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ATLAS Future Plans: Upgrade and the Physics with High Luminosity

S. Rajagopalan[1,a] on behalf of the ATLAS Collaboration

[1] *Brookhaven National Laboratory, Upton, NY 11973, USA*

Abstract. The ATLAS experiment is planning a series of detector upgrades to cope with the planned increases in instantaneous luminosity and multiple interactions per crossing to maintain its physics capabilities. During the coming decade, the Large Hadron Collider will collide protons on protons at a center of mass energy up to 14 TeV with luminosities steadily increasing in a phased approach to over 5×10^{34} cm^{-2}s^{-1}. The resulting large data sets will significantly enhance the physics reach of the ATLAS detector building on the recent discovery of the Higgs-like boson. The planned detector upgrades being designed to cope with the increasing luminosity and its impact on the ATLAS physics program will be discussed.

1 Introduction

The ATLAS detector[1] is a multi-purpose apparatus with a cylindrical geometry covering almost the entire solid angle[2] around the interaction point. Closest to the beam pipe are silicon based tracking detectors and straw-tube transition radiation detectors, located inside a superconducting solenoid that provides a 2T magnetic field. Outside the solenoid, fine-granularity Liquid Argon (LAr) electromagnetic (EM) calorimeters with an accordion geometry provide coverage up to $|\eta| < 3.2$. An iron-scintillating hadronic calorimeter extends to $|\eta| < 1.7$ while copper and LAr technology is used in the forward region $1.7 < |\eta| < 3.2$. In the very forward region, $3.2 < |\eta| < 4.5$, copper and tungsten LAr calorimeters provide measurements of the EM and hadronic showers. The muon spectrometer consists of three superconducting toroidal magnets with precision tracking provided by Monitored Drift Tubes (MDT) up to $|\eta| < 2.4$ and Cathode Strip Chambers (CSC) in the very forward region. Triggering for muons is provided using Resistive Plate Chambers (RPC) in the barrel region and Thin Gap Chambers (TGC) in the forward region up to $|\eta| < 2.4$. The ATLAS detectors provide input to three levels of trigger system that provides fast filtering capabilities and capture events of interest to physics with high efficiency.

The high energy and luminosity available at the Large Hadron Collider (LHC) offers the best opportunities for exploration of new physics beyond the Standard Model (SM) and for making precision measurements of properties of known phenomena. The ATLAS experiment has recorded 5.25 fb^{-1} of pp collision data at a center of mass energy of $\sqrt{s}$ = 7 TeV and 21.7 fb^{-1} at a center of mass energy of $\sqrt{s}$ = 8 TeV in a two year period (2011-2012) with a data taking efficiency exceeding 93%. The operational conditions of the LHC during the 2011 and 2012 data taking period are shown in Table 1. The peak luminosity delivered by the LHC at the start of the fill increased from $\mathcal{L}_{\text{peak}}$ = 3.65x10^{33} cm^{-2}s^{-1} in 2011 to $\mathcal{L}_{\text{peak}}$ = 7.73x10^{33} cm^{-2}s^{-1} in 2012. The average number of interactions per crossing during the same period has also increased from $<\mu>$ = 9.1 to 20.

Table 1. Selected LHC operational parameters for pp collisions in 2011 and 2012

Parameter	2011	2012
$\sqrt{s}$ (TeV)	7	8
Bunch spacing (ns)	50	50
Peak luminosity (10^{33} cm^{-2}s^{-1})	3.65	7.73
Integrated luminosity delivered (fb^{-1})	5.61	23.3
Average Interactions per crossing	9.1	20

During the next decade, the LHC has planned a series of upgrades that will substantially increase the instantaneous luminosity beyond its original design parameters. This will require corresponding upgrades to the ATLAS detectors to maintain physics acceptance in the high luminosity environment. These upgrades have been planned in three stages, referred to as Phase 0, Phase I and Phase II, each designed to match the expected improvements to the LHC and deteriorating performance of the ATLAS detector components due to aging effects.

