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ATLAS New Small Wheel performance studies with LHC Run3 data

C. Arcangeletti on behalf of the ATLAS Muon Spectrometer group

INFN Laboratori Nazionali di Frascati,
Frascati, Italy

E-mail: chiara.arcangeletti@cern.ch

Abstract: The most important ATLAS upgrade for LHC run-3 has been in the Muon Spectrometer, where the replacement of the two forward inner stations with the New Small Wheels (NSW) introduced two novel detector technologies: the small strip Thin Gap Chambers (sTGC) and the resistive strips MicroMegas (MM). The integration of the two NSW in the ATLAS end-caps marks the culmination of an extensive construction, testing, and installation program. The NSW actively contributes to the muon spectrometer trigger and tracking, during the concurrent finalisation of the commissioning phase of this innovative system and the optimisation of its performances. This proceeding will offer an overview of the strategies employed for simulation and reconstruction integration and optimisation, followed by a detailed report on the performance studies of the NSW system during its initial operation with LHC Run3 data.

Keywords: Muon spectrometers; Particle tracking detectors (Gaseous detectors); Performance of High Energy Physics Detectors; Trigger detectors

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Contents

1 The New Small Wheel upgrade

Following the first long shutdown of the Large Hadron Collider (LHC) [1] from 2019 to 2022, and in preparation for a second shutdown between 2025 and 2027, significant upgrades have been implemented to increase the LHC's peak luminosity to levels 5 to 7 times higher than its original design [2]. This upgrade is designed to achieve a final integrated luminosity of approximately $3000\,\mathrm{fb}^{-1}$ over the next decade. To ensure the ATLAS experiment [3] remains operational under these challenging conditions, substantial upgrades were undertaken during Phase I, with additional improvements planned for Phase II.

The most critical upgrade during Phase I was the installation of the New Small Wheel (NSW) [4] system, which replaced the innermost muon station in the end-caps. This upgrade was essential to address two primary challenges: enhancing the Level-1 muon trigger logic to eliminate fake muon triggers caused by particles not originating from the interaction point and mitigating the expected performance degradation of the previously installed detectors, particularly the Monitored Drift Tubes (MDTs), due to the increased particle rates.

The NSW upgrade involved replacing all detectors in the innermost muon station in the forward regions with new technologies, specifically Micro-Mesh Gaseous Structures (MicroMegas, MM) [5] and small-strip Thin Gas Chambers (sTGC) [6]. These new detectors are designed to meet the stringent requirements of the upgraded LHC, including a track resolution of approximately 100 μm per detector plane, ensuring an overall momentum resolution of 15% for 1 TeV muons; a tracking efficiency exceeding 95% for muons with transverse momentum greater than 10 GeV; and the ability to handle high particle fluxes to effectively reject fake triggers.

The NSW configuration comprises sixteen detector planes organised into four multi-layers, each containing four planes, arranged sequentially as sTGC-MM-MM-sTGC, as shown in figure 1. Each of the two New Small Wheels consists of eight large and eight small trapezoidal sectors, with each sector containing eight layers of MicroMegas detectors sandwiched between two wedges of sTGC detectors. This makes the NSW upgrade the first large-scale application of micropattern gaseous detectors in high-energy physics.

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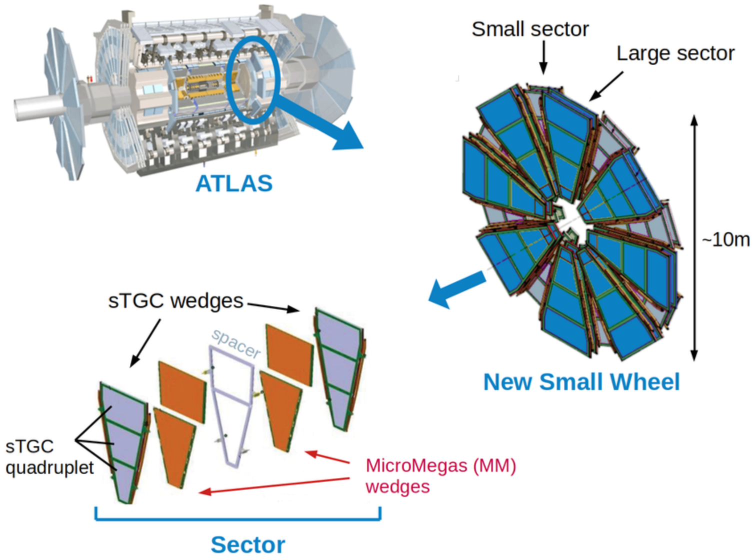

Figure 1. Schematic diagram showing the New Small Wheel upgrade, the location of MicroMegas and sTGC on the NSW and within the ATLAS detector. Reproduced with permission from [7].

