Enhancing the ATLAS Level-1 endcap muon trigger with New Small Wheel integration in Run 3

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Presented at the 32nd International Symposium on Lepton Photon Interactions at High Energies Madison, Wisconsin, USA, August 25–29, 2025

Abstract

The Level-1 muon endcap trigger in the ATLAS experiment at the Large Hadron Collider (LHC) utilises signals from the Thin Gap Chambers (TGCs) located in the outer muon stations. A significant challenge for this system has been the high background rate caused by particles not originating at the interaction point, which increased the Level-1 trigger rate. To address this issue, the New Small Wheel (NSW) detectors, installed at the inner muon stations during Long Shutdown 2, were integrated into the Level-1 endcap muon trigger system for LHC Run 3 operations. In 2024, the full integration of the NSW sectors into the Level-1 trigger decision was successfully completed. By cross-checking the consistency between muon candidates identified by TGC signals and those by the NSW, the system achieved a significant improvement in the discrimination between muons and background particles. This reduced the Level-1 single-muon trigger rate from roughly 25 kHz to 11 kHz at the instantaneous luminosity of 2×10^{34} cm^{-2} s^{-1}, corresponding to a reduction of about 14 kHz.

ATL-DAQ-PROC-2025-019
30 October 2025

1 Introduction

To explore new physics phenomena beyond the Standard Model, the ATLAS experiment performs proton–proton collision measurements at a centre-of-mass energy of 13.6 TeV using the Large Hadron Collider (LHC) [1] and the general-purpose ATLAS detector [2, 3] installed at one of its collision points, corresponding to an average instantaneous luminosity of approximately 2×10^{34} cm^{-2} s^{-1}.

The ATLAS trigger system [4–6] is designed to rapidly select, from the 40 MHz bunch crossings, the events most likely to contain interesting physics and thus to be recorded for further analysis. It consists of two stages: a hardware-based Level-1 trigger and a software-based High-Level Trigger. At the Level-1 stage, events from 40 MHz bunch crossings are reduced to an event rate of approximately 100 kHz within a latency of up to 2.5 μs. The Level-1 muon trigger identifies muons with high transverse momentum (p_T), characteristic of, for example, Higgs boson decays or potential new-physics processes.

The endcap muon trigger [4, 7] covers the pseudorapidity range $1.05 < |\eta| < 2.4$ and reconstructs muon tracks using seven layers of Thin Gap Chambers (TGCs) Big Wheel (BW), arranged as three, two, and two layers forming three TGC stations located outside the toroidal magnetic field region (Fig. 1). A TGC-BW is a multi-wire proportional chamber with a time response of approximately 40 ns, consisting of anode wire channels sensitive to the η direction and cathode strip channels sensitive to the azimuthal angle ϕ. In the frontend electronics mounted next to the detector, coincidences of two out of three layers in the innermost station and three out of four layers in the two outer stations are required, followed by inter-station coincidences processed independently for wire and strip signals. The η and ϕ positions of the muon segment at the outermost layer, together with their deviations ΔR and $\Delta\phi$, are calculated and transmitted to the downstream Sector Logic board. Here, ΔR represents the radial deviation from the infinite-momentum line connecting the interaction point (IP) to the outermost hit position, and $\Delta\phi$ denotes the corresponding azimuthal deviation. The Sector Logic performs η–ϕ coincidence, identifies the muon track, estimates its transverse momentum, and transmits the reconstructed position and momentum information to the Muon Central Trigger Processor Interface, and subsequently to the Central Trigger Processor, where the Level-1 trigger decision is issued.

