The ATLAS Phase II Upgrade

1. Introduction

The high energy and luminosity available at the Large Hadron Collider (LHC) [1] offers the best opportunities for the exploration of new physics beyond the Standard Model (SM) and for making precision measurements of the properties of known phenomena. The ATLAS experiment [2] has collected 5.25 fb^{-1} of *pp* collision data at a center of mass energy of 7 TeV and 21.7 fb^{-1} at a center of mass energy of 8 TeV in the two year period, 2011-2012. During the next decade, the LHC accelerator plans a series of upgrades that will substantially increase the instantaneous luminosity, colliding protons on protons (*pp*) at a center of mass energy of ~14 TeV.

The first LHC upgrade is planned for 2013-2014 (called Long Shutdown 1 or LS1), following which the LHC will deliver 100 fb^{-1} over a period of three years at a center of mass energy of ~14 TeV, with luminosities peaking at around 10^{34} cm^{-2} s^{-1} (Phase 0). The planned upgrades [3] to the LHC during the second long shutdown (LS2) in 2018 will allow operating at instantaneous luminosity exceeding 2×10^{34} cm^{-2} s^{-1}. The LHC will deliver an integrated luminosity of 300 fb^{-1} over another three-year period (Phase I). The final upgrade, scheduled for 2022, will usher in the Phase II operation of the High Luminosity LHC (HL-LHC). The HL-LHC will operate at a nominal leveled instantaneous luminosity of 5×10^{34} cm^{-2} s^{-1}, over twice the expected Phase I instantaneous luminosity. The aim of the HL-LHC program is to deliver a total of 3000 fb^{-1} over the course of Phase II. This represents an order-of-magnitude increase in the size of the data sample that will significantly enhance the physics reach of the ATLAS experiment.

These LHC accelerator upgrades require major upgrades of the ATLAS detector in order to maintain the current performance capabilities under new challenging operating conditions. Thus the upgrade of the ATLAS detector is absolutely central to the exploitation of the rich physics potential [4,5] provided by these large LHC data sets.

2. Physics Motivation

The discovery of the Higgs boson will pave the way forward for measuring its properties with the highest possible precision for testing the validity of the Standard Model and to search for new physics at the energy frontier. The high-luminosity upgrade will shed light on some of the key physics questions that are still open in the Higgs sector, such as:

- Is the mechanism for generating fermion and weak gauge bosons masses linked as implied by the Standard Model?
- Does the SM correctly predict the unitarity of vector boson scattering at high energies?
- Can the Higgs self-coupling, which plays a critical role in electroweak symmetry breaking, be detected?

The uncertainties in the production cross-section times the branching ratio (σ×BR), for some of the Higgs decay modes, will be reduced to less than 5%. The measurement of the ratio of the partial widths, which is a measure of the Higgs couplings to other particles, can indirectly probe new physics at the TeV scale in the Higgs sector. The measurement uncertainties of the relative signal strength for a 3000 fb^{-1} data sample is compared to a 300 fb^{-1} data sample for a SM 125 GeV Higgs boson in Figure 1(left). The corresponding ratio of partial widths is shown in Figure 1(right). Rare processes become accessible with a large data sample including: $H \rightarrow \mu\mu$ that provides a direct measurement of the Higgs coupling to second generation fermions (Figure 2-left); and associated Higgs production via $t\bar{t}H \rightarrow \gamma\gamma$ that allows the measurement of the top Yukawa coupling (Figure 2-right). The $H \rightarrow \mu\mu$ observation is especially important as a test of the Higgs mechanism for leptons by allowing a comparison of the muon to tau coupling ratio. The full luminosity data sample will also allow the measurement of the Higgs self-couplings to a precision of 30%, in the Higgs pair production channels $HH \rightarrow bb\tau\tau$ and $HH \rightarrow \gamma\gamma bb$.