Along with the detector upgrades, a sophisticated custom electronics system was developed, featuring 2.5 million readout channels for rapid triggering and precise muon tracking. The NSWs successfully completed surface commissioning in 2021 and have since been installed in the underground experimental cavern. This proceeding details the current operational status and performance of the NSW detector system, based on data recorded during 2022–2023 and in the first months of 2024.

Run 3 data taking. Since the start of Run 3, the New Small Wheels (NSWs) have been fully integrated into the ATLAS data acquisition system and interfaced with the ATLAS DAQ for data-taking. Currently 98.5% of the high-voltage channels on the MicroMegas chambers and 95% on the sTGC chambers are functioning.

Notably, the NSWs utilise a next-generation data acquisition system developed specifically for ATLAS Run 3 and future upgrades. This system, known as FELIX (Front End LInk eXchange) [8], is being deployed on a large scale for the first time. Additionally, the software component, swROD, is integrated into this setup. During initial commissioning runs, some instabilities were encountered in the data acquisition process, such as issues with FELIX buffer filling and data link de-synchronisation. However, these problems now affect only few percent of the data collection process.

One of the initial measurements made is the measurement of the number of reconstructed clusters per unit area and time, which directly correlates with the particle rate. This measurement was carried out using a layer from a small sTGC sector. The highest rate was observed at the smallest radius, where background particles are most prevalent. The peak rate as a function of instantaneous luminosity is depicted in figure 2. A linear fit was applied, and the extrapolated value of the particle rate was determined to be 27 kHz/cm^2 at 7.5×10^{34} cm^{-2}s^{-1}. This value exceed the designed goal of few 10%, for this reason mitigation effects are under investigation.

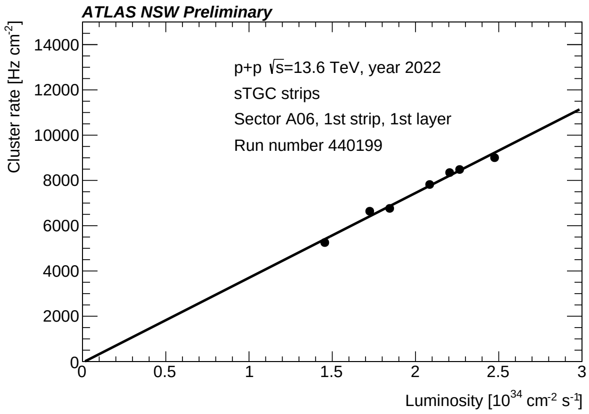

Figure 2. Number of reconstructed clusters per cm^2 per s, measured with the sTGC strips at the innermost radius of the first layer, as a function of the luminosity, using one run of data recorded by ATLAS in 2022 at a pp collision energy of $\sqrt{s}$ = 13.6 TeV. Reproduced with permission from [10].

2 Trigger performance

The sTGC trigger operates at two levels: the Pad trigger, which provides fast, coarse information and seeds the strip trigger (deployed in 2023 for data taking), and the Strip trigger, which reconstructs strip clusters for precise measurement of the segment angle (currently under commissioning for the HL-LHC). Additionally, an independent MicroMegas (MM) Level-1 trigger was recently deployed: it uses the addresses of the earliest strips from each VMM [9] (64 strips) across multiple layers. The trigger segments from both the MM and sTGC detectors are merged and forwarded to the Sector Logic (SL).

Figure 3 on the left shows that after the deployment of the Tile and NSW (only sTGC-Pad) coincidences in the level-1 trigger decisions in 2023 data, the rate of fake events significantly reduced in the high-η regions.