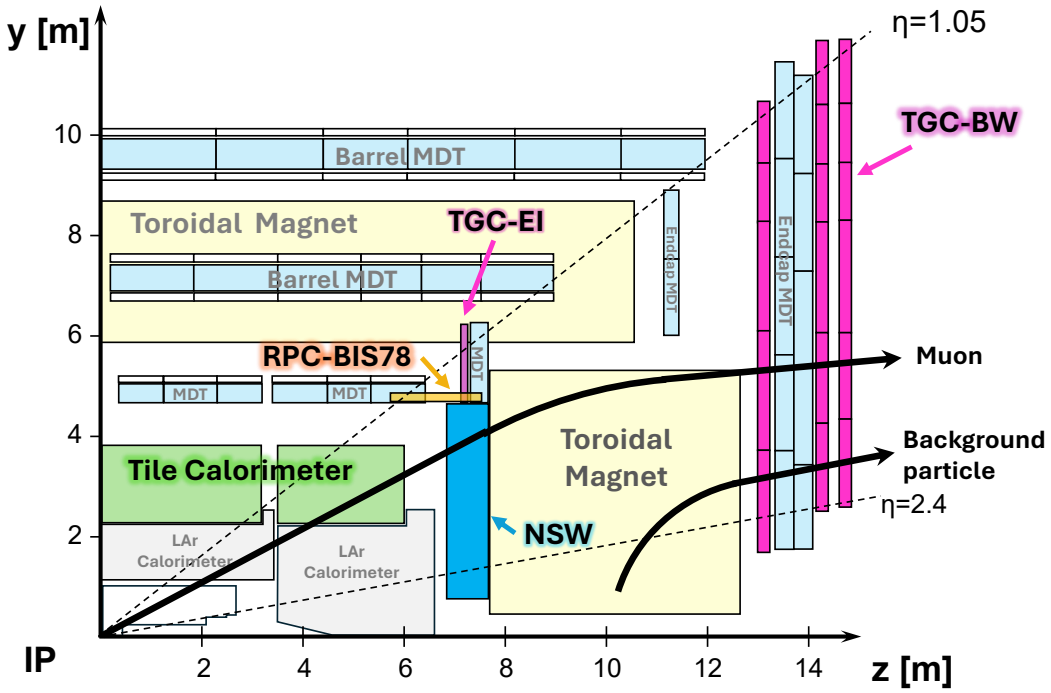

Figure 1: A schematic quadrant view of the ATLAS detector for Run 3. The origin represents the interaction point (IP). Black arrows indicate examples of a muon track originating from the IP and a background particle.

The primary single-muon trigger with a transverse momentum threshold of 14 GeV, which serves as the benchmark for the Level-1 muon trigger, had a rate of approximately 25 kHz with the barrel muon trigger and TGC-BW alone, at an instantaneous luminosity of 2.1×10^{34} cm^{-2} s^{-1}. Previous studies had shown that a significant fraction of the trigger rate originated from fake muon triggers caused by background particles such as cavern backgrounds not originating from the IP [5, 8]. It was demonstrated that the fake muon rate could be reduced by requiring coincidences between the TGC-BW and detectors located inside the magnetic field, the TGC Endcap Inner (EI) and the Tile Calorimeter, in the η region $1.05 < |\eta| < 1.3$ during Run 2 (2015–2018). As part of the Phase-I Upgrade for Run 3, a new coincidence mechanism was introduced in the η range $1.3 < |\eta| < 2.4$, utilising the newly implemented New Small Wheel (NSW) detector and upgraded electronics, resulting in an expected rate reduction of more than 40% based on simulation studies [5].

2 Phase-I Upgrade

A new algorithm that combines muon-segment information from the TGC-BW and detectors located inside the toroidal magnet was introduced to suppress fake muon triggers. Four detectors with different η–ϕ coverages are employed to fully cover the TGC-BW region [5], whose locations are shown in Fig. 1): for $1.05 < |\eta| < 1.3$, the TGC-EI, Resistive Plate Chamber Barrel Inner Small 7 and 8 (RPC-BIS78), and Tile Calorimeter are used; and for $1.3 < |\eta| < 2.4$, the NSW. The RPC-BIS78 coincidence is currently under preparation for integration, and that region is temporarily covered by the Tile Calorimeter.