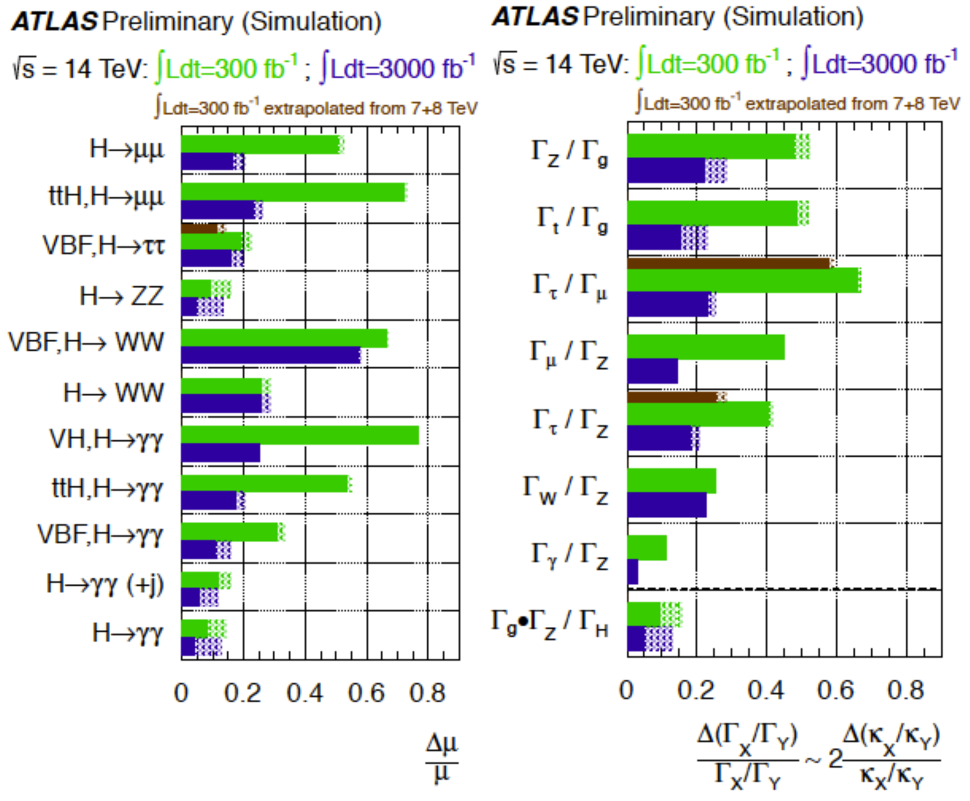


Figure 1(left): Expected precision on the measurement of the signal strength $\mu = (\sigma\times BR)/(\sigma\times BR)_{SM}$ *in all considered channels. Figure 1(right): Expected precision on the ratio of Higgs boson partial widths, without any theory assumption on the particle content in Higgs loops or the total width. In both figures, the bars give the expected relative uncertainty for a SM Higgs boson with a mass of 125 GeV (the dashed areas include current theory uncertainties from QCD scale and PDF variations) for luminosities of 300* fb^{-1} *(in green) and 3000* fb^{-1} *(in blue).*

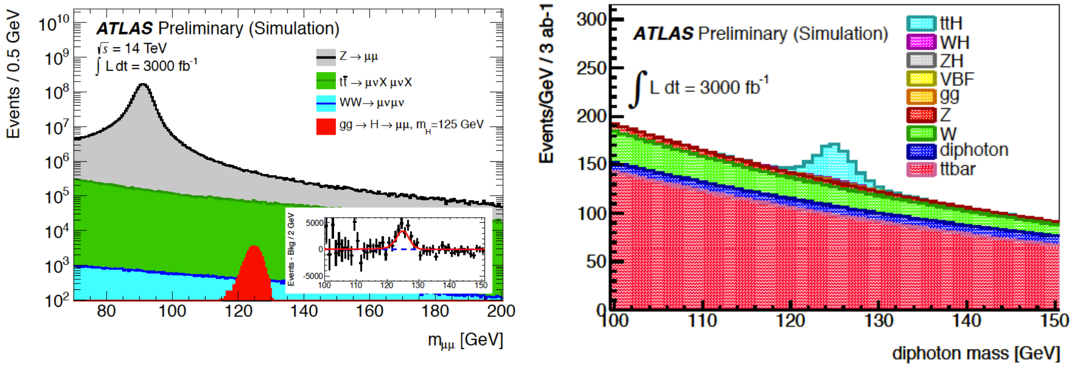


Figure 2(left): Expected invariant mass distribution for the inclusive H → μμ channel, for an assumed integrated luminosity of 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV. The inset shows the expectation for the H → μμ signal after the subtraction of the fitted background. Figure 2(right) Expected γγ invariant mass distribution for the $t\bar{t}H$, H → γγ channel in the single lepton decay mode for an integrated luminosity of 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV.

