PROCEEDINGS OF SCIENCE

ATLAS New Small Wheel Performance Studies with LHC Run3 data

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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 endcaps marks the culmination of an extensive construction, testing, and installation program. The NSW actively contributes to the muon spectrometer trigger and tracking. Hence the concurrent finalization of the commissioning phase of this innovative system and the optimization of its deployment will be presented here. This proceeding will offer an overview of the strategies employed for reconstruction, integration and optimization, followed by a detailed report on the performance studies of the NSW system during its initial operation with LHC Run3 data.

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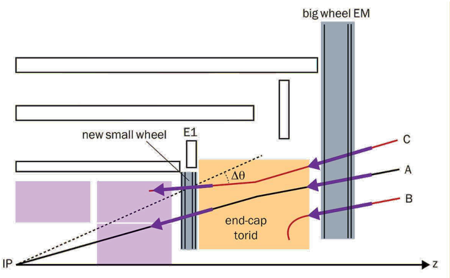
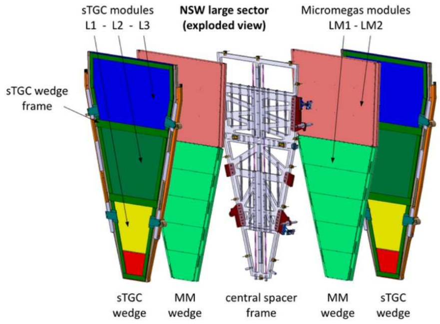


(a) Illustraion of the background rejection by including the NSW in the L1 endcap muon trigger.



(b) Structure of a NSW sector.

Figure 1: Structure of the NSW and ilustrations of its background rejection capabilities in the trigger system. Figures taken from [1] (left) and [2] (right).

1. The ATLAS New Small Wheels (NSW)

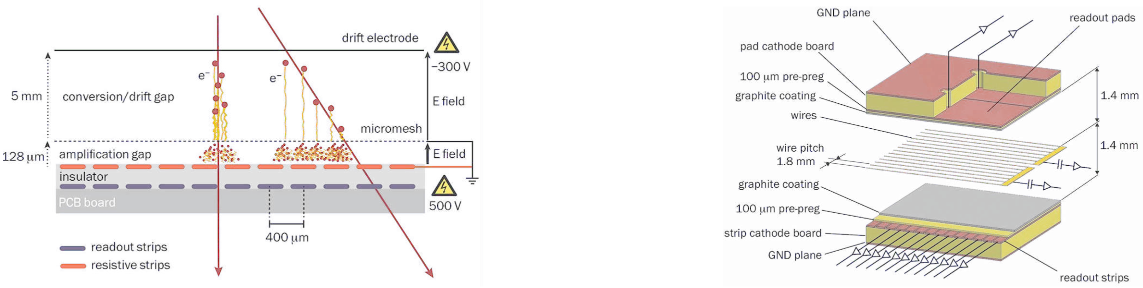
The high luminosity upgrade of the Large Hadron Collider (LHC) at CERN, near Geneva, Switzerland, necessitates corresponding enhancements to the experiments at the LHC's interaction points. One significant upgrade in the ATLAS experiment is the replacement of its two innermost endcap muon stations with the New Small Wheels (NSWs).

The motivation for the NSW project is twofold: it is essential for maintaining low muon momentum trigger thresholds in the first-level single muon hardware trigger (L1) despite the high particle rate environment in the High Luminosity LHC (HL-LHC), by reducing the fake trigger rate. It also enables precise tracking of muons under these challenging conditions.

Figure 1a illustrates the working principle of the muon endcap L1 trigger with the NSW. The Big Wheel (BW) only trigger, used before the NSW was installed, accepted tracks A (good muon), B (beam background), and C (calorimeter punch through) leading to a fake trigger rate of about 90 % [2]. Requiring the confirmation of the BW trigger by the NSW allows to reject the fake tracks B and C and therefore to significantly reduce the fake trigger rate [2, 3].