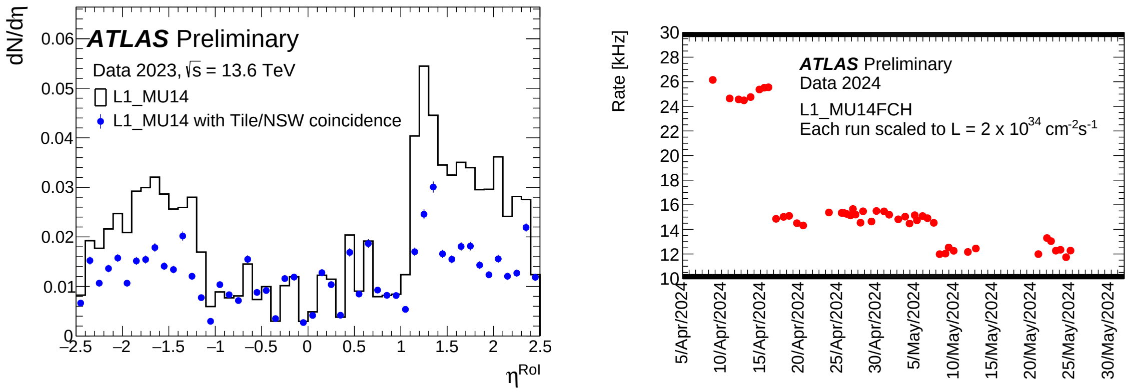

Figure 3. (*on the left*) The pseudorapidity $|\eta|$ distribution of the level-1 Region-of-Interests (RoIs), which fulfill the primary level-1 muon trigger with a threshold of the transverse momentum of 14 GeV before and after the deployment of the Tile and NSW coincidences in the level-1 trigger decisions in 2023 data. (*on the right*) Level-1 trigger rate of the primary single muon trigger with a transverse momentum threshold of 14 GeV, as a function of date at the beginning of 2024. Reproduced with permission from [11].

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Data taking in 2024 began with the NSW Pad trigger in coincidence, leading to an expected 8% efficiency loss due to geometrical factors and local inefficiencies. However, enabling the MicroMegas in the NSW trigger, which merges the sTGC Pad and MM segments, has improved overall efficiency. Figure 3 on the right, shows the effect on the fake rate rejection with the integration of the MicroMegas segments progressively included in Trigger Processor (TP) coincidence since May 2024. The coincidence between the TGC Big Wheel, Tile calorimeter, and all sTGC Pad and MM sectors reduced the Muon Level-1 rate at 11 kHz and improved the trigger efficiency up to 98%.

3 Detector efficiencies

NSW is fully integrated in ATLAS simulation and reconstruction framework. In the data processing path, individual hits are retrieved from the front-end electronics, decoded, and mapped to detector readout channels. The second coordinate, ϕ, is derived from MM stereo layers and sTGC pads/wires. Raw hits are then fed to hit clusterization algorithms for event reconstruction or high-level triggering. Clusters are then used to build tracks segments across detector layers that finally go in the muon track fit that combine all the segments from other muon detectors as well as the inner ones.

Single layer efficiencies are affected by HV trips or DAQ/LV issues, leading to an efficiency of about 70/80% per layer. For this reason, to optimise muon reconstruction efficiency from the NSWs, different majority logic schemes were studied. The most effective approach, which minimises fake signals without compromising efficiency, requires at least four MicroMegas layers (out of eight) or four sTGC strip layers (out of eight) to register hits. This method achieved a reconstruction efficiency greater than 95% in 2023, as shown in figure 4.

In 2024 situation significantly improved thanks to the huge work on improving DAQ stability leading to a reconstruction efficiency greater than 99% as shown in figure 5.

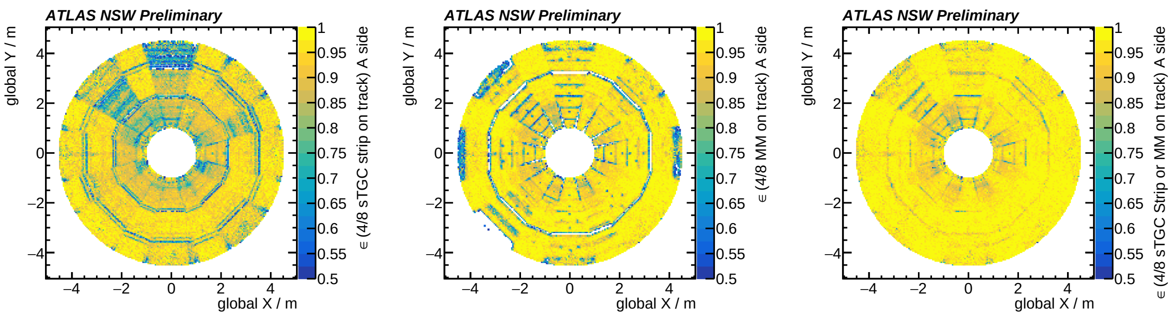

Figure 4. Efficiency for having at least four out of eight layers of MicroMegas (*on the left*), sTGC (*in the center*) and either MicroMegas or sTGC strips (*on the right*) associated to a muon track with $p_T > 15$ GeV passing through the NSW using one run of data recorded by ATLAS in 2023 at a pp collision energy of $\sqrt{s} = 13.6$ TeV. Regions of low efficiency can be explained by detector or readout issues at the time of data taking. Reproduced with permission from [10].

4 Detector resolutions

The reconstruction of the muon position is, for the moment, based on centroid cluster position, namely the charge weighted average strip position. Alternative reconstruction methods are under investigation to improve the single layer position reconstruction. In the MM case a new time-based reconstruction algorithms will significantly improve the resolution also providing a flatter distribution in η, while for the sTGC a cluster shape analysis will improve the resolutions.

