ATLAS Detector Upgrade Prospects

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Abstract. After the successful operation at the centre-of-mass energies of 7 and 8 TeV in 2010-2012, the LHC was ramped up and successfully took data at the centre-of-mass energies of 13 TeV in 2015 and 2016. Meanwhile, plans are actively advancing for a series of upgrades of the accelerator, culminating roughly ten years from now in the high-luminosity LHC (HL-LHC) project, which will deliver of the order of five times the LHC nominal instantaneous luminosity along with luminosity levelling. The ultimate goal is to extend the dataset from about few hundred \( fb^{-1} \) expected for LHC running by the end of 2018 to 3000 \( fb^{-1} \) by around 2035 for ATLAS and CMS. The challenge of coping with the HL-LHC instantaneous and integrated luminosity, along with the associated radiation levels, requires further major changes to the ATLAS detector. The designs are developing rapidly for a new all-silicon tracker, significant upgrades of the calorimeter and muon systems, as well as improved triggers and data acquisition. ATLAS is also examining potential benefits of extensions to larger pseudorapidity, particularly in tracking and muon systems. This report summarizes various improvements to the ATLAS detector required to cope with the anticipated evolution of the LHC luminosity during this decade and the next. A brief overview is also given on physics prospects with a \( pp \) centre-of-mass energy of 14 TeV.

1. Introduction
The Large Hadron Collider (LHC) started the second period of collisions and data acquisition in 2015 at a centre-of-mass energy of 13 TeV. Run 2 has been successful so far, with smooth operation and many physics results published with the newly recorded data by all experiments. Given the uniqueness of the LHC facility, plans have been made to extend the capabilities of the machine, such that it is able to deliver up to seven times the nominal luminosity. The upgrades to the accelerator and to the detectors will take place in two phases. During Phase I several detector systems will be upgraded: the calorimeter trigger system and the associated Liquid Argon Calorimeter trigger electronics, the installation of the New Small Wheel and the installation of the Fast Tracker Trigger. During Phase II a new all-silicon tracker and new muon trigger chambers will be installed, a complete upgrade of readout electronics will be made and changes will be applied to the trigger and readout systems in order to increase the trigger rate and improve the readout capabilities. The increased luminosity will lead to higher data volumes to be processed and to a dramatic increase in the pileup rates. The plans for the upgrade of the ATLAS detector are aiming to ensure that the detector will cope with the data volumes and the pileup rates expected. The Run 1 configuration of the ATLAS detector is detailed in Ref. [1].

In the following an overview of the upgrades of the main detector subsystems will be given, followed by the impact of the upgrades on the physics objects performance and on selected physics analyses. The studies mentioned were discussed in more detail in the Scoping Document.
and in the notes published for the workshop organized this year by the European Committee for Future Accelerators (ECFA).

2. Detector Upgrades

In the Scoping Document there are three scenarios discussed for the upgrade of the ATLAS detector, each aiming to maximize the physics performance and output within a given budget in conditions of very high pileup rates. The three scenarios are called Reference, Middle and Low and they are summarized in Table 1. At the time this report was written no decision was taken regarding the final configuration of the detector. Only changes from the Reference scenario are presented here, with more recent updates cited where available.

Table 1. The three detector configurations considered for the HL-LHC upgrade of the ATLAS detector.

| Subsystem                  | Reference Scenario | Middle Scenario | Low Scenario |
|----------------------------|--------------------|-----------------|--------------|
| Calorimeter Trigger (e/γ) | |                |              |
| Pixel Detector             | |                |              |
| Very forward muon tagger   | 2.6 < |η| < 4.0 | -             | -            |

The current ATLAS detector electronics was designed to buffer data for a maximal latency of 2.5 µs and cope with Level-1 (L1) trigger rates up to 100 kHz. During Phase-II Upgrade an additional trigger level, referred to as L0, will be introduced to accommodate latencies less than 6 µs and trigger rates up to 1 MHz, with the L1 trigger rates expected to reach 400 kHz. The L0 trigger will have two components: L0 Muon Trigger and L0 Calorimeter Trigger. The former is expected to have an efficiency of 92-96% in the barrel region. L0 Calorimeter Trigger will reuse the system installed as part of the Phase-I ATLAS Upgrade and will be adapted for the Phase-II Upgrade. L0 Calorimeter Trigger will be based on feature extractor processors with very fine granularity covering areas of |η| < 2.5 for electrons, photons and taus, |η| < 4.9 for jets and allowing an entire event to be processed in a single module.

