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Muon Physics at Run-I and its upgrade plan

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Abstract. The Large Hadron Collider (LHC) and its multi-purpose Detector, ATLAS, has been operated successfully at record centre-of-mass energies of 7 and TeV. After this successful LHC Run-1, plans are actively advancing for a series of upgrades, culminating roughly 10 years from now in the high luminosity LHC (HL-LHC) project, delivering of order five times the LHC nominal instantaneous luminosity along with luminosity leveling. The final goal is to extend the data set from about few hundred fb−1 expected for LHC running to 3000 fb−1 by around 2030. To cope with the corresponding rate increase, the ATLAS detector needs to be upgraded. The upgrade will proceed in two steps: Phase I in the LHC shutdown 2018/19 and Phase II in 2023-25. The largest of the ATLAS Phase-1 upgrades concerns the replacement of the first muon station of the high-rapidity region, the so called New Small Wheel. This configuration copes with the highest rates expected in Phase II and considerably enhances the performance of the forward muon system by adding triggering functionality to the first muon station. Prospects for the ongoing and future data taking are presented. This article presents the main muon physics results from LHC Run-1 based on a total luminosity of 30 fb^-1. Prospects for the ongoing and future data taking are also presented. We will conclude with an update of the status of the project and the steps towards a complete operational system, ready to be installed in ATLAS in 2018/19.

1 Introduction

After the first successful years of LHC [1] running, plans are actively advancing for a series of upgrades leading eventually to about five times the design-luminosity some 10-years from now which will allow the reach of the physics program to be significantly extended. Fig. 1 shows an approximate timeline for the planned LHC and ATLAS upgrades. The ATLAS experiment [2] was designed for a broad physics program, including the precise studies of the observed resonance with mass 126 GeV, studies of associated Higgs production, searches for new phenomena and new particles predicted by theoretical models such as SUSY, technicolor, compositeness, extra-dimensions. In order to take advantage of the improved LHC operation the ATLAS detector will also require upgrades for this HL-LHC program, to maintain its capabilities at the planned instantaneous luminosity, which corresponds to an a average of 140 interactions per crossing. The ATLAS upgrades phases for HL-LHC are described in the Letter of Intent [3, 4]. The importance of these upgrades to various physics cases are discussed in [5].

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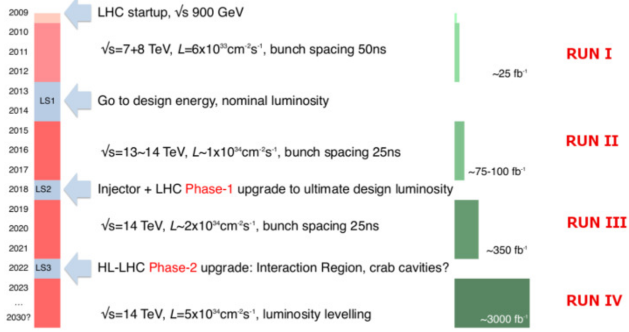


Figure 1: An approximate timeline of the scheduled LHC and ATLAS upgrades.

2 The ATLAS Upgrade

The main focus of the *Phase-I* ATLAS upgrade [3] is on the Level-1 (LVL1) trigger. The objective is to sharpen the trigger threshold turn-on as well as discriminate against background while maintaining the low transverse momentum (p_T) threshold for single leptons (e and μ) and keeping the LVL1 rate at a manageable level. Upgrades are planned for both the muon and the calorimeter trigger systems, without which the single lepton LVL1 triggers would have to be either pre-scaled or p_T threshold raised, resulting in a significant loss of acceptance for many interesting physics processes. The *Phase-II* upgrade [4] of ATLAS includes a full replacement of the central tracking system as well as major upgrades of the trigger and readout systems.