For precise tracking of muons in the high-rate environment of the HL-LHC, the NSW is indispensable because the detector technologies used in its predecessor, the Small Wheels, lacked the required rate capability and would have consequently suffered from a severe loss in tracking efficiency. To achieve the desired precision in reconstructing the transverse momentum p_T of muons with p_T = 1 TeV to an average accuracy of 15 %, each tracking layer in the NSW must have a spatial resolution of 150 – 175 µm [3].

The NSW deploys two types of gaseous detectors: small-strip Thin Gap Chambers (sTGCs) and Micro-Mesh Gaseous Structure detectors (Micromegas, MM). Figure 1b shows a sketch of a NSW sector where one can see that two MM wedges are sandwiched by 2 sTGC wedges. Each wedge contains four active gas gaps leading to in total 16 active layers in the NSW. Figure 2 illustrates the working principles of both detector technologies. In Micromegas, shown in Figure 2a, the gas gap is divided into two electric field regions by a stainless steel mesh. Primary ionization occurs in the 5 mm wide drift gap, where an electric field of about 600 V/cm is applied. The resulting electrons drift through the mesh into the 128 µm thin amplification gap, where a field of 40 kV/cm is applied, generating an electron avalanche. The charge signal is read out via copper strips with a pitch of



(a) Micromegas **(b)** sTGC

Figure 2: Sketches of working principles of the detector technologies deployed in the NSW. Figures taken from [3].

425 – 450 µm, placed below a resistive layer.

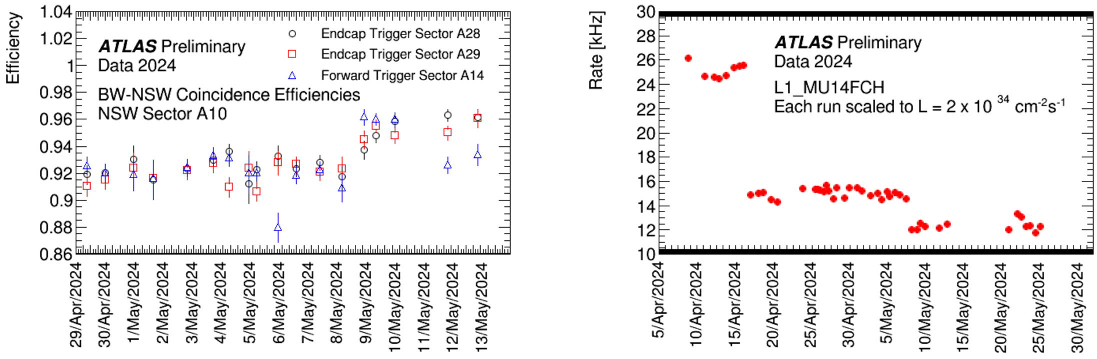
The sTGCs, shown in Figure 2b, are multiwire proportional chambers utilizing a thin gas gap to achieve excellent time resolution, enabling bunch crossing identification capabilities. One of the cathodes is segmented into pads of approximately a few square centimeters, while the other is segmented into strips with a pitch of 3.2 mm. The strips offer excellent spatial resolution in the bending plane of the muons for both the trigger and reconstruction. The information from the pads and wires are used to reconstruct the non-bending coordinate. Additionally the pad information is used in the trigger.

2. Trigger Performance

A detailed description of the NSW trigger can be found in [3]. In the following a brief summary is given. For the sTGCs, a coarse region of interest (ROI) is initially defined by the pads, reffered to as the pad trigger, which was successfully commissioned in 2023. Ultimately, the ROIs from the pad trigger serve as seeds to read out the strips in that region which are subsequently used to build the track segments. This is referred to as the strip trigger, which is not yet fully in operation. Therefore the pad trigger ROIs are forwarded to be merged with the MM trigger candidates. The MM trigger utilizes the front-end chip's capability to forward the address of the first of 64 channels in real time[1], followed by building a coincidence across the MM layers. Finally, the two chains are merged by undergoing a duplicate removal, and the merged segments are forwarded to build the coincidence with the Big Wheel.

