

Performance of the ATLAS Muon Trigger in Run I and Upgrades for Run II

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Abstract. The ATLAS experiment at the Large Hadron Collider (LHC) has taken data at a centre-of-mass energy between 900 GeV and 8 TeV during Run I (2009-2013). The LHC delivered an integrated luminosity of about 20 fb^{-1} in 2012, which required dedicated strategies to ensure the highest possible physics output while effectively reducing the event rate. The Muon High Level Trigger has successfully adapted to the changing environment from low instantaneous luminosity ($10^{32} \text{ cm}^{-2} \text{ s}^{-1}$) in 2010 to the peak high instantaneous luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$). The selection strategy has been optimized for the various physics analyses involving muons in the final state. We will present the excellent performance achieved during Run I.

In preparation for the next data taking period (Run II) several hardware and software upgrades to the ATLAS Muon Trigger have been performed to deal with the increased trigger rate expected at higher centre-of-mass energy and increased instantaneous luminosity. We will highlight the development of novel algorithms that have been developed to maintain a highly efficient event selection while reducing the processing time by a factor of three. In addition, the two stages of the high level trigger that was deployed in Run I will be merged for Run II. We will discuss novel approaches that are being developed to further improve the trigger algorithms for Run II and beyond.

1. Introduction

The ATLAS experiment [1] at the LHC has a broad physics program with a wide variety of final state objects populating different kinematic ranges. These include high-mass resonances decaying into muon pairs, Higgs decays to electroweak bosons decaying into muons or muon pairs ($H \rightarrow W^*W$, $H \rightarrow Z^*Z$), and some rare decay searches using multi-muon signature (eg $B_s \rightarrow \mu\mu$). In these analyses, mainly data acquired by the muon trigger were used. Therefore, it is important to understand and model the trigger performance over a wide kinematic range with different event topologies. To prepare for high energy and luminosity running conditions of Run II, there have been several upgrades to both the trigger hardware and software.

2. Muon trigger in ATLAS

Four different detector technologies are used to trigger and reconstruct muons in the ATLAS muon spectrometer. The Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) have fast response times ($\sim$ nanoseconds) and are active every beam crossing. These chambers have a position resolution of the order of a few millimeters. On the other hand, the other two types of detector, the Monitored Drift Chambers (MDT) and Cathode Strip Chambers (CSC) are high resolution detectors with spatial resolution on the order of 100 microns but have longer



response times and are therefore not used in the first level trigger. A schematic layout of the muon spectrometer is shown in Figure 1.

The trigger system is very important for hadron collider experiments to reduce the large event rates while maintaining high efficiency for processes of interest. An overview of the ATLAS trigger and DAQ as configured during Run I is shown in Figure 2. It consisted of three steps:

- Level-1 (L1) is the first step of the trigger system and based on custom electronics. The geographical location of muon candidates, called Region of Interest (RoI), are determined by RPC and TGC hits and coincidence requirement.
- Level-2 (L2) is software based and seeded by the Level-1 RoIs. The track parameters are estimated by incorporating the information from the MDT with the information from the TGCs and RPCs. The transverse momentum (p_T) is estimated from these hit patterns and the magnetic field. The L2 track is extrapolated to the interaction point and the muon spectrometer tracks are combined with inner detector tracks reconstructed from the RoI. The final track parameters at L2 are estimated from this combined track.
- The Event Filter (EF) has access to the full event data and reconstructs the events with a precision that is comparable to that obtained by offline reconstruction. It is also possible to combine the muon information with other signatures because the algorithms are run after event building.