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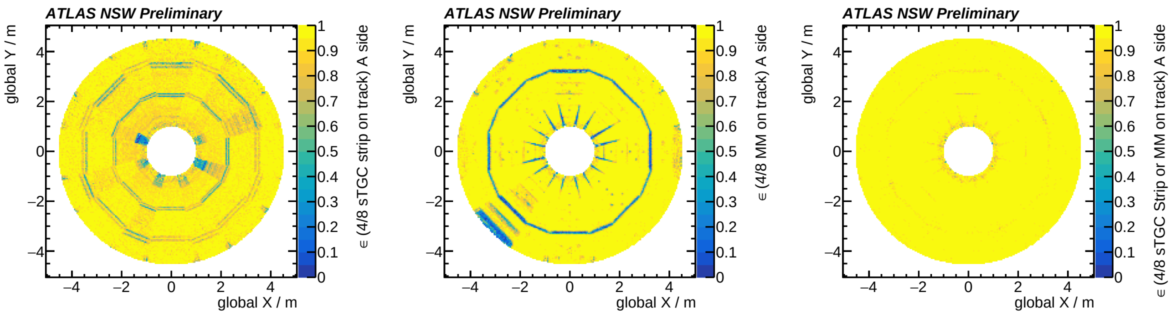

Figure 5. Efficiency for having at least four out of eight layers of MicroMegas (*on the left*), sTGC (*in the center*) and either MicroMegas or sTGC strips (*on the right*) associated to a muon track with $p_T > 15$ GeV passing through the NSW using one run of data recorded by ATLAS in 2024 at a pp collision energy of $\sqrt{s} = 13.6$ TeV. Reproduced with permission from [10].

Furthermore, the single point resolution is affected by residual misalignments between layers and the as-built geometry. Figure 6 shows the resolutions for both technologies including preliminary alignment corrections. The uncertainty on the alignment is expressed in terms of sagitta bias on the global muon track of about 80–100 µm in the NSW region.

The average resolutions are ∼350 µm and ∼250 µm for MicroMegas and sTGC respectively.

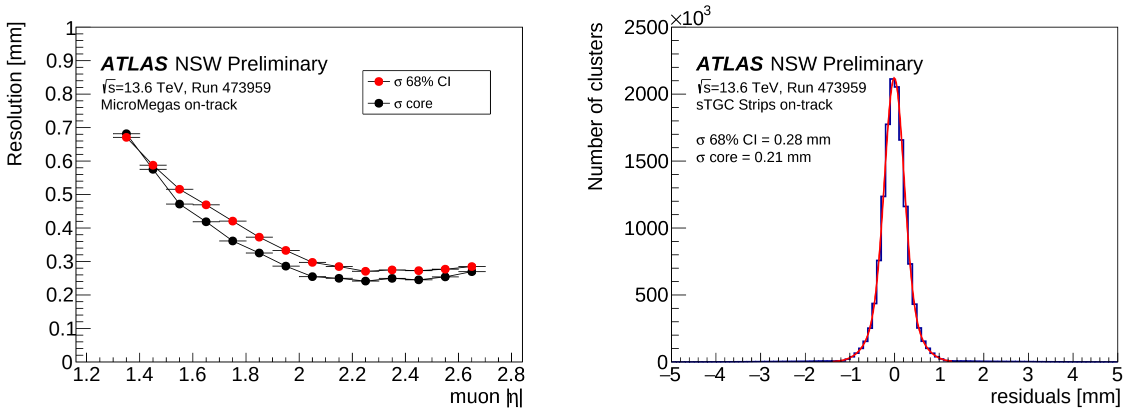

Figure 6. (*on the left*) MicroMegas resolution as a function of muon $|\eta|$ and (*on the right*) inclusive sTGC resolution in $|\eta|$, both obtained by performing a double-gaussian fit to the residuals calculated between the reconstructed cluster position and the muon track for clusters associated to a muon track with $p_T > 15$ GeV passing through the NSW using one run of data recorded by ATLAS in 2024 at a pp collision energy of $\sqrt{s} = 13.6$ TeV. Reproduced with permission from [10].

5 Conclusions

The New Small Wheel was among the most significant upgrades undertaken for experiments at the LHC. Installed in the ATLAS detector since 2021, the New Small Wheels are actively collecting data, contributing to trigger decisions and participating at the muon track reconstruction. In 2024 the performance of the detectors improved significantly thanks to the work done to improve the DAQ stability. The inclusion of both sTGC and MicroMegas in the trigger coincidence reduced the fake

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rate in the high-η region as designed. A preliminary implementation of the alignment correction also improved the detectors resolutions and other reconstruction methods are under investigation to further improve the performance.

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