2 Phase 0 Upgrade

The planned upgrades to the LHC during the 2013-2014 shutdown period will increase the center of mass energy of pp collisions to $\sqrt{s}$ = 13 - 14 TeV with a peak luminosity of $\mathcal{L}_{\text{peak}}$ = 10^{34} cm^{-2}s^{-1}. Following this upgrade, the LHC will continue operations for three years (2015-2017) collecting an additional 100 fb^{-1} of pp collision data. The average number of interactions is 27 while operating with 25 ns bunch spacing at a luminosity of 10^{34} cm^{-2}s^{-1}. The

[a] e-mail: srini.rajagopalan@cern.ch

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ATLAS experiment will repair and consolidate its detector sub-systems during the two year shutdown and prepare for the higher center of mass energy and higher luminosity operations. It must also prepare itself for a possible LHC operations with 50 ns bunch spacing that will result in a significant increase in the number of interactions per crossing. The ATLAS detector plans on the following improvements to the detector systems as part of its Phase 0 upgrade:

- A new Aluminum beam pipe is planned to replace the existing iron beam pipe that will substantially reduce activation of detector components.
- An additional new layer of pixel detectors, referred to as the Insertable B-Layer or IBL[3], will be added, occupying the region closest to the beam pipe. The IBL will use 50×250 μm planar and 3D sensors mounted on Carbon-foam staves that offers reduced material. A new Beryllium beam pipe around the interaction region with a smaller radius will be installed to accommodate the IBL. The IBL will supplement the high precision tracking in a high pile-up environment improving the vertexing and b-tagging capabilities of ATLAS. Simulation studies have demonstrated that the additional layer of pixels close to the beam pipe will provide a three-fold increase in rejection while maintaining the b-tagging efficiency.
- The sensors and front-end electronics for the insertable B-layer will use a new CO_2 based evaporative cooling system providing reduced mass and maintenance free operation.
- The low voltage power supplies for the calorimeter front end electronics have been redesigned and will replace the existing power supplies, providing more robust operations.
- Additional MDT chambers in the muon spectrometer in the barrel-endcap transition region ($1 < |\eta| < 1.3$) will be installed, improving the geometrical acceptance.
- Additional neutron shielding in the forward region will be installed to withstand the expected increase in particle fluences.

3 Phase I Upgrade

The Phase I upgrade[4] is designed to enable the ATLAS experiment to fully exploit the physics opportunities afforded by the LHC machine upgrades. The Phase I LHC upgrade will increase the luminosity to $2-3\times10^{34}$ $cm^{-2}s^{-1}$ and deliver 300-400 fb^{-1} of pp collision data during a three year operation. The excellent performance of the LHC in 2011 and 2012 has demonstrated its ability to deliver luminosity that exceeds expectations and it is therefore prudent to plan for higher than anticipated luminosity and pile-up conditions. The ongoing data taking operations at lower luminosities has helped the ATLAS experiment gain experience to plan for upgrades at the higher luminosity.

The ATLAS experiment maintains a rich and diverse physics program with a strong emphasis on probing the origin of electroweak symmetry breaking as predicted by the SM, leading to a major focus on the Higgs boson. The ATLAS experiment recently announced[5] the discovery of a new boson that resembles a Standard Model Higgs with a mass of 126 ± 0.4(stat) ± 0.4(sys) GeV. The increased statistics collected following the Phase I upgrade will confirm if the observed resonance is a Higgs boson as predicted by the SM and precisely measure its properties. This includes precision measurement of its mass, width, production rates, branching ratios and its couplings to fermions and bosons. These precision measurements would also need to incorporate results from rarer processes such as the associated production of Higgs, e.g. W+H with Higgs decaying to $b\bar{b}$, $\tau\tau$ and WW^*.

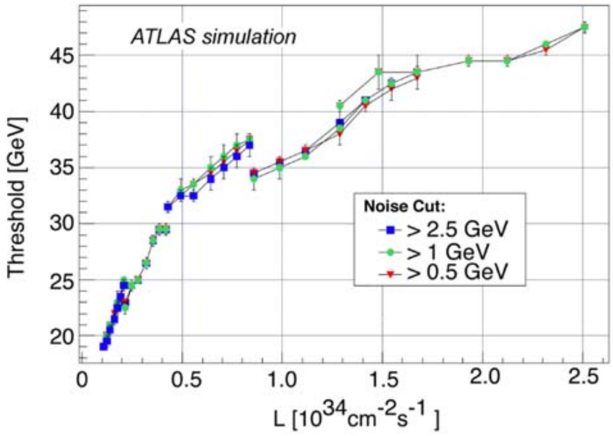

Figure 1. Predicted E_T threshold at Level-1 for non-isolated EM clusters as a function of instantaneous luminosity that will yield a 20 kHz Level-1 trigger rate[4].