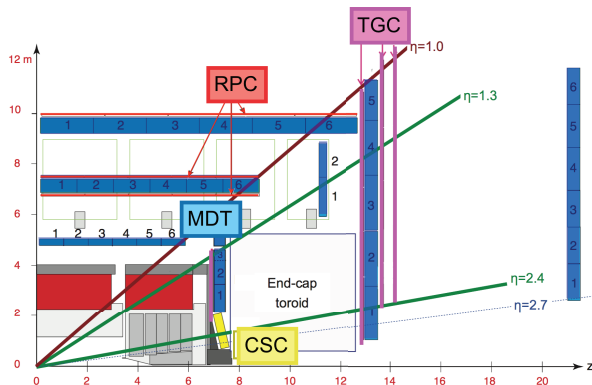


Figure 1. Four kinds of muon detector in ATLAS. TGC and RPC are used mainly in Level-1 and MDT and CSC are used in HLT.

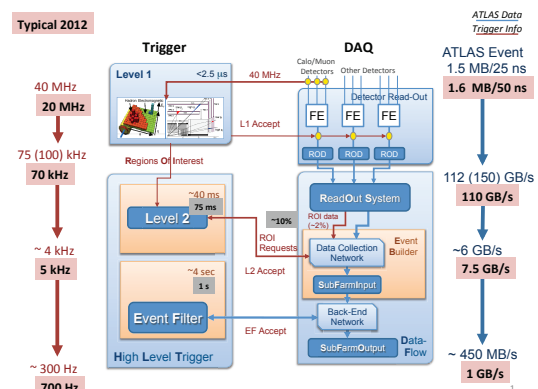


Figure 2. The ATLAS trigger system in Run I.

In Run I, the L2 and EF selections were executed on two separate computer farms. For Run II, they have been merged into a single High-Level Trigger (HLT) farm. However, the logic underlying the trigger decision remains very similar to Run I.

3. Efficiency measurement for Run I

The measurement of the trigger efficiency is one of the most critical checks in understanding the performance of the system and crucial for physics analysis. Since only events satisfying a trigger are recorded, special precautions are taken to perform an unbiased measurement of the trigger efficiency. The primary method used for determining the trigger efficiency is the "Tag and Probe" using di-muon events. One of the muons is required to trigger the event. The efficiency is then estimated by examining the probability for the other muon to also fire the trigger. The muon that is required to trigger the event is called the "tag" muon while the other side muon is called the "probe" muon. The Z boson and J/ψ meson are used to measure the

trigger efficiency for high and low- p_T muons. The procedures and results are described separately and are described in detail in Ref. [2].

3.1. Efficiency measurement for high- p_T muons using Z tag and probe

The decays of the Z boson are used to measure the trigger efficiency for muons with $p_T > 10$ GeV. The tagged muon is required to have passed the single muon trigger p_T threshold of 24 GeV. Although there were many different muon triggers utilized in Run I, the 24 GeV trigger is focused on, as it was the lowest unprescaled single muon trigger for the bulk of the data collected at 8 TeV. This trigger also had an isolation requirement with a loose criterion of $\sum_{\Delta R < 0.2} p_T^{trk} / p_T < 0.12$ to reduce the rate. The lowest unprescaled single-muon trigger without an isolation requirement in Run I had a p_T threshold of 36 GeV. The resulting efficiency measurement using the combined data sample for pseudorapidity range $|\eta| < 1.05$ and $|\eta| > 1.05$ is shown in Figure 3.