Figure 3a shows the efficiency for the NSW-BW coincidence as a function of time over a few weeks of the 2024 data-taking period for one of the 32 NSW sectors. Until May 8$^{\text{th}}$ 2024, only the pad trigger was enabled in this sector; after that date, the MM trigger was also activated following successful commissioning. It can be observed that with only the pad trigger active, this sector exhibited efficiency values around 93 % due to local defects, which prevented it from being included in the coincidence. However, once the MM trigger was introduced, it compensated for the regions of local inefficiency in the sTGC, achieving efficiencies greater than 95 % with the combined MM and sTGC trigger candidates. This improvement allowed the sector to be included

[1]This corresponds to the first hit in time per readout chip.



(a) Efficiency of the NSW/BW trigger coincidence with the pad trigger only and pad trigger and MM trigger combined.

(b) Rate of the L1 muon trigger vs time during for the first two months of data taking in 2024.

Figure 3: Trigger performance of the NSW. Figures taken from [4].

in the coincidence, further reducing the L1 muon trigger rate by effectively eliminating a significant fracion of fake trigger rate.

Figure 3b shows the rate of the L1 muon trigger as a function of time for the first 2 months of the 2024 data taking period, scaled to a reference luminosity of $2 \times 10^{34}/(\mathrm{cm}^2\,\mathrm{s})$. Enabling the coincidence in about 65 % of the the pad trigger sectors on April 17$^{\text{th}}$ 2024 reduced the rate by 10 kHz[2]. After further improvements another 20 % of the pad trigger sectors were enabled on May 8$^{\text{th}}$ 2024 leading to a further reduction of the trigger rate by 3 kHz. On May 21$^{\text{st}}$ 2024 the MM trigger was enabled along the pad trigger increasing the rate by 1 kHz due to increased efficiency. However, at high luminosities, the readout system reached its limit so the MM trigger had to be temporarily disabled again but was swifly re-enabled after the limitations had been mitigated a few days outside the range of the plot.

3. Reconstruction Performance

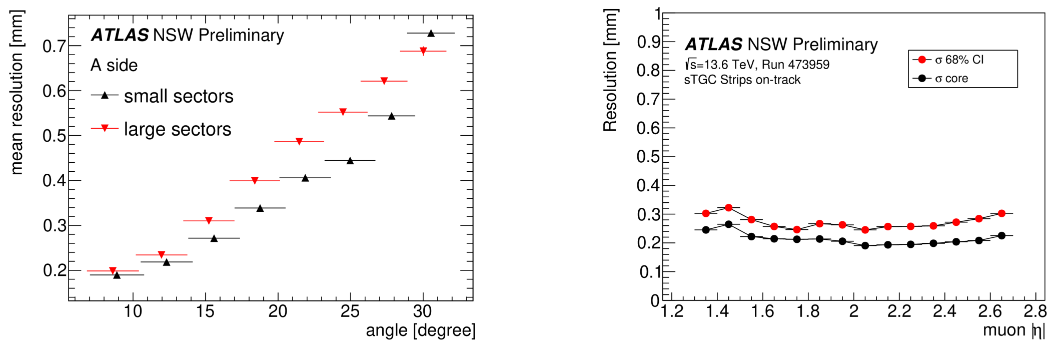
This section discusses the reconstruction performance of the NSW. In all presented studies, the selected muons need to pass a 15 GeV p_t threshold and be reconstructed by both the muon spectrometer and the inner detector. In the region of $|\eta| > 2.5$ muons only reconstructed by the muon spectrometer are accepted since there is a limited coverage from the inner detector.

Figure 4 shows the spatial resolutions of both NSW detectors. For the MMs the residual distribution is determined by comparing the reconstructed position of charge clusters on neighboring layers. For the sTGCs the distance between the muon track and the cluster position is used. The resolution is subsequently determined by fitting the residual distribution with the sum of two Gaussian and quoting either the width of the narrow Gaussian (σ_{core}) or the 68 % confidence interval of the fit function around the mean value of the core Gaussian. The later one also considers the tails of the residual distribution. For both technologies the clusters position is reconstructed using the charge weighted mean of the strip positions of neighboring fired strips.

