The ATLAS Muon Trigger at high instantaneous luminosities

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Abstract. The ATLAS experiment at CERN’s Large Hadron Collider (LHC) has taken data with colliding beams at instantaneous luminosities of $3.65 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. The LHC delivered an integrated luminosity of about 5 fb$^{-1}$ in the run period 2011, which required dedicated strategies to guard the highest physics output while reducing effectively the event rate. The Muon High Level Trigger has successfully adapted to the changing environment of the low luminosity running of LHC in 2010 to the luminosities encountered in 2011. The selection strategy has been optimized for the various physics analyses involving muons in the final state. This note reports about the performance of the muon trigger.

1. Introduction

Final states containing muons are distinctive signatures of many physics studies at the Large Hadron Collider at CERN, such as the searches for the Higgs boson and physics beyond the Standard Model, as well as the measurements of the Standard Model processes themselves. The accurate determination of the muon trigger performance of the ATLAS detector at the LHC is essential for muon-related physics analyses.

The ATLAS experiment collected proton-proton collision data in 2011 at a centre-of-mass energy of 7 TeV with a maximum instantaneous luminosity of $3.65 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. The muon trigger performance has been evaluated primarily with samples containing a pair of muons from the decay of $Z$ bosons.

The ATLAS muon trigger system has been designed to select muons in a wide momentum range with high efficiency. A detailed description of the ATLAS detector can be found elsewhere [1]. Muons are independently measured in the Inner Detector (ID) and in the Muon Spectrometer (MS). The ID measures tracks up to an absolute value of pseudorapidity of $|\eta| = 2.5$ in a solenoidal magnetic field of 2 T with three types of detectors: a silicon pixel detector closest to the interaction point, a silicon strip detector (SCT) surrounding the pixel detector, and a transition radiation straw tube tracker (TRT) covering $|\eta| < 2.0$ as the outermost part of the ID. The MS consists of three large air-core superconducting toroidal magnet systems (two endcaps and one barrel) providing an average field of approximately 0.5 T. The deflection of the muon trajectories in the magnetic field is measured via hits in three layers of precision drift tube chambers (Monitored Drift Tubes, MDT) for $|\eta| < 2.0$. In the $\eta$ region of $2.0 < |\eta| < 2.7$, two layers of MDT chambers in combination with one layer of Cathode Strip Chambers (CSC) are used. Three layers of Resistive Plate Chambers (RPC) in the barrel region ($|\eta| < 1.05$) and...
three layers of Thin Gap Chambers (TGC) in the endcap regions \((1.05 < |\eta| < 2.4)\) provide the first level (L1) muon trigger. The calorimeters cover the \(\eta\) region of \(|\eta| < 4.9\) and consist of the electromagnetic calorimeter (EC) and the hadronic calorimeter (HC).

2. Muon Trigger and Reconstruction Algorithms

The muon system is the largest sub-detector of the ATLAS experiment and has the capability to reconstruct muons in standalone mode, as well as in combination with the ID tracking systems. The selection of events with muons in the trigger system is performed in three stages. The L1 muon trigger system receives input from fast muon trigger detectors (RPC and TGC). Fast sector logic boards select muon candidates, which are passed to the Central Trigger Processor and subsequently to the High Level Trigger (HLT). The Muon HLT is purely software based and encompasses a Level 2 trigger (L2) followed by an Event Filter (EF) for a staged trigger approach. The HLT has access to data of the precision muon detectors (MDT and CSC) and other detector elements to refine the muon hypothesis. The L1 muon system has six programmable transverse momentum \((p_T)\) thresholds to label the muon candidate with estimated \(p_T\) information. Also position information is available to identify the "region of interest" (RoI) that is used by the subsequent trigger stages. Muons are triggered within a pseudorapidity range of \(|\eta| < 2.4\). In addition to the L1 trigger chambers (RPC and TGC), the HLT makes use of information from the CSC and MDT chambers, which provide precision hits in the \(\eta\) coordinate.

At L2, each L1 muon candidate is refined by including the precision data from the MDTs in the RoI defined by the L1 candidate. There are different algorithms used sequentially at L2, each building on the results of the previous step.