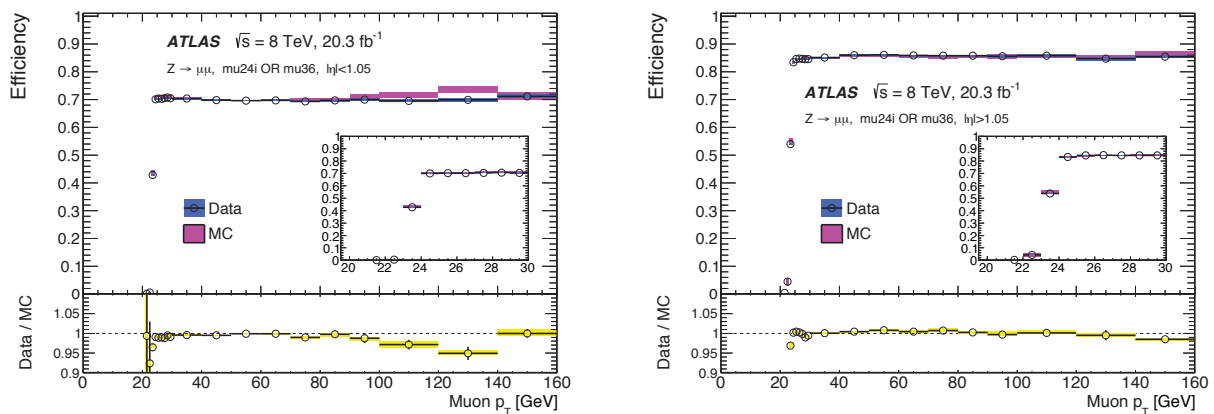


Figure 3. Efficiency of a high- p_T threshold trigger at $|\eta| < 1.05$ (left) and $|\eta| > 1.05$ (right).[2]

The efficiency was measured in the range 10-160 GeV using this method. This was extended to slightly higher transverse momentum by utilizing W+jet and $t\bar{t}$ events that were triggered with missing transverse energy trigger. The data and simulation show good agreement at the percent level with a very sharp turn-on curve.

3.2. Efficiency measurement for low- p_T muons using boosted J/ψ tag and probe

The efficiency for low momentum muons ($p_T < 10$ GeV) cannot be measured precisely with the Z tag and probe method as there are not many muons in this kinematic range from the Z boson decays. The $J/\psi \rightarrow \mu\mu$ signature is complimentary to the $Z \rightarrow \mu\mu$ signature and allows a precise performance measurement in the low- p_T region. To overcome the low momenta of both muons, only the boosted $J/\psi \rightarrow \mu\mu$ signal was used. In this case the tagged muon was required to have a p_T greater than 18 GeV. We focused on only the boosted J/ψ signal and two specific triggers were installed for this measurement. Finally, the tag muon was required to pass single muon trigger with an 18 GeV threshold which collected enough probe muons below 10 GeV. Results are shown in Figure 4.

However the precision of this measurement is worse than Z tag and probe method. As in the high- p_T case, good agreement between data and simulation was also validated.

4. Level-1 trigger upgrade for Run II

The Level-1 muon trigger was stable and highly efficient in Run I but it was suffering from a very high fake rate for $|\eta| > 1.05$ as shown in Figure 5. This high fake rate has been attributed