The ATLAS physics program also includes continued searches for other new phenomena and new particles predicted by alternate theoretical models such as supersymmetry, technicolor, compositeness, extra-dimensions and others. The experiment will also continue to make precision measurements of know SM processes that would provide crucial indirect probes of new physics.

The physics studies mentioned above demand a low p_T (~20 GeV) single isolated lepton trigger at the first stage of the trigger (Level-1) to maximize the physics acceptance. The total output bandwidth of the Level-1 trigger system is constrained to 100 kHz. Experience with early data taking has shown that ~20 kHz each can be allocated to single isolated electron and muon trigger at Level-1, the remaining bandwidth needed for an assortment of other triggers. With peak LHC luminosity expected to increase to 2 to 3 $\times10^{34}$ cm^{-2}s^{-1}, the lepton p_T thresholds in the current system will have to be raised to well above 20 GeV to meet the bandwidth limitations. This will have a severe and negative impact on the physics acceptance.

The transverse energy (E_T) threshold for a non-isolated EM cluster as a function of instantaneous luminosity that will yield a 20 kHz Level-1 trigger output rate is shown in Figure 1. At 2×10^{34} cm^{-2}s^{-1}, the single non-isolated lepton threshold would have to be set at 45 GeV (35 GeV for isolated) with the current system.

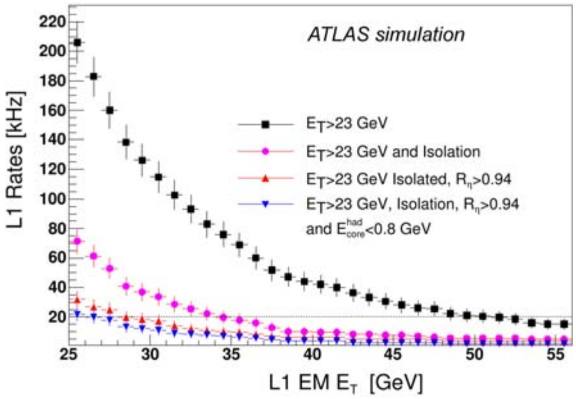

Figure 2. Level-1 trigger rate estimated using simulation as a function of E_T threshold at 3×10^{34} cm^{-2}s^{-1} with different selection conditions[4].

Hence the focus of the Phase I upgrade is to deploy additional means of controlling increasing trigger rates while retaining low p_T lepton thresholds at Level-1. The principal components of the ATLAS Phase I Upgrade are:

- An upgraded calorimeter trigger readout to provide finer granularity data to Level-1.
- Forward muon chambers using a combination of micromegas technology and resistive plate chambers.
- Fast tracking capabilities for all Level-1 accepted triggers.

3.1 A finer granularity calorimeter trigger

The current Level-1 EM calorimeter trigger uses E_T thresholds that are computed using a $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ trigger towers. Additional lateral and longitudinal isolation selections can also be deployed to increase background rejection. The Phase I upgrade will transfer additional data within these trigger towers to exploit the lateral and longitudinal EM shower profiles. In particular, the second sampling of the calorimeter, where the peak of the EM shower occurs, can provide additional rejection capabilities against jets. As shown in Figure 2, an additional three-fold rejection can be obtained over the existing Level-1 trigger system as a function of the E_T threshold when the new shower shape cuts (denoted by R_η) provided by the upgraded readout is applied. The physics impact of an upgraded trigger readout is demonstrated in Table 2 using the associated production of Higgs (WH), which triggers on the single electron from the W decay. The upgrades will allow operations at lower E_T thresholds thereby improving the acceptance to *WH* process while maintaining low trigger rates.

3.2 Forward muon chambers

The ability to trigger efficiently with muons at high luminosity is critically important to the ATLAS physics program. The associated production of Higgs (W+H), with the *W* decaying to $\mu\nu$ that relies on a single muon trigger has been extensively studied. These physics processes

Table 2. The Level-1 trigger efficiency for the W+H process (ε_{WH}) and the corresponding estimated trigger rates for several conditions on the single EM cluster trigger. The "I" denotes the isolation selection. The shape cuts, realized through an upgrade, refer to requirements on the lateral shape on second sampling where the peak of the EM shower occurs.