The HL-LHC also offers an opportunity to extend the reach for new physics beyond the SM, including SUSY and extra-dimensions (see Figure 3). Anomalies in the vector boson scattering amplitudes can be probed to higher mass scales to test whether the role of the Higgs uniquely describes electroweak symmetry breaking. The studies of rare processes, such as the FCNC decays of the top quark, will be sensitive to branching ratios of 10^{-5} and therefore provide further indirect probes of new physics.

A ten-fold increase in integrated luminosity allow us to make:

- An improvement of 20% in the mass reach for searches of strongly coupled heavy objects;
- Substantial improvements in probing new vector bosons with smaller couplings than those assumed by the sequential SM;
- Substantial improvements in probing new states beyond the kinematical reach of 14 TeV through precise measurement of the Higgs properties.

3. Detector Upgrades

The primary detector challenges in the HL-LHC environment are to maintain the excellent performance in vertex and track reconstruction, lepton identification and heavy flavor tagging. These will be addressed via three fundamental detector upgrades: a complete replacement of the current tracking system; new radiation-hard readout electronics using state-of-the art technologies for the tracking, calorimeter and muon detector systems; and an upgraded Trigger and Data Acquisition (TDAQ) architecture that will cope with the increasing rates. These upgrades [5] are necessary to offset the effects of aging and the high rate and radiation environment of the HL-LHC and are strategically designed to exploit the physics potential of the LHC.

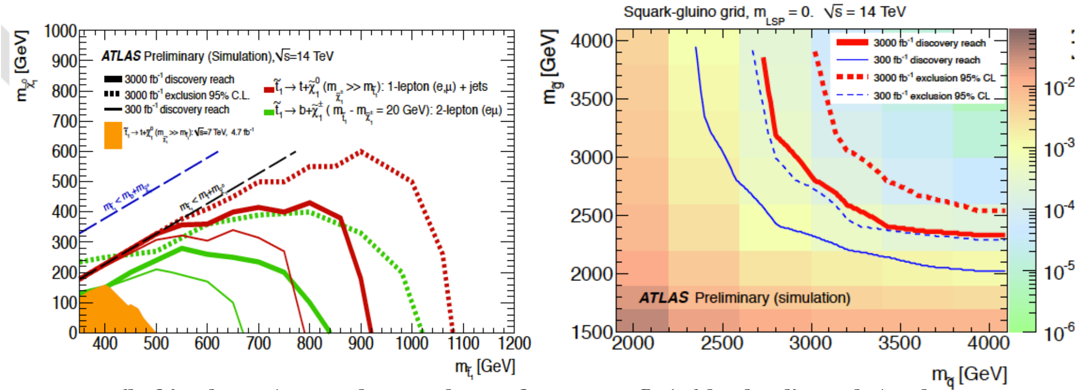


Figure 3(left) The 95% exclusion limit for 3000 fb^{-1} (dashed) and 5σ discovery reach (solid) for 300 and 3000 fb^{-1} in the $\tilde{t}\tilde{\chi}_1^0$ mass plane. Figure 3(right): The 95% CL exclusion limits (solid lines) and the 5σ discovery reach (dotted lines) in a simplified squark-gluino model with a massless neutrino for 300 fb^{-1} (blue lines) and 3000 fb^{-1} (red lines).