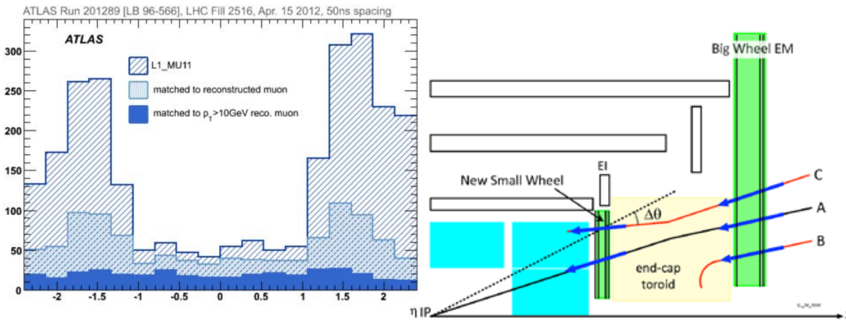
2.1 Upgrade of the MuonSpectrometer: the New Small Wheel (NSW)

Coping with the HL-LHC will be a great challenge for the ATLAS MS detector and will require changes specially those at low radii and large η, as well as in its trigger architecture. The ATLAS muon system [6], based on a toroidal magnet configuration, has excellent performance at high rapidity where the central solenoid can no longer provide momentum dispersion. Roughly 63% of the ATLAS muon system rapidity coverage is provided by the EC and therefore high performance in that region is of absolute importance in reaching the physics goals of the upgraded LHC. The high rapidity region imposes heavy demands on the rate capability of the trigger and tracking chambers of the EC as well as on the p_T trigger discrimination.

Performance studies using collision data have shown the presence of unexpectedly high rates of fake triggers in the EC region. Fig. 2a shows the η distribution of candidates selected by the LVL1 trigger as muons with at least 10 GeV. The distribution of those candidates that indeed have an offline reconstructed muon track is also shown, together with the muons reconstructed with p_T >10 GeV. More than 80% of the muon trigger rate is from the EC (|η|>1), and most of the triggered objects are not reconstructible offline.

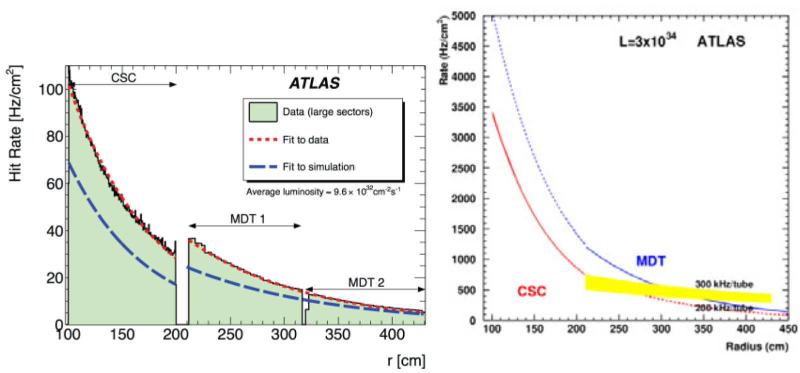
The design of the present EC muon LVL1 trigger does not require a direct bending angle determination of the muon trajectory through the EC toroid, hence, most of the EC triggers are unrelated to muons of physics interest coming from the p-p interaction point (IP) (Fig. 2b). This is the major weakness of the present muon EC design.

Another important issue concerning the present MS is the performance of the muon tracking chambers (in particular in the EC-region), which degrades, with the expected increase of cavern background rate (Fig 3a). An extrapolation from the observed rates at the lower luminosity conditions of the 2012 run to high luminosity and high energy conditions indicates a substantial degradation of tracking performance, both in terms of efficiency and resolution in the inner EC-station. Fig. 3b shows the observed hit rates in the MDT (r >210 cm) and the CSC (r <200 cm), scaled to the value corresponding to the nominal Run-III luminosity of 3 x $10^{34}cm^{-2}s^{-1}$. Given that the high-resolution muon momentum measurement crucially depends on the presence of measured points at the SW (i.e. in front of the EC toroid magnet), this degradation is detrimental for the performance of the ATLAS detector.