- **L2 MS-only Muon (stand alone, SA):** The MS-only algorithm uses only the MS information. The algorithm uses L1 trigger chamber hits to define the trajectory of the L1 muon and opens a narrow road around this to select MDT hits. A track fit is then performed using the MDT drift times and positions and a \(p_T\) measurement is assigned using look-up tables. CSC information is not used.

- **L2 Combined (CB) Muon:** This algorithm combines the MS-only tracks with tracks reconstructed in the ID to form a muon candidate with refined track parameter resolution.

- **L2 Isolated Muon:** The isolated muon algorithm starts from the result of the Combined-Muon algorithm and incorporates tracking and calorimetric information to find isolated muon candidates. The algorithm sums the \(|p_T|\) of ID tracks and evaluates the electromagnetic and hadronic energy deposits, as measured by the calorimeters, in cones centred around the muon direction. For the calorimeter, two different concentric cones are defined: an internal cone chosen to contain the energy deposited by the muon itself; and an external cone, containing energy from detector noise and other particles.

At the EF, the muon reconstruction starts from the RoI identified by L1 and L2, reconstructing segments and tracks using information from the trigger and precision chambers. There are different reconstruction strategies used in the EF:

- **EF MS-only:** Tracks are reconstructed using MS information and extrapolated to determine track parameters at the interaction point and form MS-only muon candidates.

- **EF Combined:** Using an outside-in strategy, muon candidates from the MS are combined with ID tracks to form combined muon candidates.

- **EF Inside-Out:** The inside-out strategy starts with ID tracks and extrapolates them to the MS to search for candidates in order to form combined muon candidates.

- **EF Isolated Muon:** The isolation algorithm starts from an outside-in muon candidate and uses tracking information to define a track based isolation criterion.

The trigger system is configured via a trigger menu which defines trigger chains. A sequence of reconstruction and selection steps for a specific muon object in the trigger system is specified.
Table 1. Sequence of the muon trigger chains and $p_T$ cut applied at each step used in this paper. The L2 thresholds at the SA stage are generally lower compared to the thresholds at the CB stage because of the inferior resolution of the SA reconstruction.

| Trigger chain         | Level 1           | Level 2           | Event Filter         |
|-----------------------|-------------------|-------------------|----------------------|
| mu18 outside-in       | MU10/MU11         | SA 6 GeV → CB 18 GeV | EF outside-in 18 GeV |
| mu18 inside-out       | MU10/MU11         | SA 6 GeV → CB 18 GeV | EF inside-out 18 GeV |
| mu18 medium outside-in| MU11              | SA 6 GeV → CB 18 GeV | EF outside-in 18 GeV |
| mu18 medium inside-out| MU11              | SA 6 GeV → CB 18 GeV | EF inside-out 18 GeV |

by a trigger chain which is often referred to simply as a trigger [2]. Table 1 shows the sequence of the trigger chains used in this presentation.

3. Processing Time
The processing times of HLT algorithms have been determined on Intel® Core™2 Duo CPU E8500 with clock speed of 3.16 GHz running on raw data from events selected by jet, tau or missing transverse energy triggers at a luminosity of about $3.1 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$. Events selected exclusively by the muon trigger were not used to avoid biasing the measurement. The computing nodes of the actual HLT consisted in 2011 mainly of Intel Harpertown quad-core CPUs running at 2.5 GHz. The processing time for the L2 combined muon chain is shown in Figure 1(a). The mean processing time was 17 ms, of which 63% was consumed by the L2 ID tracking part of the L2 CB algorithm, about 9% was used by the L2 SA and the rest was spent on data unpacking and decoding. Figure 1(b) shows the corresponding times for the EF outside-in and inside-out algorithms. The average processing times were 267 ms and 1119 ms for outside-in and inside-out algorithms, respectively. The composition of the processing time for the outside-in algorithm is: 65% for SA algorithm, 29% for CB algorithm and the remainder for unpacking and decoding of the data. The execution times have been measured for each invocation of the algorithm, and were well within the time restrictions for both L2 and EF of about 40 ms and 4 s at L2 and EF, respectively. Due to a higher track multiplicity in the ID compared to the MS especially in high occupancy events, the inside-out algorithm takes more processing time as it needs to extrapolate all the ID tracks in an RoI to the MS. The average number of muon RoI’s per event seeding the 18 GeV $p_T$ threshold (mu18) trigger chains is about 1.06. The times were also measured with a data sample taken at a lower luminosity of about $1.0 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$. The times are approximately 25% lower compared to the sample taken at $3.1 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$. For the 2012 data taking period, a set of selection criteria on input ID tracks is under study in order to minimise the processing time by reducing the number of tracks to be extrapolated.