Level-1 trigger	ε_{WH} (%)	Rate (kHz)
$E_T \geq 35$ (GeV)	73	54
$E_T \geq 35$I (GeV)	71	16
$E_T \geq 35$I & shape cuts (GeV)	71	6.5
$E_T \geq 23$I & shape cuts (GeV)	88	23

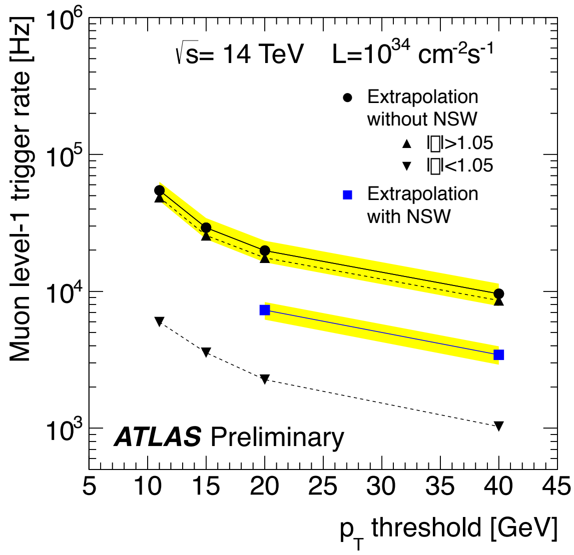

Figure 3. Level-1 muon trigger rate as a function of muon momentum at a luminosity of 10^{34} cm^{-2}s^{-1}. The solid line shows the total muon rates with and without the new small wheel. The dotted lines show the currently observed rates in the central and forward region[4].

typically require a single muon trigger above 20 GeV at Level-1 to maximize the physics acceptance. The rates for a single muon trigger are dominated by the presence of fakes in the forward region from cavern backgrounds. The introduction of an additional trigger plane in the inner region of the forward muon system (referred to as the small wheel) would measure the vector of the muon track to a precision of 1 mrad, thereby reducing the fake contributions that dominate in this region. The new small wheel chambers cover the rapidity region $1.2 < |\eta| < 2.4$ and consist of four layers of micromegas chambers[6] providing precision tracking interspersed with TGC providing rapid triggering capabilities. The Level-1 muon trigger rate as a function of the muon p_T threshold with and without the presence of the new small wheel chambers is shown in Figure 3. The addition of the new small wheel would significantly reduce the fake rate contributions allowing deployment of lower muon p_T thresholds at Level-1. This will significantly increase the acceptance for the associated production of Higgs as shown in Table 3.

Table 3. The Level-1 trigger efficiency for the W+H process (ε_{WH}) and the corresponding estimated trigger rates demonstrating the effectiveness of the new small wheel (NSW) chambers in maintaining the high efficiency and providing high background rejection.

Level-1 trigger	ε_{WH} (%)	Rate (kHz)
$p_T(\mu) \geq 20$ (GeV)	82	40
$p_T(\mu) \geq 20$ (GeV)	50	15
$p_T(\mu) \geq 20$ with NSW	78	18

3.3 Fast Track Trigger

The ATLAS hardware based Level-1 trigger system uses inputs from the calorimeter and the muon systems only. Information from the inner detectors is used in the second and third stages of the trigger, collectively referred to as the High Level Trigger, that executes software algorithms on a large computing farms. The second stage trigger (Level-2) reconstructs tracks within roads in the tracking system and associates them to objects found in the calorimeter and muon systems. The Fast Track Trigger (FTK)[7] is a highly parallel hardware system that provides rapid tracking capabilities for all Level-1 accepted triggers in two stages. The first stage consists of matching the hits in the silicon detectors to 10^9 pre-stored patterns in associative memory. The second stage consists of fast linear fitting in FPGAs for matched tracks using the hit information in the silicon detectors yielding precise track information. These tracks are subsequently used as inputs by the algorithms relying on tracking information at Level-2. This will not only provide tracking information comparable to offline precision at Level-2 but will also reduce the otherwise significant computing power that is required at Level-2 to reconstruct tracks in a high pile-up environment. The single track efficiency that can be acheived with the FTK is compared with offline reconstruction as a function of the rapidity at a luminosity of 3×10^{34} cm^{-2}s^{-1} in Figure 4.

