluated separately in the barrel (left) and end-cap (right) regions. The black dots represent the efficiency for the L1 trigger with 20 GeV threshold. HLT efficiency for p_T thresholds of 60 GeV and 26 GeV with additional isolation requirement are given by the red dots. In blue the HLT efficiency with respect to the L1 efficiency is shown. The pure HLT efficiency is nearly 100%. A small degradation at higher numbers of reconstructed vertices is observed, indicating that the dependence of the efficiency on pile-up is small.

6. Conclusion

Muon triggers are of crucial importance for fulfilling the physics program of the ATLAS experiment. They have been successfully adapted to cope with the increased challenges during LHC Run 2 data-taking at a center-of-mass energy of 13 TeV. A high data-taking efficiency has been observed and measured in $Z \rightarrow \mu\mu$ events. Installation of additional chambers increasing the detector acceptance yielded higher L1 efficiencies. Additional updates on the muon trigger design have further increased the efficiency in LHC Run 2.

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