L1Track will use hits from the Internal Tracker (ITk) strips and pixels to find tracks within Regions of Interest (RoI) which are seeded by L0 triggers. The transverse momentum of the tracks used for the reconstruction templates will be restricted to p_T > 4 GeV. L1Global is a time-multiplexed trigger system receiving input from the LAr and Tile Calorimeters, and from L0 and L1Track, with the calorimeter data being transmitted to it with a latency of 1-2 µs after the L0 decision. The central trigger processors for L0 and L1 will ensure that L1Track and L1Global do not overflow. The data from the detector will be transferred to the readout system, then to a network which will pass it to the event filter and to the monitoring and calibration processors.

During the Phase-I Upgrade, the detectors of the inner layer in 1.3 < |η| < 2.7 of the Muon Spectrometer (MS) will be replaced by an additional layer of Resistive Plate Chambers (RPC), small-strip Thin Gap Chambers (sTGC) and MicroMegas detectors. During Phase-II Upgrade, the replacement of the whole readout electronics is foreseen, in order to be able to cope with the larger data rates expected.

The current Monitored Drift Tubes (MDT) chambers can safely operate in most of the MS during the HL-LHC period, with the exception of the end-cap inner layer, which will benefit from the installation of the New Small Wheel in Phase-I Upgrade. Also, new small MDTs will replace some of the current ones to make space for the additional RPCs, and a new type of TGC will be installed in the end-cap inner layer to improve the accuracy of the muon track θ angle measurement during Phase-I. Other upgrades of the MS include adding a muon tagger for the large pseudorapidity region to extend the inner tracker capabilities, and the replacement of
the power supplies during Phase-II to cope with the larger radiation doses foreseen. The $R-z$ view of the upgraded MS is shown in figure 1, with the various upgrades planned marked with colours.

![Figure 1](image)

**Figure 1.** Drawings of the ATLAS Muon Spectrometer with the new chambers proposed for installation in the Phase-II upgrade indicated with red text, those to be installed during LS2 indicated with green text, and those that will be kept unchanged from the Run 1 layout indicated with black text. The figure was published in Ref. [2].

The Internal Tracker (ITk) for the Phase-II Upgrade will be an all-silicon tracker. There are plans to extend the pseudorapidity coverage up to $|\eta| = 4.0$. ITk will have two components, Pixel and Strip. For the Pixel part two designs are currently under study, the Extended and the Inclined [3]. The Pixel barrel design is divided into an insertable two-layer inner barrel, surrounded by a fixed outer barrel. The insertable part is necessary in order to ensure high performance for the entire HL-LHC runs, as it may necessitate replacement due to radiation damage. The Strip part of the ITk is situated just outside the Pixel detector and it consists of four double-sided barrels and six strip discs in each of the two forward regions. Due to the large increase in the number of both strip (from 4088 to 20000) and pixel modules (from 1744 to 10000), the powering scheme needs to be changed with respect to the one of the current Inner Detector, such that groups of modules will share the same low voltage and high voltage supplies.

The Liquid Argon Calorimeter, the Scintillating Tile hadronic barrel detectors (TileCal) and the Hadronic End-cap Calorimeter (HEC) maintain their required performance under HL-LHC conditions and will not be replaced. An option considered for helping to mitigate the effects of pileup rates in the forward and end-cap regions is adding in front of the LAr a High Granularity Timing Detector (HGTD). The readout electronics of the LAr and of the TileCal need to be exchanged due to limited radiation tolerance and the necessary upgrade in the trigger chain. During Phase-I Upgrade additional electronics will be installed to ensure finer granularity signals for the L1 calorimeter triggers.

### 3. Physics Objects Performance

The performance of the upgraded detector in reconstructing physics objects is assessed using events generated at an energy in the centre-of-mass system of 14 TeV for several Standard Model processes, which include the $Z^0$ decay in a charged lepton-antilepton pair, the top-antitop quark
pair production (ttbar) and the vector boson fusion production of the Higgs boson decaying in a pair of photons. Minimum bias pileup events are overlaid on the hard scatter events of interest and the resulting information is used to reconstruct the physics objects. The response of the detector is simulated in a sequence of two steps: the smearing of the transverse momentum and the energy of the reconstructed physics objects using smearing functions, and then applying reconstruction efficiencies for the physics objects. The trigger response is also simulated by applying trigger efficiency functions.

The extension of the tracker to a larger pseudorapidity region has a significant impact on the identification of physics objects and on pileup mitigation. The most visible contributions of this extension take place in the area of jets and missing transverse energy ($E_T^{miss}$) performance. The latest tracking performance study [3] used ttbar and minimum bias samples. It showed very good tracking efficiency across the full acceptance of the upgraded tracker, excellent track parameters resolutions and the non-primary and fake tracks are understood and under control. Although the performance of the ‘Inclined’ layout is usually shown as representative, no conclusion was yet reached about the choice of layout for ITk.