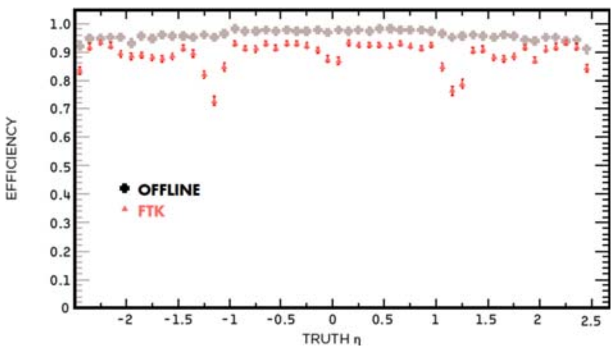

Figure 4. Comparison of offline reconstructed single particle track efficiency with those reconstructed in FTK as a function of the track rapidity[7].

4 Phase II Upgrade

The High Luminosity Upgrade of the LHC (HL-LHC), foreseen for the early 2020s, is expected to deliver peak luminosity exceeding 5×10^{34} cm^{-2}s^{-1} with the goal of accumulating $\sim$ 3000 fb^{-1} of pp collision data over ten years. The order of magnitude larger statistics will further enhance the physics reach of the ATLAS experiment[8], fully exploiting the investments in the LHC project. It paves the way forward for precision measurement of the Higgs boson, reducing uncertainties on the production cross section times the branching ratio ($\sigma \times BR$) to less than 5% for some Higgs decay modes. The ratio of the partial widths provide a measurement of the Higgs couplings, its precision measurement offering an indirect probe of new physics. The improvements that can be achieved in measurement uncertainties of the signal strength and the couplings with ten-times more statistics is shown in Figure 5. Rare processes such as H$\to$ $\mu\mu$, shown in Figure 6, become accessible that will provide a direct measurement of the Higgs couplings to second generation fermions. The full luminosity will also allow measurement of the Higgs self-couplings to a precision of 30%, determined via the Higgs pair production in $HH \to \tau\tau$ and $HH \to \gamma\gamma bb$ channels.

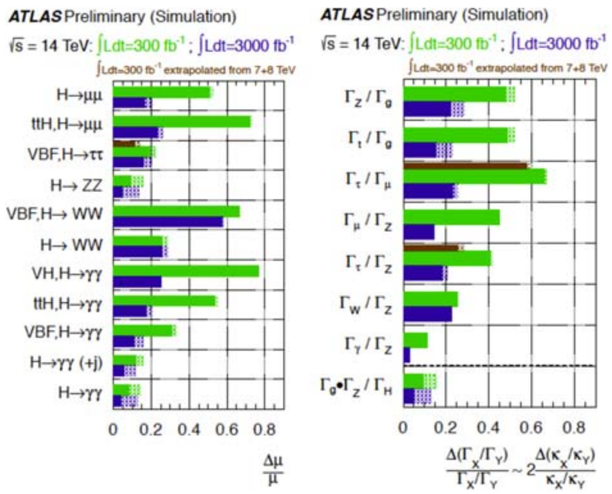

Figure 5. Expected measurement precision on the signal strength $\mu = (\sigma \times \mathrm{BR})/(\sigma \times \mathrm{BR})_{\mathrm{SM}}$ (left figure) and ratio of Higgs boson partial widths (right figure) without theory assumptions for 300 (light shade) and 3000 (dark shade) fb^{-1}[8].

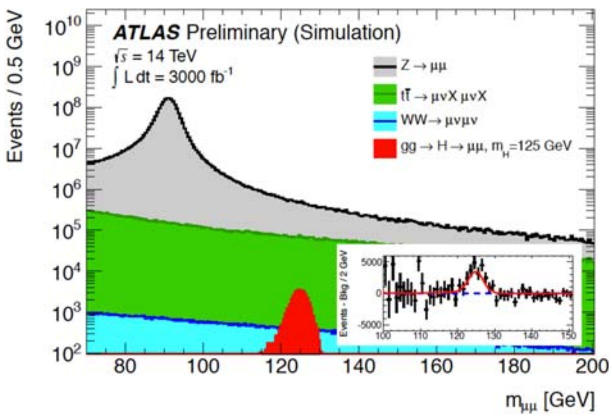

Figure 6. Simulated H $\to$ $\mu\mu$ signal predicted to be observed with a 6σ significance over backgrounds with 3000 fb^{-1}[8].

The HL-LHC also offers an opportunity to extend the reach for new physics beyond the SM, including SUSY and extra dimensions, into the multi-TeV region. Anomalies in the WW scattering amplitudes can be probed to higher mass scales. The studies of rare processes such as the FCNC decays of the top quark that are highly suppressed by the SM are accessible to 10^{-5} and can provide further indirect probes to new physics.

