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ATLAS New Small Wheel Performance Studies After First Year of Operation

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Abstract

After successfully completing Phase I upgrades during LHC Long Shutdown 2, the ATLAS detector is back in operation with several upgrades implemented. The most important and challenging upgrade is in the Muon Spectrometer, where the two inner forward muon stations have been replaced with the New Small Wheels (NSWs) system featuring two entirely new detector technologies: small strip Thin Gap Chambers (sTGC) and the resistive Micromegas (MM). After massive construction, testing and installation work in ATLAS, the two NSWs end-caps have now been in operation for about a year in the experiment, participating in the muon spectrometer tracking system and muon trigger system. A huge effort has gone into the operation of the new data acquisition system, as well as the implementation of a new processing chain within the muon software framework. Tracking is performed with full consideration of the absolute alignment of each individual detector module by the ATLAS Muon Spectrometer optical alignment system. All the deviations from the nominal geometry of all the constituent elements of each sTGC and MM module are accounted for through the modelling of the real chamber geometry reconstructed from the information of the construction databases. After an overview of the strategies adopted for the simulations and reconstruction, the studies on the performance of the NSW system in its first year of operation with LHC Run3 data will be reported.

Keywords: LHC; ATLAS; New Small Wheel; Muon Spectrometer; Performance

1. The ATLAS New Small Wheel (NSW) upgrade

Following the shutdowns of the Large Hadron Collider in 2019-2022 and 2025-2027, there will be a significant increase in the instantaneous luminosity, approximately 5-7.5 times higher than the original design specifications [1, 2]. In order to maintain the ATLAS detector's [3] current high performance and operate effectively in this elevated background environment, substantial upgrades are required for certain components, particularly within the ATLAS Muon System.

The most substantial upgrade project for the ATLAS Muon System involves replacing the existing first station in the forward regions with a new set of detectors known as the New Small Wheels [5]. To fulfil the demands for precise position resolution, efficiency, and timing at the anticipated high background rate, two technologies, namely Micro-Mesh Gaseous Structures (MicroMegas, MM) and small-strip Thin Gas Chamber (sTGC), have been selected.

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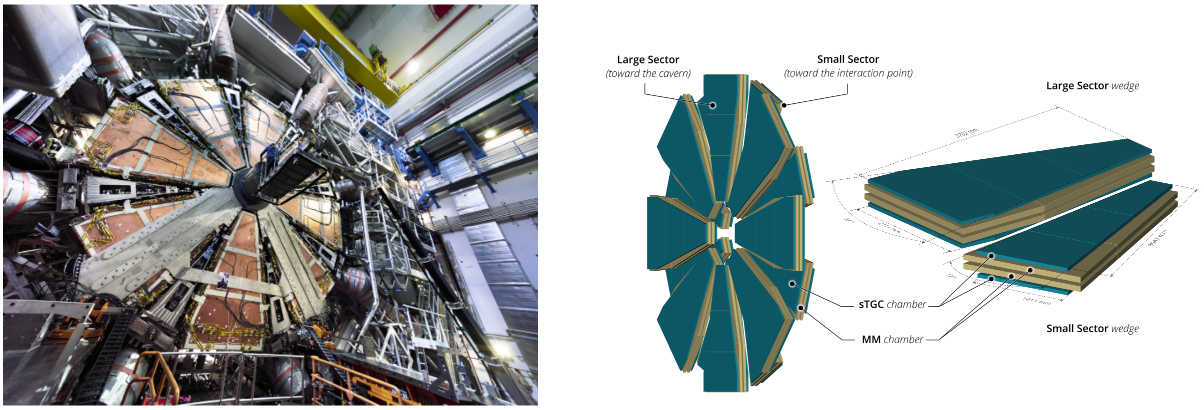
The NSW configuration consists of sixteen detector planes organized into four multi-layers, each containing four planes. These layers are arranged sequentially from the inside to the outside of the experiment as follows: sTGC-MM-MM-sTGC.

Each of the two New Small Wheels is composed of eight large and eight small trapezoidal sectors, as illustrated in Figure 1b. Each sector comprises 8 layers of Micromegas positioned between two wedges of sTGC detectors, each consisting of four layers. In total, the gas gaps within the constructed detector cover an area exceeding $2400m^2$. Notably, the NSW upgrade represents the initial utilization of micro-pattern gaseous detectors on such a large scale within high-energy experiments. To support the NSW, a sophisticated custom-made electronics system has been meticulously designed and constructed, boasting 2.5 million readout channels dedicated to rapid triggering and precise tracking of muons.

Two NSWs successfully completed surface commissioning in 2021 and were subsequently installed in the underground experimental cavern [6], as shown in Figure 1a. This achievement followed over a decade of collaborative efforts by the ATLAS team. In this proceedings, the current operational status of the NSWs detector system together with the performance of the detector are presented using the 2022-2023 recorded data.