4. Trigger Rate
Figure 2(a) shows L1 trigger rates during a run recorded on 22 October 2011 with a fill of 1332 proton bunches in 12 trains with 50 ns bunch spacing. The L1MU10 trigger is composed of the 2-station coincidence RPC trigger in the barrel region and the 3-station coincidence TGC trigger in the endcap regions. The L1MU11 is made of 3-station coincidence triggers in both RPC and TGC regions. The L1MU11 rate is about 30% of the L1MU10 due to a longer lever arm to select muons above $p_T$ threshold in the toroidal magnetic field, allowing L1MU11 to be running continuously during the 2011 data taking period. Figure 2(b) shows the 18 GeV $p_T$
threshold trigger (mu18) rates for the same run. Triggers seeded by L1_MU10 were pre-scaled\(^1\) for luminosities above 1.9 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} due to the limited bandwidth allocated for the L1 muon trigger.

5. Trigger Performance

The trigger performance was investigated with a sample of \(Z\) boson events, and using the "tag-and-probe" method. In the tag-and-probe method, \(Z \rightarrow \mu^+\mu^-\) decays were selected by requiring a pair of oppositely charged muons with a di-muon invariant mass near the mass of the \(Z\) boson. Further the offline-reconstructed muons had to fulfil certain quality requirements to ensure a high purity of the sample. The tag muon is required to match to a triggered muon, the probe muon is required to be separated from the tag muon by \(\Delta \phi > 2.0\) in the azimuthal angle. The invariant mass of the tag-and-probe pair is required to be close to the nominal \(Z\) mass:

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|m_{Z} - m_{(\text{tag,probe})}| < 10 \text{ GeV}.
\]

The efficiency of a muon trigger chain with respect to offline muons is defined as the fraction of the probe muons which have an associated EF trigger track that passed all the steps of the muon trigger chain in a cone of \(\Delta R = 0.15\) around the probe muon\(^2\).

5.1. The First Level Trigger

Figures 3(a) and 3(b) show the \(p_T\) dependence of the L1 RPC (\(|\eta| < 1.05\)) and TGC (1.05 < \(|\eta| < 2.4\)) trigger efficiency with respect to isolated offline CB muons. The plateau efficiency of the L1 RPC is about 20% lower compared to the L1 TGC efficiency due to differences in the geometrical acceptance. These triggers seed the 18 GeV threshold trigger chains in the HLT. For the RPC trigger, efficiencies of both L1_MU10 and L1_MU11 are shown. Due to a smaller geometrical coverage and additional chambers to form three-station coincidence triggers, L1_MU11 shows about 6% lower efficiency compared to L1_MU10. In the endcap regions L1_MU11 was used to seed mu18 HLT chains. The L1 triggers become fully efficient well below 18 GeV in both barrel and endcap regions.

5.2. The High Level Trigger

Efficiencies of mu18_medium triggers with respect to isolated offline combined muon have been evaluated with the tag-and-probe method using \(Z \rightarrow \mu\mu\) events. Figure 4 shows measured efficiencies in barrel and endcap regions for outside-in algorithm as a function of muon \(p_T\). The trigger is fully efficient at \(p_T\) of 20 GeV. The efficiency in data in the plateau region is described by Monte Carlo and the turn-on region is modelled reasonably well.

Figure 5 shows the efficiency of the mu18_medium trigger in terms of the number of interactions per bunch crossing for muons with \(p_T > 20\) GeV with data collected during LHC operation corresponding to an integrated luminosity of about 2 fb\(^{-1}\). The efficiency shows a weak dependence on the number of interactions per bunch-crossing due to the performance degradation of L2 ID tracking for large numbers of simultaneous interactions.