The performance of primary vertex finding is studied using samples of ttbar, $Z \rightarrow \mu\mu$ and $H \rightarrow \gamma\gamma$ events considering a pileup value of $\mu = 200$. Good vertexing performance is expected. The primary vertex finding performance does not depend strongly on the layout, but on the physics process [3].

The electron identification algorithms need to be re-optimized in the context of a different detector configuration. The main backgrounds for electron identification are the photon conversions and jet fakes. The identification efficiency is estimated to be around 70% compared to 85% in Run 2 [4]. The pileup is affecting only the resolution of electrons having low transverse momenta. The forward electron performance still needs to be optimised for the new detector.

The photon identification is studied using calorimeter-based variables only. Applying a cut on the transverse energy of $E_T < 6$ GeV in a radius of 0.2 around the photon leads to a good isolation and to an efficiency of over 95%, but the mean combined efficiency will be at around 70% [4].

The upgrades to the Muon Spectrometer are not expected to change significantly the reconstruction performance of the muons, but improvements are expected in the resolution for combined muons\(^1\) and in the large pseudorapidity region. The muon performance studies were updated this year [4] with full ITk simulation replacing the parametrised resolution.

The reconstruction of jets will be among the most affected by the large pileup rates. There are several algorithms being investigated for pileup mitigation at various levels. Extending the $\eta$ coverage is bringing clear advantages for those analyses relying on a good separation between hard scatter and pileup jets or based on an exclusive jet selection. The jet reconstruction efficiency was investigated for jets having $p_T < 100$ GeV, for which the anti-$k_T$ algorithm [5] was used. Efficiencies of pileup jets as a function of the efficiency of hard scatter jets are shown in figure 2, as well as the reconstruction of the jet mass using information from various detector subsystems.

The resolution of missing transverse energy depends on the identification of all the objects in the event, including leptons, photons and jets, and on the soft-term contribution from objects with low $p_T$. The extension of the tracker to larger pseudorapidity values and the use of the $R_{p_T}$ variable, defined as:

$$ R_{p_T} = \frac{\sum_{i \in PV} p_{T,\text{track},i}^{\text{jet}}}{p_T^{\text{jet}}} $$  \hspace{1cm} (1) $$

improve the resolution of $E_T^{miss}$. The effects are documented in Refs. [6] and [7].

\(^1\) ‘combined muons’ means that information from both the tracker and the Muon Spectrometer was used for reconstructing the muons.
The flavour tagging efficiency is evaluated using a ttbar sample with at least one semileptonic top quark decay. Considering a working point of 70% average b-tagging efficiency, the mistag rate is 0.1-1%, the c-jet efficiency is 10-25% and the b-jet efficiency is 40-80%. The most recent estimates were published in Ref. [4].

4. Physics Prospects

The physics prospects for HL-LHC were studied for analyses falling under three categories: Higgs production and rare processes, Standard Model precision measurements and beyond Standard Model searches. Here will be presented briefly only the most recently published studies in each category.

The ATLAS Collaboration presented comprehensive results for Higgs boson couplings at HL-LHC at the ECFA workshop in 2014 [8]. The subsequent studies [9, 10, 11, 12, 13, 14, 15] concentrated on the impact of various detector designs on the precision Higgs boson measurements and on the study of rare Higgs boson processes. Among the most interesting analyses in this area are the production of a Higgs boson pair, with both bosons decaying to b-quarks, and the associated production of a t-quark pair and a Higgs boson pair.

The sensitivity at 3000 fb$^{-1}$ to the non-resonant production of a Higgs boson pair, with both bosons decaying to b-quarks, is estimated by extrapolating the results obtained with the 2016 dataset, which has $\int L dt = 10.1$ fb$^{-1}$ of proton-proton collision events at 13 TeV. The base selection is at least four b-jets having $p_T > 30$ GeV and $|\eta| < 2.5$. In the absence of any signal and without (with) systematic uncertainties, cross-sections 1.5 times (5.2 times) greater than the SM prediction are excluded at the 95% confidence level [14]. In figure 3 the distribution of the invariant mass of the four jets is shown, for both the 13 TeV analysis and for the HL-LHC scenario.