3.1 The Inner Tracker Upgrade

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

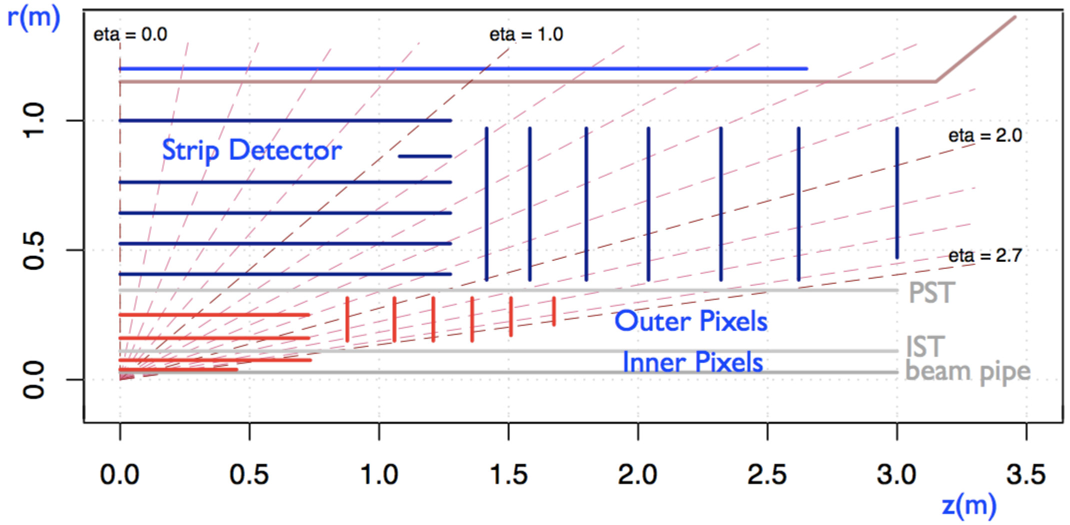


Figure 4: Proposed layout of the Phase II upgrade Inner Tracker (one quarter side view).

The baseline design for the new tracker, shown in Figure 4, consists of an all-silicon detector with pixel sensors at the inner radii and surrounded by microstrip sensors. In the central region, the sensors are arranged in cylinders with four pixel layers followed by three short-strip layers and two long-strips 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, equivalent to 10^{16} n_{eq}/cm^2, are designed to be replaceable. They make use of 25 μm × 150 μm sensors bump bonded to a readout chip using 65 nm CMOS technology. The outer pixel layers use 50 μm × 250 μm sensors. The strip layers are double-sided with axial strip orientation on one side and sensors rotated by 40 mrad on the other side to provide a second coordinate measurement.

The new tracker has about half as much material compared to the present tracker, thereby minimizing 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 with the new tracker is compared to the present tracker as a function of rapidity for three different momentum tracks in Figure 5.

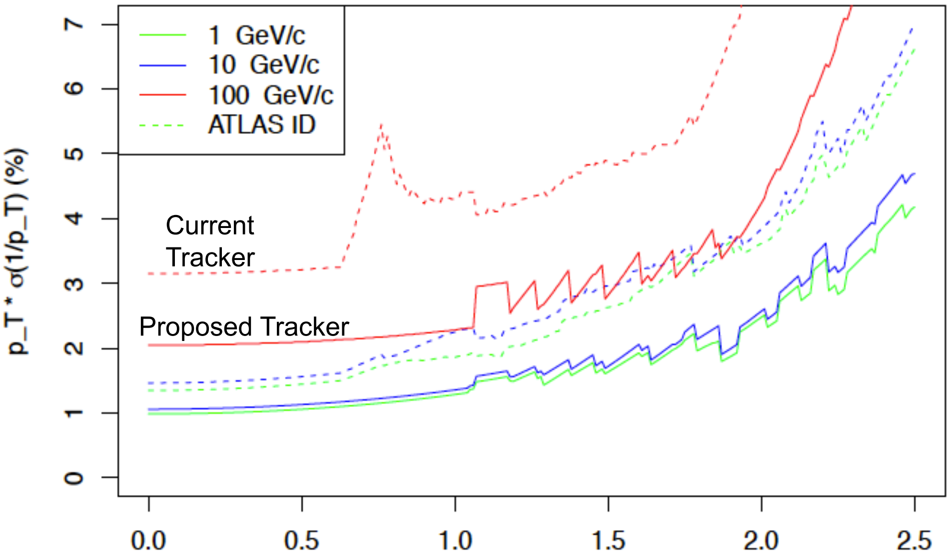


Figure 5: Predicted muon momentum resolution as a function of pseudorapidity is shown for the new inner tracker (solid lines) and compared with observations from the current tracker (dotted lines) for three different momentum tracks.

3.2 The Calorimeter Upgrade

The on-detector front-end electronics for the LAr and Tile calorimeters will be exposed to much higher radiation levels during the HL-LHC operation. The current front-end electronics uses many ASICs that were not designed to sustain the radiation environment of the HL-LHC. The proposed upgrades to the front-end electronics will exploit technological progress to implement a robust architecture with the high radiation tolerance required to operate in the HL-LHC environment. The upgraded electronics will also be able to handle the high digitization rate as well as very high data volumes and transmission rates up to the 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 will allow for multiplexing and serialization of data and transmission over high-speed optical links.