[2]About 1 kHz of the reduction stems from enabling the coincidence of the tile calorimeter with the BW at the same time.

Figure 4a shows the spatial resolution of the MMs, quoting the 68 % confidence interval. At low incident angles of the muons, the resolution is around 200 µm, increasing to approximately 740 µm when the muon hits the detector under a large incident angle. In general, the small sectors show better resolution than the large sectors, as the shorter readout strips result in lower noise levels. However, at the very outside of the wheel the toroidal magnetic field influences the resolution significantly. The current resolution, especiallly at higher angles, does not yet meet the required specifications, but significant improvements are expected from an enhanced cluster position reconstruction technique under development, which will incorporate drift time as an additional input.

The sTGC resolution, shown in Figure 4b, is barely sensitive to the incident angle, with a resolution around 200 µm when quoting the width of the core Gaussian, and around 300 µm when quoting the 68 % confidence interval. This performance is nearly in agreement with the required specifications. Further improvements are expected from an advanced cluster position reconstruction method and enhanced corrections for internal chamber alignment, both of which are currently being studied.



(a) Resolution of the Micromegas. **(b)** Resolution of the sTGCs.

Figure 4: Spatial resolution of the NSW detector layers. Figures taken from [5].

To build track segments with the NSW and thereby contribute to the reconstruction of muons, at least four out of the eight layers of either technology (sTGC or MM) need to be active. Consequently, the efficiency of the NSW is defined as having at least four hits from either the sTGCs or MMs associated with a muon track. Figure 5 shows this efficiency for the sTGCs (left), MMs (center), and the combination of both detectors (right). The individual detectors reach a system efficiency of greater than 90 %, including inefficiencies due to detector geometry and local defects of the readout, the low and high voltage, or the detectors themselfs. The combined efficiency exceeds 98 %. These efficiency levels remained stable throughout the 2024 data-taking period.

4. Conclusion

Before the current data-taking period of the LHC, one of the most significant upgrades to the ATLAS detector was the installation of the New Small Wheel (NSW), which replaced the innermost end-cap stations of the muon spectrometer. The NSW has already made a substantial impact by reducing the rate of fake muon triggers, with the pad trigger and Micromegas (MM) trigger being

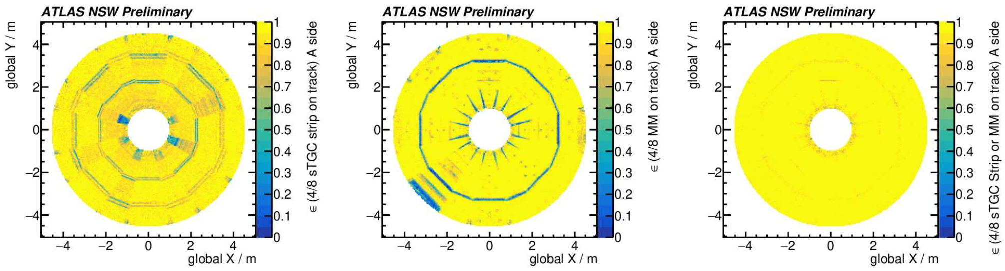


Figure 5: Efficiency of the NSW in contributing to the reconstruction of muon tracks. Figure taken from [5].

successfully commissioned. The strip trigger, which will be crucial for the next data-taking period with the HL-LHC, is currently under commissioning. A notable reduction in the L1 muon trigger rate of 12 kHz was achieved while maintaining a high trigger efficiency. Additionally, the NSW is contributing effectively to the reconstruction of muon tracks. While further improvements in the resolution of individual layers are under investigation, the efficiency of the NSW in contributing to the reconstruction of muons is consistently above 98 %.

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