5.3. Isolated Muon Trigger

The isolated muon trigger takes isolation criteria into account for the selection of muon candidates. This trigger provides higher rejection than the non-isolated muon trigger whilst keeping a high efficiency for isolated muons. Two muon samples were used for performance measurements of the isolated muon trigger. In the first sample, muons were analyzed with the tag-and-probe method to measure the efficiency of the isolation algorithms. In the second sample, all muons selected by the non-isolated muon trigger were used. This sample contains

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\(^{1}\) The trigger rate is reduced by discarding a pre-defined fraction of L1 trigger events. The pre-scaling is deterministic, taking every \(n\)-th event.

\(^{2}\) \(\Delta R\) is defined as \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\).

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background processes, such as $b\bar{b}$ production, as well as the signal processes, $W$ and $Z$ production, and is used to measure the rejection rate of the isolation algorithms.

5.3.1. The Second Level Trigger   The L2 isolated muon trigger uses calorimetric and tracking information to detect isolated muons. For the calorimetric information the energy deposition in an annulus around the muon candidate in the electromagnetic (EC) and hadronic calorimeter (HC), subtracting the energy loss of the muon along its trajectory inside the calorimeter estimated by look-up-table based extrapolation ($\Sigma E_T$) is used. Contributions from calorimeter noise are also subtracted. The annulus is defined as $0.07 < \Delta R < 0.2$ for EC and $0.1 < \Delta R < 0.2$ for HC, respectively.

For track based isolation the sum of the $p_T$ of tracks having $p_T > 1$ GeV found in the ID in a cone of $\Delta R = 0.2$ around the muon candidate, after subtracting the $p_T$ of the muon ($\Sigma p_T$) is used. Only the L2 ID tracks satisfying the condition, $|z_0(L2IDtrack) - z_0(L2SA)| < 15$ mm, are considered for the above calculation\(^3\).

Figure 6 shows the dependence of the mean values of $\Sigma p_T$ and $\Sigma E_T$ as a function of the number of vertices reconstructed in an event. The mean value of $\Sigma p_T$ is insensitive to the number of interactions per event. On the other hand the mean value of $\Sigma E_T$ shows a linear dependence on the number of interactions per event. Figure 7(a) and 7(b) show efficiency and rejection (defined as $1 - \text{efficiency}$) of the L2 isolated trigger as a function of the cut on $\Sigma E_T/p_T(\mu)$ and in terms of the cut on $\Sigma p_T/p_T(\mu)$, respectively. Each plot shows both the efficiency for isolated muons selected with the tag-and-probe method using $Z \rightarrow \mu\mu$ events and the rejection for inclusive L2 CB muons. The efficiency curve in 7(b) starts from about 0.95 due to the threshold in the track reconstruction used in the $\Sigma p_T$ calculation. The ID track based isolation shows less rejection power compared to the calorimeter isolation due to the limitations in the ID tracking performances available at L2. The timing constraint at L2 restricts track reconstruction to $\Delta R < 0.2$ around the muon and an implicit $p_T > 1$ GeV cut is applied at track reconstruction which leads to worse track isolation performance compared to offline. Figure 8 shows the rejection for inclusive L2 CB muons as a function of efficiency for muons from $Z$ decays with the optimized calorimeter and track isolation criteria. For each value of the rejection achievable with the L2 isolation trigger, the curve gives the efficiency that can be obtained for isolated muons from $Z \rightarrow \mu\mu$ events. Dots on the curve show operating points for tight isolation and loose isolation triggers.

5.3.2. The Event Filter   The EF isolated muon trigger uses track isolation information to either refine the L2 isolated muon trigger or to apply isolation criteria only at EF. The track isolation variable used in the EF isolated muon trigger was studied with the data. Figure 9 shows the $\Sigma p_T$ distributions for muons from $Z \rightarrow \mu\mu$ samples and for muons selected by inclusive EF CB algorithm. Figure 10 shows the mean of the track isolation variable of the isolated muon trigger as a function of the number of reconstructed vertices in an event. The isolation variable is relatively insensitive to the number of vertices which makes the isolation trigger directly applicable for the 2012 data taking period with higher luminosity. Figure 11 shows relative efficiencies of the EF isolated muon trigger as a function of offline isolated muon $p_T$. With the nominal requirement ($\Sigma p_T/p_T(\mu) < 0.1$) the efficiency is close to 1 without noticeable dependence on $p_T(\mu)$. Figure 12 shows the rejection for inclusive EF CB muons in terms of efficiency for muons from $Z$ decays with optimised isolation criteria. A rejection of about 55% can be obtained without noticeable loss of efficiency to isolated muons.