Figure 2 illustrates the concept of the NSW–BW coincidence. The NSW is a muon detector employing two technologies: eight layers of Micromegas detectors (MM) sandwiched between two sets of four-layer small-strip TGCs (sTGC) [9]. In the Level-1 trigger circuits of the MM and sTGC, each detector independently performs inter-layer coincidences [10].

The sTGC detector consists of cathode strip channels (sensitive to η), anode wire channels (sensitive to ϕ), and cathode pad channels. The pads are staggered in η by half their width, and by requiring

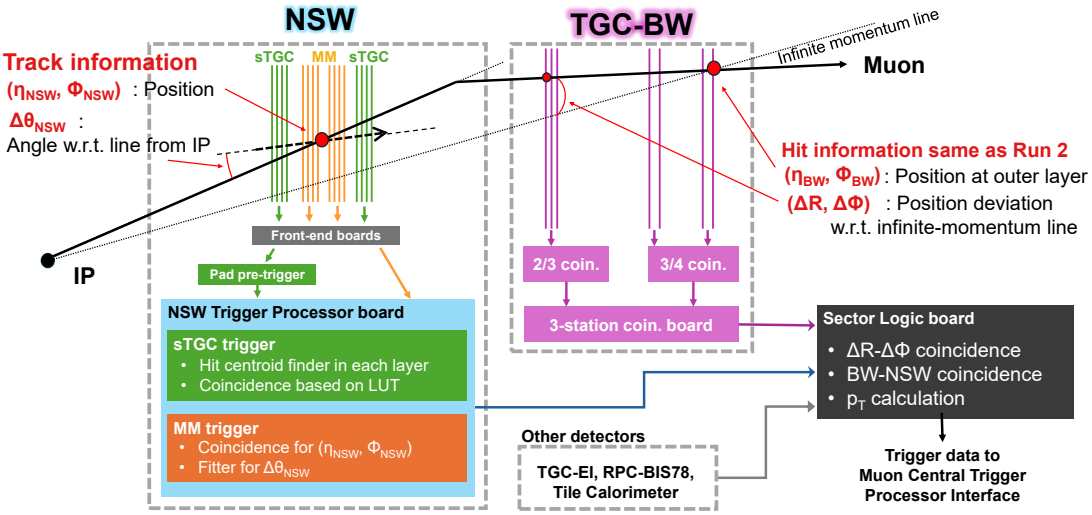

Figure 2: Conceptual illustration of the coincidence between the NSW and TGC-BW in the Level-1 endcap muon trigger. On the NSW side, the hit position (η_{NSW}, ϕ_{NSW}) of the muon segment is determined using the sTGC and MM detectors. On the TGC-BW side, as in Run 2, the muon hit position (η, ϕ) and its deviations (ΔR, $\Delta\phi$) from the infinite-momentum line are derived through inter-layer coincidences. All this information is collected in the downstream Sector Logic, where muon track identification and transverse momentum reconstruction are performed, and the results are then sent to the Muon Central Trigger Processor Interface.

three-out-of-four or two-out-of-four coincidences of these staggered pads in the Pad Trigger Logic board [11], the hit position is determined. As a pad-only path, the segment position information η_{NSW} and ϕ_{NSW} is transmitted via the NSW Trigger Processor [11] to the downstream Sector Logic.

The MM detector comprises four precision strip layers, oriented to measure the η coordinate, and four stereo strip layers, tilted by $\pm 1.5°$ relative to them. From the strip data sent to the NSW Trigger Processor, inter-layer coincidences are performed to obtain the η_{NSW} and ϕ_{NSW} information.

The Sector Logic receives muon-segment information from the TGC-BW frontend, as well as from the NSW Trigger Processor and other inner detectors. Using reconstructed η and ϕ coordinates from both systems, the coincidence is determined by referencing pre-calculated transverse momentum values stored in look-up tables (LUTs). Subsequently, based on the positional differences between the NSW and TGC-BW muon segments, another LUT-based coincidence is applied to further suppress fake segments.