(a) (b)

Figure 1: (a) Picture of the New Small Wheel during the installation in the ATLAS detector [9]. (b) Structure of the small and large sectors of the NSW [4].

2. Detector Conditions

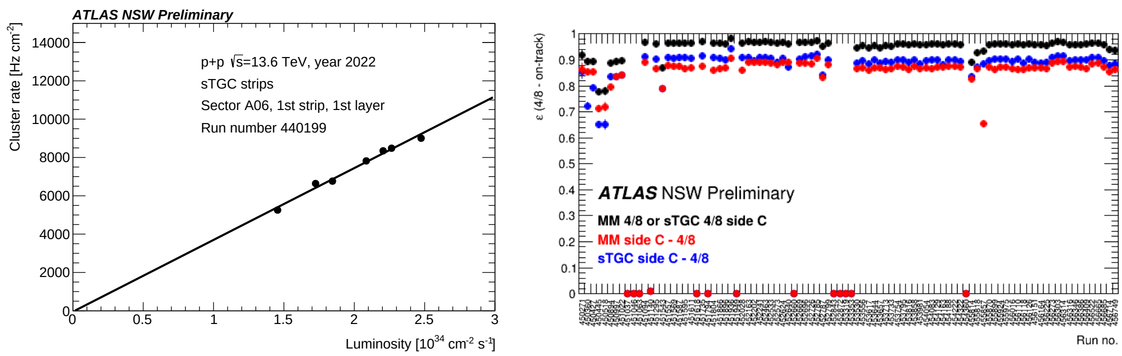
Since the beginning of the Run3, the NSWs were included in the ATLAS data-acquisition and they are interfaced with the ATLAS DAQ for the data-taking. The detector status (high-voltage, low-voltage, T-sensor, B-sensor, cooling and gas flow) are controlled trough the NSW Detector Control System (DCS) which is currently fully integrated in the ATLAS DCS main panel. On the MicroMegas chambers, 98.5% of the high-voltage channels are working while on the sTGC chambers 95% high-voltage channels are working.

Concerning data acquisition, it's essential to emphasize that the New Small Wheel employs a new generation data acquisition system developed specifically for ATLAS Run3 and later upgrades. This system, known as FELIX (Front End LInk eXchange), is being used on a large scale for the first time. Additionally, the software component, known as swROD, is integrated into this setup. During the initial commissioning runs, we encountered instabilities in the data acquisition process, including issues with the filling of FELIX buffers and de-synchronization of data links, which is now affecting only 10% of the data collection process.

3. Latest measurements

3.1. Particle Rate

One of the first measurements performed is the number of reconstructed clusters per units of area and time which has a one-to-one relationship with the particle rate. This measurement is performed using a layer of a small sTGC sector. The measured rate peaks at the smallest radius where the background particles dominate. The peak rate as a function of instantaneous luminosity is shown in Figure 2a. A linear fit is performed and the extrapolated value of the particle rate at $5 \times 10^{34}\ cm^{-2}\ s^{-1}$ is 18 kHz/cm^2 which is within the design goal of the NSW (20 kHz/cm^2).



(a) (b)

Figure 2: (a) 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. Run 440199 was a test run which reached higher instantaneous luminosity than normal runs in 2022 and 2023 [7]. (b) Efficiency for having at least four out of eight layers of Micromegas (red), sTGC strips (blue), or of either of the two (black) associated to a muon Combined (ID+MS) or Standalone (MS) track with $p_T > 15\ GeV$ passing through the NSW on the C side for all physics runs taken in 2023. With at least four active layers each of the detector technologies is able to independently seed and reconstruct a segment in the NSW which can then be combined with the segments in the two outer end-cap stations. Therefore this plot indicates the efficiency with which the NSW is contributing to the muon track reconstruction in the ATLAS end-caps. Regions of low efficiency can be explained by detector or readout issues at the time of data taking [7].