\(^3\) $z_0$ is the distance from the interaction point measured along the beam line.
6. Conclusions
The performance of the ATLAS muon trigger system has been evaluated with proton-proton collision data collected in 2011 at a centre-of-mass energy of 7 TeV. Events containing a pair of muons from the decay of $Z$ bosons are primarily used for this performance evaluation.

The processing times of the HLT chains were well within the time restrictions allowing stable trigger operation at a luminosity of $3.0 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ with an output rate of about 110 Hz for the 18 GeV threshold muon triggers. The track parameters derived by L2 and EF muon reconstruction algorithms have been compared to those of offline muon algorithms. The observed performance at L2 was sufficient to reject muons below the $p_T$ threshold effectively. The track parameters available at EF showed good agreement with offline track parameters.

The muon trigger efficiencies have been determined from data using the tag-and-probe method with $Z \rightarrow \mu\mu$ samples. The efficiencies at the plateau region were about 70% in barrel and 90% in endcap regions, limited by the acceptance and the hit efficiency of the L1 trigger detectors. The efficiencies showed weak dependence on the number of interactions per bunch crossing due to performance degradation of L2 ID tracking for events with a large number of interactions.

The study of isolation triggers has been performed with data. It was demonstrated that effective rejection of non-isolated muons can be achieved keeping high efficiency for isolated muon samples. The track isolation variable was found to be insensitive to the number of interactions per bunch crossing whereas the calorimeter isolation variable was found to be dependent on this quantity. The ATLAS muon trigger system will actively use the isolation trigger in 2012 data taking.

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Figure 1. Measured execution times per RoI of the HLT algorithms [3]. The mean time of each algorithm is indicated in the legend.

(a) L2 combined reconstruction chain. 
(b) EF outside-in and inside-out reconstruction chains. Solid and dashed lines are for outside-in and inside-out chains, respectively.

Figure 2. Trigger rates for a run recorded on 22 October 2011 with a fill of 1332 proton bunches in 12 trains with 50 ns bunch spacing [3].
Figure 3. L1 trigger efficiency with respect to isolated offline combined muons for (a) the barrel region and (b) the endcap regions [3]. In the barrel region, L1_MU10 is the two-station coincidence trigger shown as filled circles. Open circles are for L1_MU11 which is the three-station coincidence trigger.

Figure 4. Efficiencies of the mu18_medium trigger in terms of reconstructed muon $p_T$ [3]. The lower part of each plot shows ratio of data efficiencies to those determined in Monte Carlo.
Figure 5. Efficiency of the mu18_medium trigger in terms of the number of interactions per bunch crossing for muons with $p_T > 20$ GeV of number of reconstructed vertices [3].

Figure 6. Mean values of L2 isolation variables in terms of number of reconstructed vertices [3].
Figure 7. Efficiency and rejection of the L2 isolated trigger as a function of the cut on $\Sigma E_T/p_T(\mu)$ (a) and in terms of the cut on $\Sigma p_T/p_T(\mu)$ (b) [3]. The efficiency is estimated with respect for isolated muons from $Z \rightarrow \mu\mu$ decays and the rejection (defined as 1. - efficiency) was derived with respect to inclusive L2 CB muons.
Figure 8. Rejection for inclusive L2 CB muons in terms of the efficiency for muons from $Z$ decays with optimised isolation criteria [3]. Dots on the curve show operating points for tight isolation and loose isolation triggers.

Figure 9. Distribution of the isolation variable $\Sigma p_T/p_T(\mu)$ for the EF isolated trigger [3]. The distributions for isolated muons coming from $Z$ decays (red hatched histogram) and distributions for muon candidates identified by the inclusive muon trigger (black hatched histogram) are shown.
Figure 10. EF isolated muon trigger, mean of track isolation variable relative to offline reconstructed isolated muons as a function of number of reconstructed vertices [3].

Figure 11. EF isolated muon trigger efficiency with respect to offline reconstructed isolated muon in terms of $p_T(\mu)$ [3].
Figure 12. Rejection at the EF isolated trigger for inclusive EF CB muons in terms of efficiency for muons from Z decays with optimised isolation criteria [3].