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

3.3 The Muon Spectrometer Upgrade

The muon spectrometer must continue to provide precision tracking and triggering capabilities in the high rate environment of the HL-LHC. The present readout system for the Resistive Plate Chambers (RPC) and the Thin Gap Chambers (TGC), which provide the first stage muon trigger, 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 Muon Drift Tube (MDT) chambers will need to be upgraded to provide precision coordinate measurements to the Level-1 trigger in order to improve the sharpness of the muon trigger efficiency turn-on and to 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 momentum trigger thresholds.

3.4 The Trigger and Data Acquisition Upgrade

The Phase II upgrade of the ATLAS trigger and data acquisition is motivated by the desire to maintain low transverse momentum thresholds with increasing luminosity for isolated electrons and muons, in order to maximize the physics acceptance for rare processes. A new trigger architecture, shown in Figure 6, is being developed that can sustain the increasing trigger rates and data volumes up to a luminosity of 7×10^{34} $\text{cm}^{-2}\text{s}^{-1}$. A split Level-0/Level-1 hardware trigger is 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 a 500 kHz accept rate and a 6 μs latency. 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

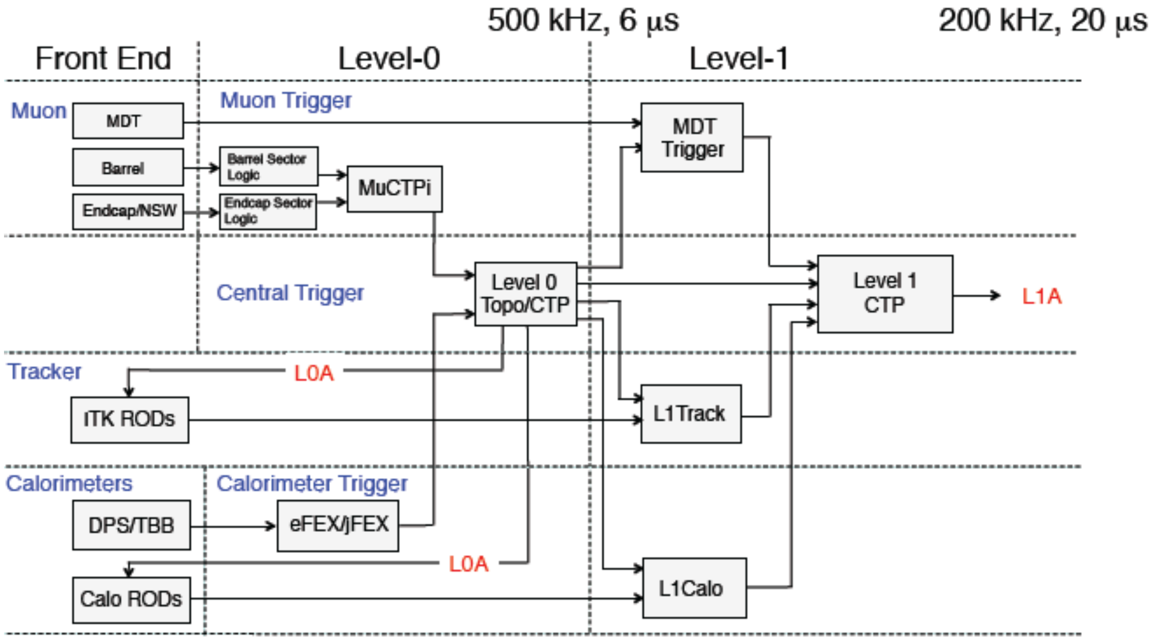


Figure 6: A block diagram of the proposed Trigger and Data Acquisition architecture for the HL-LHC operation that would utilize a split Level-0/Level-1 hardware trigger.

and by building topological triggers that match data across detector systems. The High Level Trigger 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 technology. The event storage rate for offline analysis is expected to be 5 – 10 kHz during data collection at peak luminosity during the HL-LHC operation.

4. ATLAS Phase II Projected Schedule, Cost and Cost Sharing

4.1 US ATLAS Collaboration

The US ATLAS collaboration consists of about 500 U.S. physicists from 44 U.S. institutes. The U.S. has had major roles in the construction of the original detectors, which has translated into the current Operations Program responsibilities. The Operations Program is funded by DOE (~$26M/yr) and NSF (~$9M/yr) to support technical personnel and computing hardware in the areas of M&O, Computing and Upgrade R&D. In addition, US ATLAS has recently received CD-0 for the Phase I upgrade of the ATLAS experiment (~$50M), and is planning to proceed to CD-1 this summer (2013). The U.S. groups comprise about 20% of the full ATLAS collaboration.