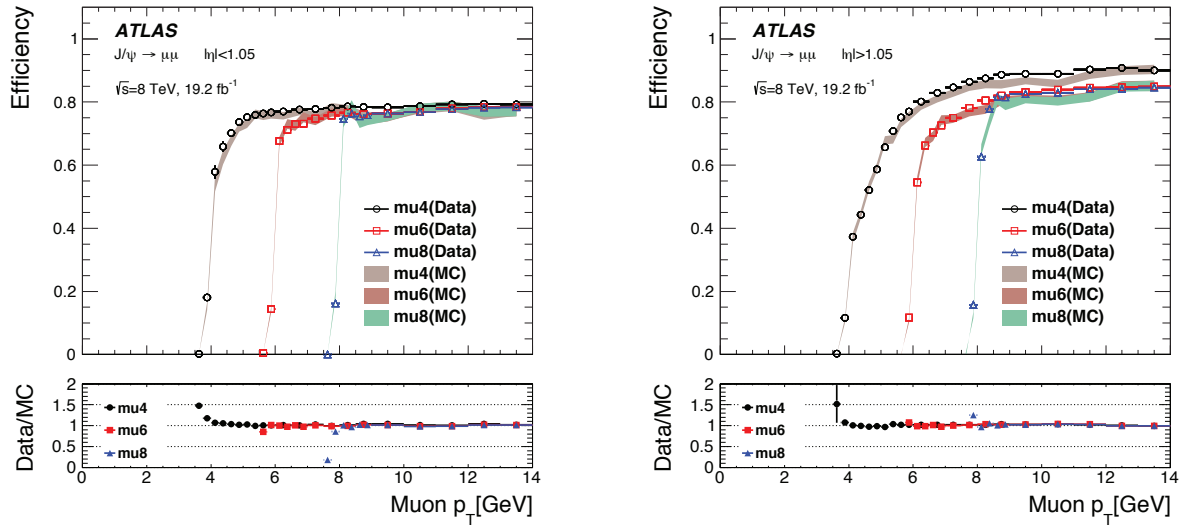


Figure 4. Efficiency of a low- p_T threshold trigger at $|\eta| < 1.05$ (left) and $|\eta| > 1.05$ (right).[2]

to protons from beam-line radiation and scattering in shielding or other materials. These fake muons were irreducible since the Level-1 endcap trigger decision in Run I did not exploit the information from the innermost muon detector (small wheel) resulting in reduced vertex pointing and reduced momentum resolution. To reduce this fake rate in Run II a new coincidence has been introduced between the inner TGC and the outer layer of the hadronic calorimeter (tile calorimeter), the so-called D-layer[3]. A graphic display of this coincidence is shown in Figure 6.

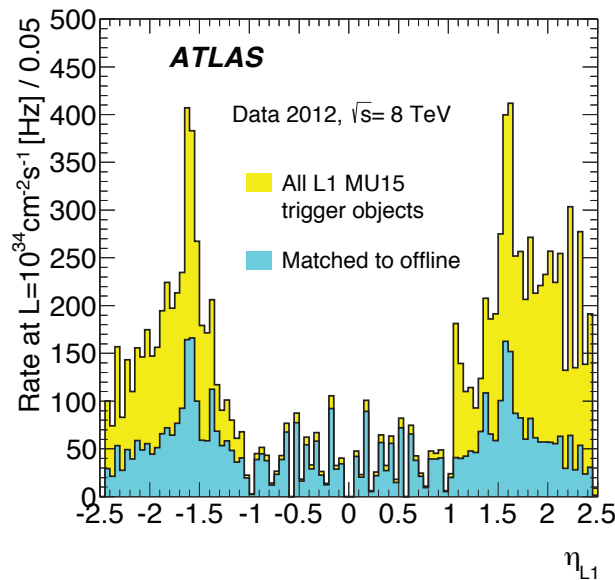


Figure 5. All L1_MU15 trigger objects (yellow) and those matched to offline (blue) are shown as a function of the rate vs. the L1 η region. The discrepancy between the the yellow and blue distribution are fake muon candidates at Level-1. [2]

The expected rate reduction and efficiency as a function of the threshold value for the energy deposited in the outer layer of the hadronic calorimeter is shown in Figure 7. It can be seen that for a threshold of 500 MeV, an 80% reduction in the fake rate can be achieved without lowering trigger efficiency.