The average number of interactions per crossing will increase from 55 at $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to $\sim$ 140 at 5×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ assuming 25 ns bunch spacing. The ATLAS detector will have to operate at large particle fluences, expected to increase to $\sim 10^{16}$ $\mathrm{n_{eq}/cm^2}$ in the innermost layer of the pixel tracking system. The on-detector front-end electronics that were designed to be operated for ten years at nominal LHC luminosity will be subject to large radiation fluences. The readout electronics will also have to be able to operate with an order of magnitude higher trigger rates. The high rates and increased radiation fluences expected at the HL-LHC, together with the aging of the current detectors and readout electronics, will require a significant upgrade of the ATLAS detector systems. The Phase II upgrade[9] of the ATLAS detector will allow operation at five-times the nominal luminosity ($5{\times}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$) and fully exploit the physics accessible with a total integrated luminosity of 3000 fb^{-1}.

4.1 ATLAS Inner Tracker

The ATLAS inner tracker plays an essential role in the reconstruction and identification of leptons, photons and hadronic decays and in the tagging of b-jets. The role of the tracker in the ATLAS physics program becomes even more pronounced with increasing luminosity and pile-up conditions as expected with the HL-LHC. The current tracker has been designed for ten years of operation at a peak luminosity of 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with an assumed 23 pileup events per 25 ns bunch crossing at a Level-1 trigger rate of 100 kHz. It therefore cannot meet the performance requirements of the HL-LHC and will need to be replaced.

The baseline design, shown in Figure 7, for the new tracker consists of an all-silicon detector with pixel sensors at the inner radii surrounded by microstrip sensors. In the central region, sensors are arranged in cylinders with four pixel layers followed by three short-strip layers and two long-strip layers. The forward region consists of six pixel disks and seven strip disks. The two inner pixel layers that would see the largest radiation fluences are replaceable. They make use of 25 μm$\times$150 μm sensors bump bonded to a readout chip using 65 nm CMOS technology. The outer pixel layers use 50 μm $\times$ 250 μm sensors. Strip layers are double-sided with axial strip orientation on one side and sensors rotated by 40 mrad on the other side to provide the second coordinate measurement.

The new tracker has significantly reduced material compared to the present tracker that minimizes the effects of losses due to hadronic interactions and Bremsstrahlung. The layout has been arranged to maximize the length of the trajectory of the particles inside the solenoid, providing at least 14 hits for each track up to a pseudorapidity of 2.5. The momentum resolution that can be achieved using the new tracker is compared with the current tracker as a function of rapidity for three different p_T tracks in Figure 8.

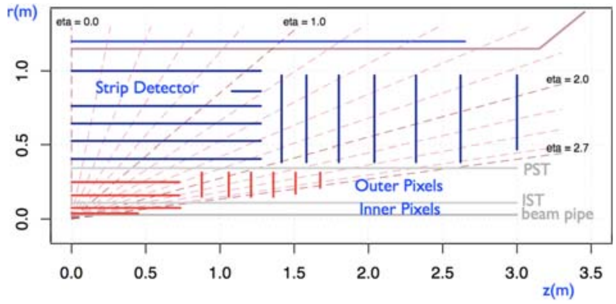

Figure 7. Proposed layout of the Inner Tracker for operations during HL-LHC[9].

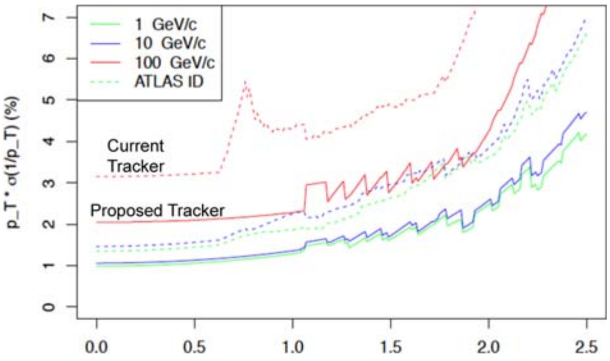

Figure 8. Predicted muon momentum resolution of the new tracker (solid lines) compared with observations from current tracker (dotted lines) for three different momentum tracks[9].

