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# The ATLAS Muon Trigger

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Events containing muons in the final state are an important signature for many analyses being carried out at the Large Hadron Collider (LHC), including both standard model measurements and searches for new physics. To be able to study such events, it is required to have an efficient and well-understood muon trigger. The ATLAS muon trigger consists of a hardware based system (Level-1), as well as a software based reconstruction (high-level trigger). Due to high luminosity and pile-up conditions in Run 2, several improvements have been implemented to keep the trigger rate low while still maintaining a high efficiency. Some examples of recent improvements include requiring coincidence hits between different layers of the muon spectrometer, improvements for handling overlapping muons, and optimised muon isolation. We will present an overview of how we trigger on muons, recent improvements, and the performance of the muon trigger in Run 2 data.

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## 1. Introduction

Many of the physics processes studied at the ATLAS experiment [1] are expected to produce prompt muons. The ability to select events containing prompt muons from bunch-crossings at the Large Hadron Collider (LHC) is thus a crucial part of the ATLAS physics program, leading for example to the discovery of the Higgs boson and contributing to measurements of its properties.
The muon trigger system at the ATLAS detector consists of two components, the hardware-based Level-1 (L1) and the software-based high-level trigger (HLT). Events accepted at the fast L1 step are passed on to the HLT, which runs more precise algorithms to make a final trigger decision. The ATLAS muon trigger system is undergoing continuous improvements to cope with the high instantaneous luminosity and the large number of interactions per bunch crossing (called pile-up), provided by the LHC. This allows the system to provide high quality muons for analyses over a large spectrum of transverse momenta ($p_{\mathrm{T}}$), with high efficiencies and moderate trigger rates.

## 2. The ATLAS muon spectrometer

Four different sub-detectors make up the ATLAS muon spectrometer (MS). Together with the inner detector (ID), it forms the input to the muon trigger system. The MS is located in a system of three superconducting toroidal magnets, which provide an average magnetic field of about 0.5 T. The central region of ATLAS ($|\eta| < 1.05$) is referred to as the barrel, while the forward regions ($|\eta| > 1.05$) are called endcaps. Figure 1 shows a schematic view of a cross section of a quarter of the detector.

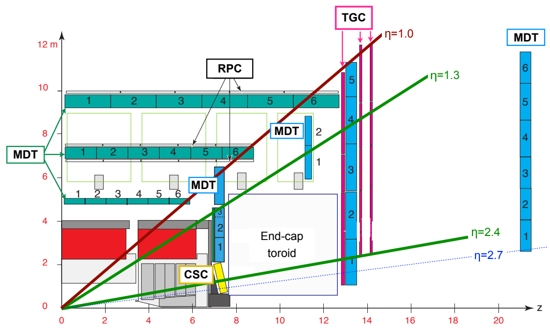


**Figure 1:** Schematic picture showing one quarter of a cross section of the ATLAS detector [2]

Three layers of resistive plate chambers (RPC) and three layers of thin gap chambers (TGC) allow for fast read-out to make the initial trigger decision at L1. Higher resolution and precise tracking information are provided by monitored drift tubes (MDT) and cathod strip chambers (CSC), which are used to refine the trigger decision at the HLT. A coincidence in multiple detector layers is required by the trigger, in general a 2 (3) layer coincidence is required for low (high) $p_{\mathrm{T}}$ muons.

## 3. Level-1 muon trigger

The L1 muon trigger is a fast hardware-based system, requiring a hit coincidence either in RPCs or TGCs pointing back to the beam interaction region. Regions of interest (RoI) of size $0.1 \times 01$ in $\eta \times \phi$ are defined for further processing at the HLT. The L1 trigger has a coverage of about 99% in the endcap region and 80% in the barrel, with limitations mostly due to detector geometry. When a collision rate of 40 MHz is supplied by the LHC, the L1 trigger system (including additional trigger systems other than the muon trigger) reduces this rate to about 100 kHz.

## 4. High-level muon trigger

The HLT is a software-based system to further refine the trigger decision. It has an efficiency close to 100% with respect to L1, while reducing the trigger rate by roughly a factor 100. Two stages make up the HLT: a fast reconstruction step, followed by precision muon reconstruction. Starting with a L1 RoI, a fast track reconstruction is performed with only MS information, using the MDT and CSC measurements. The MS and ID information is then combined in a refined track fit. Candidates passing this stage enter the precision step of the HLT, where high resolution muon reconstruction takes place, again combining information in the MS and the ID.
Additional HLT algorithms, such as triggers using only MS information, complement this baseline strategy. Furthermore, the so-called full-scan approach searches the entire MS for muons, instead of relying on L1 RoIs. This is computationally expensive, but provides high trigger efficiencies.

## 5. Muon trigger system improvements

Additional RPC chambers in the ATLAS feet regions, where detector support structures are located, have been commissioned and are in use since 2016. The effect is shown in figure 2, displaying the L1 trigger efficiency for an exemplary trigger with a 10 GeV $p_T$ threshold as a function of muon candidate pseudo-rapidity in one of these feet regions. The 20% trigger efficiency increase obtained in this region corresponds to a 4% increase across the barrel [3].