3 Performance

The coincidence between the TGC-BW and inner detectors is designed to be activated independently for each small η–ϕ region. The NSW–BW coincidences were gradually activated during 2024.

The evolution of the primary muon trigger rate during 2024 operations is shown in Fig. 3. The rates are normalized to a luminosity of 2×10^{34} cm^{-2} s^{-1}. Initially, with the NSW coincidence inactive, the TGC-BW alone produced a rate of approximately 25 kHz. After the activation of coincidences with the Tile Calorimeter and the NSW starting on April 17, 2024, the rate was reduced by 10 kHz. Initially, 65% of the trigger sectors were activated for the NSW–BW coincidence, with another 20% added on May 8, 2024, further reducing the rate by 3 kHz. On May 21, 2024, muon segments from the MM were included along with those from the sTGC pad detector, improving efficiency and increasing the rate by about 1 kHz. Finally, on May 28, 2024, the NSW–BW coincidence was fully activated for all trigger sectors, resulting in an overall rate reduction of about 14 kHz. The performance is consistent with, or better than, the expectation from simulation.

The efficiency of the primary muon trigger with and without the NSW coincidence during the 2025 run is shown in Fig. 4. Among di-muon events reconstructed offline within the pseudorapidity range $1.05 < |\eta| < 2.4$, one muon satisfying the trigger condition is used as the "tag," while the

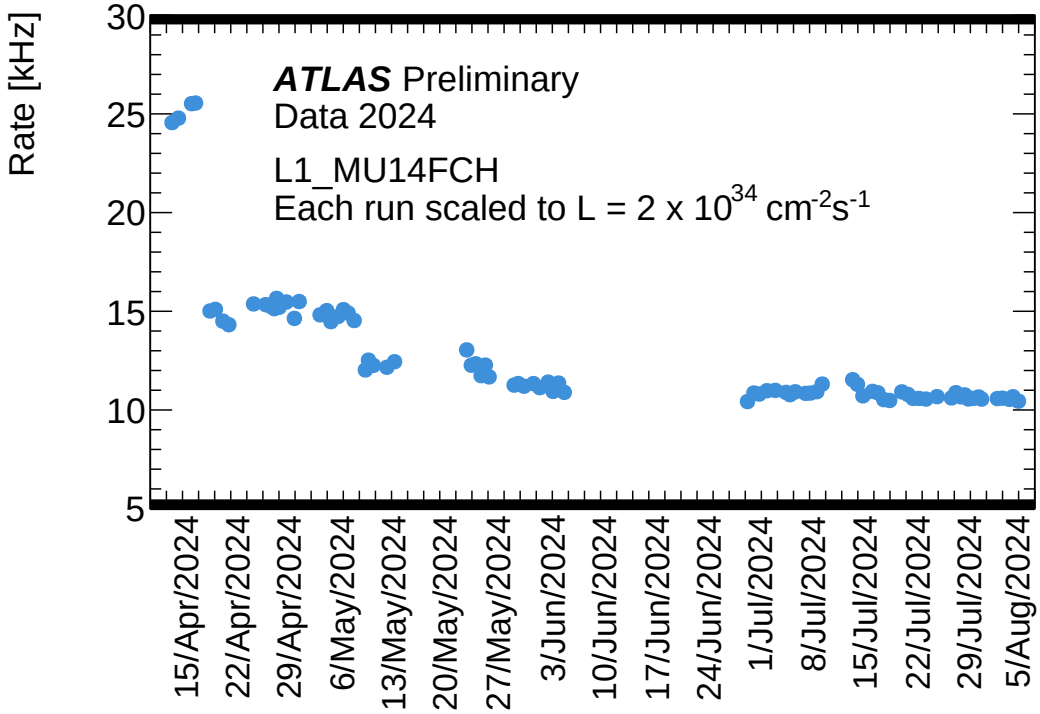

Figure 3: Level-1 trigger rate of the primary single-muon trigger (`L1_MU14FCH`, 14 GeV threshold) as a function of date in 2024 [12]. The rate for each run is normalized to an instantaneous luminosity of 2×10^{34} cm^{-2} s^{-1}.