Another rare process studied is the associated production of a top quark-antiquark pair and a Higgs boson pair. Its observation would contribute to measuring the self coupling of the Higgs boson. The event selection requires at least 7 jets having $p_T > 30$ GeV and $|\eta| < 4.0$, out of which at least 5 jets are b-tagged, and at least one electron or a muon. Assuming Standard Model rates of signal and background processes, 25 $t\bar{t}HH$ events are selected, with a background of 7100 events. The statistical significance of the production is estimated at 0.35 $\sigma$ [15].

Standard Model studies will be able to reach an unprecedented precision during the HL-LHC. Analyses like $W^\pm W^\pm$ and $WZ$ scattering will benefit from the increase in the statistics, while...
flavour-changing neutral currents (FCNC) analyses will become more attractive.

For the $W^\pm W^\mp$ and $WZ$ production in association with a high-mass dijet system, the event selection requires the presence of a lepton or a muon having $p_T > 30$ GeV, $E_T^{miss} > 30$ GeV and at least 4 small-$R$ jets or at least a large-$R$ jet and 2 small-$R$ jets. The results are interpreted as limits on the anomalous quartic gauge couplings [16].

The FCNC are strongly suppressed in the Standard Model, but they can be significantly enhanced if new physics is present. The sensitivity of top-quark decays to neutral bosons and up-type quarks is investigated in the decays $t \rightarrow Zq$ and $t \rightarrow Hq$. There are various final state topologies studied, with leptons, b-jets and light flavour jets. An increase by a factor of 2 to 6 is expected in the $t \rightarrow Zq$ channel and by a factor of 20 in the $t \rightarrow Hq$ [17].

The most recent studies of sensitivity to Beyond Standard Model (BSM) signatures at HL-LHC are the search for compressed top squark pair production, the search for direct stau production and model independent dijet resonance searches.

The search for top squarks having a mass such that $\Delta(m_{stop} - m_{N1}) \approx m_{top}$, where $N1$ is the lightest neutral supersymmetrical particle, is based on the following event selection: two charged leptons (electrons or muons) having $p_T > 25$ GeV and at least two b-jets having $p_T > 30$ GeV. At 3000 fb$^{-1}$, the discovery potential is of squarks with masses up to 480 GeV and the exclusion potential of top squarks will reach stop masses of 700 GeV [18]. In figure 4 the p-value for this analysis is shown as a function of top squark mass for two luminosity values.

The sensitivity to direct stau production at HL-LHC was also studied. The event selection requires hadronically decaying tau leptons having $p_T > 20$ GeV, electrons and muons having $p_T > 10$ GeV and jets having $p_T > 50$ GeV. The discovery potential lies in the stau mass region of 100 GeV to 400 GeV and the exclusion limit may reach stau masses between 540 and 700 GeV, depending on the model [19]. In figure 5 the discovery and exclusion limits are shown as functions of the stau mass.

Another interesting study for beyond Standard Model physics is the model-independent search for dijet resonances. The event selection requires at least two jets in the rapidity interval $|y| < 2.8$, with the next-to-leading jet having $p_T > 50$ GeV and the invariant mass of the two leading jets $m_{jj} > 1.5$ TeV. Two benchmark models are used, the production of excited $u$ and $d$ quarks and the production of quantum black holes (QBH). The discovery potential for excited
Figure 4. Expected compatibility, in terms of p-value $p_0$, with the background-only hypothesis from the analysis of 3000 fb$^1$ and of 300 fb$^{-1}$ of 14 TeV proton-proton collision data as a function of the $t$ mass. The figure was published in Ref. [18].

$u$ and $d$ quarks can already be extended after the first 100 pb$^{-1}$ to 4 TeV, and to 8.2 TeV for QBH [20].

Figure 5. The 95% CL exclusion limits and 5σ discovery contours for 3000 fb$^{-1}$ luminosity on the combined $\tilde{t}_L\tilde{t}_L$ and $\tilde{t}_R\tilde{t}_R$ production in HL-LHC. The figure was published in Ref. [19].

5. Conclusions
Detector designs and performance studies for the HL-LHC ATLAS detector configuration were published for the ECFA Workshop 2016. These will be followed by technical design reports for most of the detector subsystems in the years 2016-2017. One of the largest concern for the HL-LHC is the pileup mitigation, which is being addressed through explorations of design
options and new methods. The performance of the physics objects is expected to improve due to
the extension of the tracker in the large $\eta$ region, to new trigger strategy and to new and
updated electronics for most of the detector subsystems. Good progress has been shown in the
Higgs physics studies, many of the recent results concentrating on the rare processes. Regarding
the Standard Model measurements, the FCNC analyses are becoming more attractive, with
remarkable increases in sensitivity. Beyond Standard Model searches will also benefit from
the upgraded detector and large luminosity to extend significantly the discovery and exclusion
potentials.

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