4.2 Calorimeter Upgrades

The on-detector front-end electronics for the LAr and Tile calorimeters will be subject to significant radiation exposure during the HL-LHC operations. The current front-end electronics use many ASIC fabricated components that were not designed to sustain the radiation environment of the HL-LHC. The proposed upgrades to the front-end electronics will exploit the technological progress to implement a robust architecture with high radiation tolerance required to sustain the HL-LHC conditions. The upgraded electronics will also be able to handle the high rate of digitization, and the transmission and handling of high data volumes up to rates of 140 Tbps expected at high luminosity. The new front-end board, with a 16-bit dynamic range will provide analog to digital conversion at 40 MHz, and allow for multiplexing and serialization of data and transmission over high speed optical links.

Unlike the EM calorimeter, the analog front-end preamplifiers for the hadronic endcap calorimeter are located within the cryostats and were designed for a total integrated luminosity of 1000 fb^{-1} assuming a safety factor of 10. Studies are ongoing to determine if the safety factors can be reduced in light of the experience gained with recent LHC operations, allowing continued operation of the in-cryostat analog components during the HL-LHC operations.

The performance of the current forward calorimeter, occupying the region $3.2 < |\eta| < 4.9$, will deteriorate significantly due to space charge effects. The forward calorimeter may therefore need to be replaced for the HL-LHC operations. Several options are being considered, including a full replacement of the forward calorimeter that is located within the endcap cryostat or installing a new detector in front of the existing forward calorimeter.

4.3 Upgrades to Muon System

The muon spectrometer must continue to provide precision tracking and triggering capabilities in a high rate environment of the HL-LHC. The present readout system for the RPC and the TGC trigger chambers will not be able to cope with the high rate trigger requirements as they are limited to a 100 kHz readout rate. Furthermore, the readout electronics for the MDT chambers will need to be upgraded to provide precision coordinates of the MDT to the Level-1 trigger to improve the sharpness of the muon trigger efficiency turn-on and reduce background contributions. Consequently, the whole readout electronics chain for the muon system will have to be replaced, offering the opportunity to rebuild the readout electronics with modern technologies. This will enhance the muon trigger performance, introducing additional flexibility to the muon trigger that is vital for controlling rates while maintaining low p_T trigger thresholds.

4.4 Trigger and Data Acquisition

The Phase II upgrade of the ATLAS trigger and data acquisition is motivated by the desire to maintain low p_T thresholds for isolated electrons and muons with increasing luminosity in order to maximize the physics acceptance for rare processes. A new trigger architecture is being developed that can sustain the increasing trigger rates and data volumes up to a luminosity of 7×10^{34} cm^{-2}s^{-1}. A split Level-0/Level-1 hardware trigger is being envisaged with a Level-1 accept rate of 200 kHz and a total latency of 20 μs. The Phase II Level-0 trigger would functionally be the same as the Phase I Level-1 trigger, accepting inputs from the calorimeter and muon systems, and would operate with an accept rate of 500 kHz and a latency of 6 μs. The Level-1 trigger will have access to the full granularity data from the calorimeter, data from the Muon Drift Chambers and track segments matched to Level-1 calorimeter and muon features. The upgraded Level-1 trigger would therefore provide the necessary rejection using precision pattern recognition and by building topological triggers that match data across detector systems. The HLT selection software must be upgraded to match the detector upgrades and maintain the rejection by employing offline-type particle identification. New selection software will be developed to exploit the increased computing power available through advances in computing processors.

5 Conclusion

The ATLAS experiment is actively pursuing a series of upgrades to ensure continued high detector efficiency with increasing luminosity in an effort to optimize the physics acceptance. The various upgrades being planned as part of Phase 0, including the addition of a new pixel layer close to the beam pipe, will prepare the ATLAS experiment for nominal LHC operations. The Phase I upgrade will include enhancements of the triggering capabilities that will allow the ATLAS experiment to cope with higher luminosity conditions. The Phase II upgrade, requiring a full replacement of the inner tracker, the forward calorimeter, most front-end electronics and a new triggering architecture, are necessary to offset the effects of aging and the high rate and radiation environment of the HL-LHC. The staged incremental upgrades are strategically designed to fully exploit the physics potential at the LHC.

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[2] ATLAS uses a right-handed coordinate system where the nominal interaction point is at the center of the detector and z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP to the center of the LHC, and the y-axis points upward. Cylindrical coordinate (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -ln\ tan(\frac{\theta}{2})$.

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