other "probe" muon's probability of firing the Level-1 endcap muon trigger is plotted as a function of transverse momentum [13]. In the dataset without the NSW coincidence (circles with error bars), the plateau efficiency is approximately 88%, whereas with the NSW coincidence activated (cross markers with error bars), the plateau efficiency remains at about 86%. There is a 2% improvement compared to the 84% in 2024, achieved by optimising the matching-window size between the TGC-BW and the NSW.

4 Summary and Prospects

The ATLAS Level-1 endcap muon trigger introduced a new electronics system and algorithms utilising the newly implemented NSW detector for Run 3 operations, with the aim of reducing fake muon trigger rates originating from non-IP background particles. As a result, while keeping the inefficiency within about 2%, the trigger rate was successfully reduced from 25 kHz to 11 kHz at a luminosity of 2×10^{34} cm^{-2} s^{-1}. This reduction has significantly improved the data-collection efficiency of ATLAS.

Future plans include activating the inner coincidence using the RPC-BIS78, as well as implementing an algorithm currently under development for calculating the angle $\Delta\theta_{\mathrm{NSW}}$ of the NSW muon segment relative to the infinite-momentum straight line connecting the NSW hit position to the IP, which is expected to further reduce fake muon triggers and enhance the overall trigger performance.

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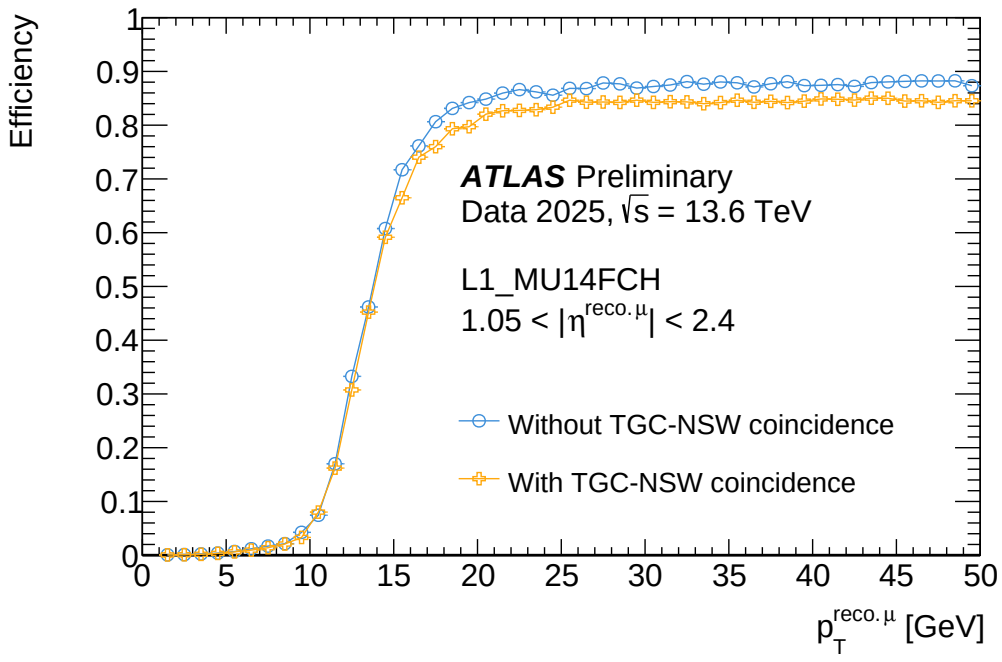

Figure 4: Efficiency of the primary Level-1 muon trigger (`L1_MU14FCH`, 14 GeV threshold) as a function of the offline muon transverse momentum (p_T), measured using the tag-and-probe method [12]. The comparison shows consistent plateau efficiency before and after the activation of the NSW–BW coincidence in the Level-1 logic.

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