(a) (b)

Figure 2 (a): η distribution of LVL1 muon signal (p_T>10 GeV) with the distribution of the subset with matched muon candidate (within ΔR <0.2) to an offline well reconstructed muon (combined inner detector and muon spectrometer track with p_T>3 GeV), and offline reconstructed muons with p_T>10 GeV. (b) LVL1 trigger upgrade to purify high p_T muon trigger.



(a) (b)

Figure 3. (a) Measured hit rate in the region of the SW for L=$9.6x10^{32}$ $cm^{-2}s^{-1}$ at $\sqrt{s}$= 7TeV in the CSC and MDT chambers as function of the radial distance from the beam line. b) Extrapolated hit rate in the CSC and MDT regions for a luminosity of $3x10^{34}$ $cm^{-2}s^{-1}$ at $\sqrt{s}$= 7TeV as a function of the radial distance from the beam line. Also indicated is the range of tube rates of 200-300 kHz.

The NSW upgrade [7] will address the above issues and its design proposal uses two types of particle detectors, MMs (Micro-Mesh-GAseous Structure) [8] and sTGCs [9,10]. MMs provide excellent spatial resolution (~100 microns) required to achieve the targeted momentum resolution while high-speed sTGCs provide precision triggering. Because MMs have a very small amplification area separate from the drift volume, it is possible to absorb the signal ions quickly giving the detector a high rate capacity (>5kHz/cm^2) and excellent time resolution (<5ns). Lastly, a strip read-out system enables higher spatial resolutions than MDTs. The proposed detector layout has two multi-layers of MMs separated by a spacer and covered on the outside on both sides by sTGCs. Small and large sectors are interleaved to give full coverage with no gaps. To enable triggering and reconstruction full simulations, the proposed geometry was implemented the ATLAS *Athena* software framework.

3 NSW Performance

The implementation of the NSW simulation infrastructure can be broken down into three steps:
Geometry: New detectors must be integrated seamlessly into the existing infrastructure and co-exist with the current detector description chain keeping a certain level of flexibility needed to accommodate new features and layouts.
Hit deposition: Information about physics processes and energy deposition in the sensitive layers must be gathered and stored in appropriate objects to be used later in the data processing chain.
Detector response/digitization: Hits and energy deposits must be processed in order to simulate the detector response and the electronics chain must be accurately modeled to reproduce the functions of an active detector.
For each event, the location where the generated particles, including all the muon-related secondaries (e.g. $e^{\pm}$), cross the active volume boundaries is saved. Particles that do not interact with the detectors or that fall outside of the geometric acceptance are ignored. Low energy secondary particles (kinetic energy below 50 MeV) are also removed. The detailed detector response to the passage of particles through the active detector material is already implemented, which has been adopted to evaluate the performance of NSW muon reconstruction.

3.1 Geometrical acceptance and reconstruction efficiency

The NSW performance is measured from a simulated sample of dimuon events, with one muon per EC per event being generated. The sample comprises 5 x 10^5 generated events, with the muons evenly distributed in the φ-coordinate and in p_T, in the range $4 < p_T < 100$ GeV. Additional samples are simulated at higher p_T values, up to 1 TeV, primarily for studies of the p_T resolution. In the η-coordinate they are flatly distributed as well, in the range $1.0 < |\eta| < 3.2$, which exceeds the NSW acceptance. Therefore, additional selection criteria are applied to study only those muons clearly passing through the NSW volume.
The acceptance is measured at two stages of the simulation chain, once at the level of simulated hits and once after the digitization of those hits. In this context, 'simulated hit' refers to the space point recorded in a sensitive detector volume assigned to either of the two technologies, MM or sTGC. In the digitization, those hits are translated into the expected signal response of the corresponding technology. These correspond to a firing strip, in case of the MM, or a firing strip, wire or pad, in the case of the sTGC. In the acceptance studies, only muons with $1.2 < |\eta| < 2.8$ at the entrance to the muon spectrometer volume are considered. Muons outside this η range are rejected because they are not expected to traverse the NSW. Thus, rare cases of muons experiencing large angle scattering or very high energy losses in the calorimeters and in consequence being bent into the NSW are excluded to avoid artificial features in the study. The entrance to the muon spectrometer volume is assumed to be a cylinder that extends to $|z| \approx 6.8$m and has a radius of 4.3m. As the shielding in front of the NSW is considered part of the spectrometer, any scattering-taking place in this structure is included. Signals generated by secondary particles, such as photons originating from bremsstrahlung, or delta electrons, are not taken into account. The acceptance of the NSW for digitized hits (total number of hits per single muon) is presented in Fig. 4 for both the MM and sTGC strips. As expected, muons are typically traversing 8 active detector layers of a given technology, in a regular sector, while at the acceptance edges in η the efficiency drops rapidly. In the regions of overlapping large and small sectors, the number of volumes with recorded hits is as large as 16. Areas of reduced efficiency visible in the η distribution are due to the radial gaps between the four η stations, around η = 1.43, 1.68 and 2.05. For the sTGC, the area of decreased efficiency due to the radial gaps is less sharp than for the MM because the distance in z between the two multiplets of a station is larger. For the area around η=2, the staircase geometry of the sTGC results in a nearly complete recovery of the efficiency.