3.2. *Efficiency*

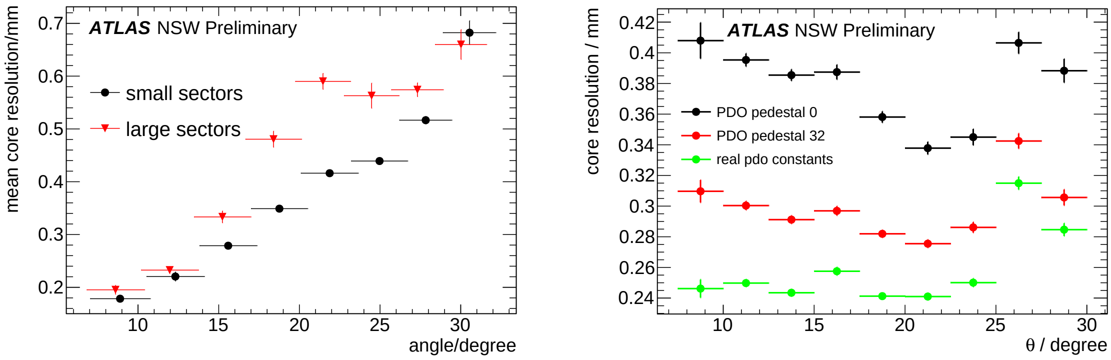
Muon reconstruction efficiency are measured using Combined muons (muon track reconstructed using the inner detector track and muon spectrometer track combined together) or Standalone (only muon spectrometer track) and selecting tracks with a reconstructed $p_T > 15\ GeV$. Despite the different problems that reduce the single layer efficiency (local defects, Readout board problems or LV board problems, HV problems, passivations) the average efficiency of each MicroMegas/sTGC layer is $\sim 65 - 80\%$ depending of the region and it is constant as a function of the time. Three different majority were studied to understand the muon reconstruction efficiency from the NSWs. The best one which reduces the amount of fakes without losing in efficiency is the request of having at least 4 MicroMegas layer (out of 8) or 4 sTGC strip layer (out of 8) which brings the NSWs reconstruction efficiency to be greater than 95%, as shown in Figure 2b.

3.3. *Resolutions*

The reconstruction of the position of the muon is still sub-optimal for both the technologies. The single point resolution is spoiled by effects from residual layer-layer mis-alignment and from the as-built geometry as shown in Figure 3. A substantial improvement in resolution is expected once all effects are considered and corrected. A further improvement in the single layer position reconstruction is expected with new time-based reconstruction algorithms.

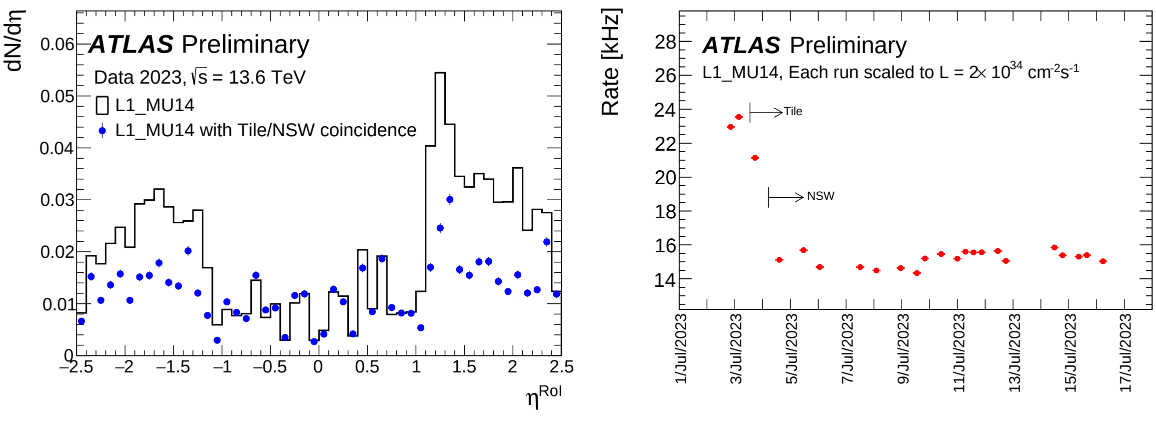
4. L1 Trigger

The inclusion of the trigger of the NSWs was one of the main aspects of the NSW upgrade project. Currently the full trigger chain has been successfully integrated into Level-1 trigger, to release the high-rate pressure and improve the efficiency in end-cap regions. Figure 4 show the rate reductions after the inclusion of 100 (out of 144) NSWs Pad trigger in the ATLAS Trigger Sector Logic.



(a) (b)

Figure 3: (a) Micromegas position resolution extracted by comparing the cluster position on two neighbouring layers corrected by the track angle for small and large sectors [7]. (b) sTGC resolution for different values of the charge calibration of the readout electronics. The resolution is calculated between the reconstructed cluster position on each layer and the muon track reconstructed with the full ATLAS detector [7].



(a) (b)

Figure 4: (a) The pseudorapidity (η) distribution of the level-1 (L1) Region-of-Interests, which fulfill the primary L1 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 L1 trigger decisions in 2023 data. Only the sTGC-Pad readout is used for the NSW coincidence of the track candidates [8]. (b) The trigger rate of the primary L1 muon trigger with a threshold of the transverse momentum of 14 GeV (L1_MU14), scaled to the instantaneous luminosity of 2×10^{34} cm^{-2} s^{-1}, as a function of time in 2023. The rate reduction after the reactivation of the Tile coincidence and after the inclusion of the NSW Pad Trigger was measured to be ~ 2 kHz and ~ 6 kHz respectively [8].

5. Conclusions

The New Small Wheel was one of the largest upgrade projects of the experiments at the LHC. More than 10 years were needed to complete it, with several issues addressed. Currently the New Small Wheels are in the ATLAS detector, collecting data and participating at the trigger decision and the muon track reconstruction.

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