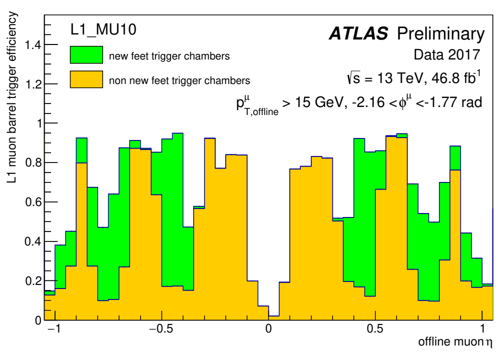


**Figure 2:** L1 trigger efficiency in a part of the ATLAS feet regions [3]

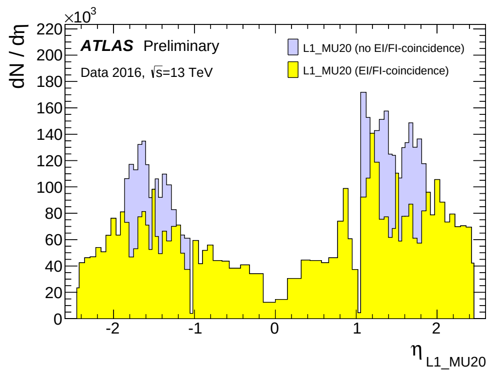


**Figure 3:** Effect of EI/FI coincidence requirement on L1 trigger rate [4]

The trigger rate in forward regions of ATLAS is dominated by low-$p_T$ backgrounds. To suppress these, a new coincidence logic has been added in 2015 and 2016, which requires hits in the forward inner (FI) and endcap inner (EI) TGC stations (located at $|z| = 7$ m and $1.05 < |\eta| < 1.9$). The effect on the L1 trigger rate for an exemplary trigger with a 20 GeV $p_T$ threshold is shown in figure 3 as a function of muon candidate pseudo-rapidity. A rate reduction of 20% is achieved with the new coincidence logic, while the trigger efficiency decrease is only 1% [4].

## 6. Muon trigger efficiency measurement

Muon trigger efficiencies are measured via a tag-and-probe method, using the clean signature provided by $Z \to \mu\mu$ events. A set of events is selected via a tag trigger, which triggers on the tag muon in the event. An unbiased efficiency measurement of the probe trigger can then be obtained by checking its performance on the second muon (probe muon) in each event. The probe trigger efficiency is the fraction of probe muons identified by the probe trigger in all events passing the tag trigger requirements [5].

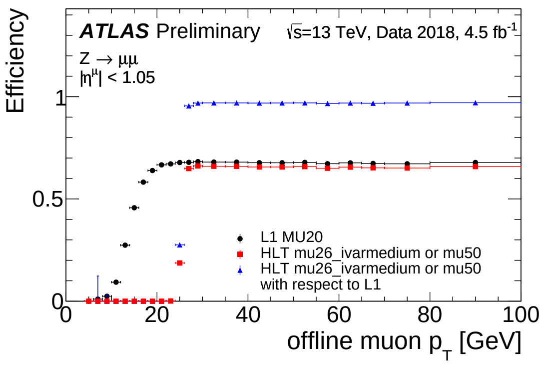


**Figure 4:** Muon trigger efficiencies as function of muon $p_{\mathrm{T}}$ at L1 and HLT in the barrel [5]

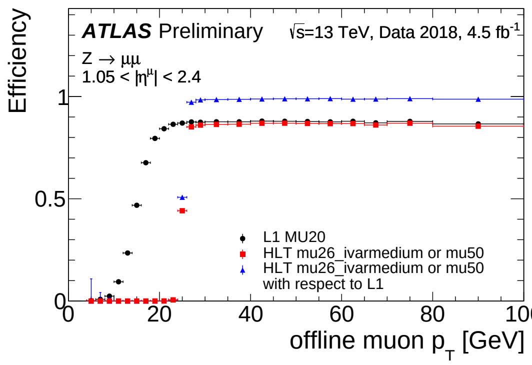


**Figure 5:** Muon trigger efficiencies as function of muon $p_{\mathrm{T}}$ at L1 and HLT in the endcaps [5]

Figures 4 and 5 show muon trigger efficiencies as a function of muon $p_{\mathrm{T}}$ at L1 and HLT using data collected in 2018 for barrel and endcaps, respectively. At L1, a muon trigger with a $p_{\mathrm{T}}$ threshold of 20 GeV is shown, the events at the HLT step pass either a trigger with a 26 GeV $p_{\mathrm{T}}$ requirement and an isolation cut, or a trigger requiring 50 GeV of $p_{\mathrm{T}}$. The L1 trigger efficiency is limited by the coverage of trigger chambers, while the HLT with respect to L1 is almost 100% efficient. A sharp turn-on curve of the trigger efficiency at the HLT is visible above the trigger $p_{\mathrm{T}}$ threshold. The efficiencies in the endcaps are higher than in the barrel, mostly caused by geometric coverage.

## 7. Conclusions

The muon trigger system is a crucial ingredient to the ATLAS physics campaign. Its operation during Run 2 of the LHC has been very successful, providing muons with high efficiency as seen from tag-and-probe measurements performed with $Z \to \mu\mu$ decays. The two-step approach allows to cope with the high luminosity and pile-up conditions delivered by the LHC, and the trigger system is continuously being upgraded to maximize trigger efficiency with reasonable trigger rates.

## References

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