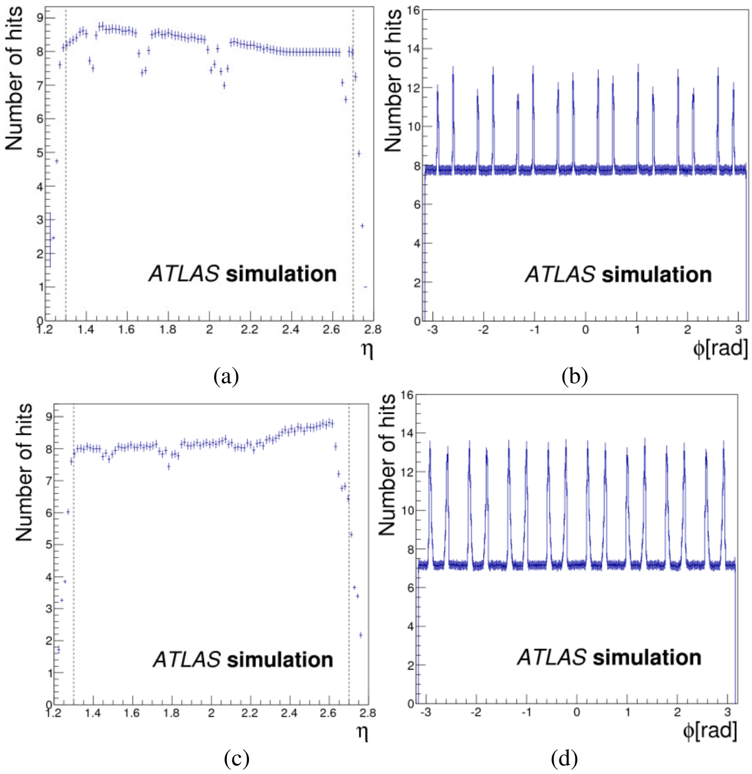


Figure 4. Number of digitized simulation hits of various types for a single muon traversing the NSW: (a) MM strips, as a function of |η|; (b) MM strips, as a function of φ; (c) sTGC strips, as a function of |η|; (d) sTGC strips, as a function of φ.

4 Conclusions

In order to benefit from the expected HL-LHC performance that will be provided by the *Phase-I* upgraded LHC, ATLAS proposes to replace the present muon SW with the NSW. The NSW is a set of precision tracking (MMs) and trigger detectors (sTGC) able to work at high rates with excellent real-time spatial and time resolution. These detectors can provide the muon LVL1 trigger system with online track segments of good angular resolution to confirm that muon tracks originate from the IP. In this way the EC fake triggers will be considerably reduced. With the proposed NSW the ATLAS muon system will maintain the full acceptance of its excellent muon tracking at the highest LHC luminosities expected. At the same time the LVL1 low p_T (typically p_T >20 GeV) single muon trigger rate will be kept at an acceptable level.

This detector combination has been designed to be able to also provide excellent performance for the eventual HL-LHC upgrade.

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