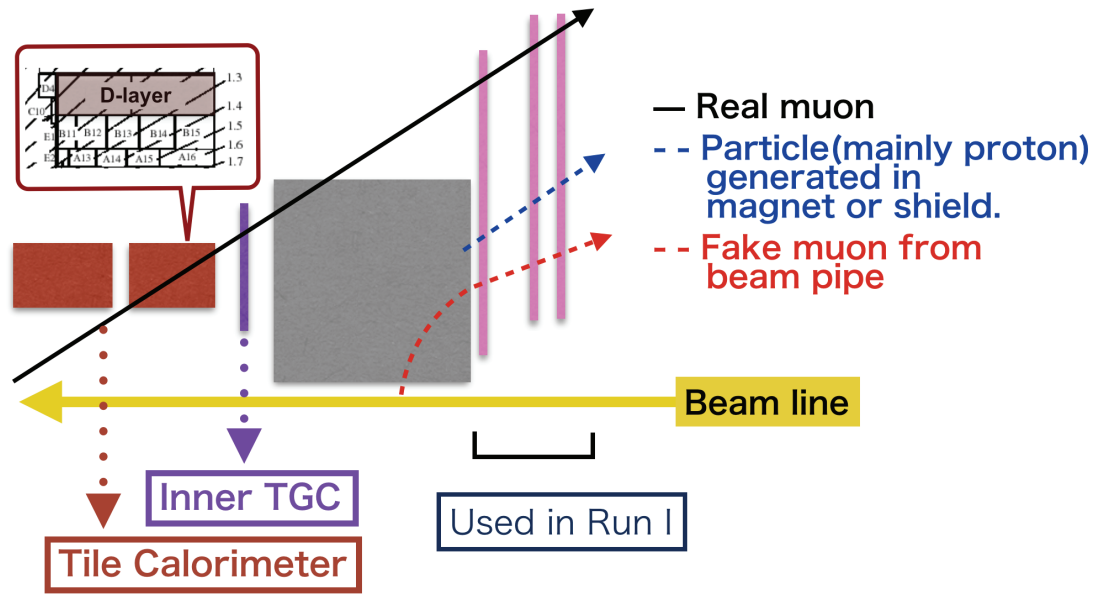


Figure 6. The inner TGC and tile calorimeter are located inside the toroidal magnetic field. A coincidence requirement between these components is expected to reduce the fake muons (shown in by the red arrow).

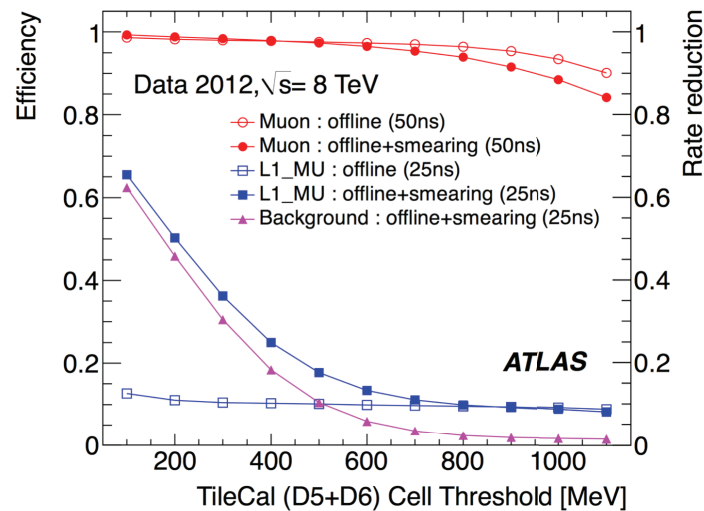


Figure 7. Threshold value dependency of the Tile calorimeter as a function of rate reduction and efficiency.[3]

5. Conclusion

The ATLAS Level-1 muon endcap trigger plays an important role in many analysis channels. During Run I both the hardware and software selection were stable and provided an efficient muon trigger. The tag and probe method applied to $Z \rightarrow \mu\mu$ and boosted $J/\psi \rightarrow \mu\mu$ samples has allowed determination of the trigger efficiency over a wide range of p_T with good agreement between data and simulation. In Run I, a significant increase in the fake muon rate above $|\eta|$ of 1.05 was observed. To mitigate against these fakes, the outer layer of the tile calorimeter in the endcap region has been incorporated into the endcap muon trigger during the long shutdown of

the LHC. Studies show that this additional coincidence will reduce the fake rate by 80% without lowering trigger efficiency.

References

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- [2] ATLAS Collaboration, Performance of the ATLAS muon trigger in pp collisions at $\sqrt{s} = 8$ TeV, *Eur.Phys.J.C* (2015) 75:120
- [3] ATLAS Collaboration, Technical Design Report for the Phase-I Upgrade of the ATLAS TDAQ System, CERN-LHCC-2013-018 ATLAS-TDR-023