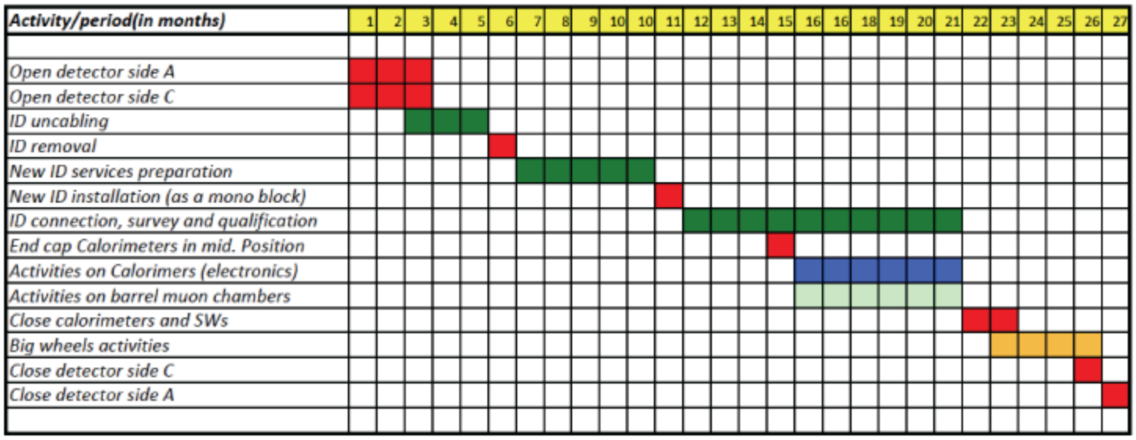
4.2 ATLAS Phase II Cost & Schedule

The ATLAS experiment has developed a core cost estimate for the Phase II upgrade. The core costs include material and supplies, but exclude labor, basic infrastructure and contingency. The core costs thus include components, outsourced parts of assembly, outsourced parts of installation, testing and commissioning, and labor costs for industrial staff. The core cost does not include the labor costs incurred at institutes, including labor costs associated with engineers and technicians at institutes. It also does not include R&D, design and early stage prototyping. The total estimated core cost is 230 MCHF with possible additions totaling 45 MCHF in fixed 2012 Swiss Francs. The detailed core cost for each detector system is given in Table 1. The core cost is largely driven by the full replacement cost of the inner tracker. The Phase II upgrade construction funding profile covers the period from 2015 to 2022. The common costs cover items related to infrastructure and shielding upgrades, installation in the ATLAS cavern and computing resources.

Item	CORE cost (MCHF)	Possible Additions	2015	2016	2017	2018	2019	2020	2021	2022
New Inner Detector	131.500	26.000	2.400	5.600	35.660	32.460	29.160	15.360	10.860	0.000
Lar Calorimeter upgrades	32.124	15.096	0.547	3.170	1.015	2.003	4.517	14.379	6.494	0.000
Tile Calorimeter upgrades	7.483	2.517	0.000	0.000	0.000	1.122	1.629	4.070	0.602	0.060
Muon Spectrometer upgrades	19.632	0.500	0.100	0.275	0.675	3.791	5.041	6.750	2.800	0.200
Trigger and DAQ upgrades	23.315	0.900	0.000	0.075	0.315	1.565	2.085	9.805	4.350	5.120
Common Fund	16.280	0.000	0.000	0.100	0.400	0.600	2.850	4.100	4.880	3.350
TOTAL (MCHF)	**230.334**	**45.013**	**3.047**	**9.220**	**38.065**	**41.541**	**45.282**	**54.464**	**29.986**	**8.730**

Table 1: Total core costs and funding profile for the ATLAS Phase II Upgrade in fixed 2012 Swiss Francs, and broken out by major subsystems.

The areas of U.S. interest and expertise, as well as the fraction of U.S. physicists in the ATLAS collaboration will determine the potential U.S. share. We estimate the U.S. share of the Phase II upgrade to be 200 – 300 M (AY$). This assumes a 20% share, with core costs scaled to include labor and contingency.



Activity/period(in months)	1	2	3	4	5	6	7	8	9	10	10	11	12	13	14	15	16	16	18	19	20	21	22	23	24	25	26	27
Open detector side A	🟥	🟥	🟥																									
Open detector side C	🟥	🟥	🟥																									
ID uncabling			🟩	🟩	🟩																							
ID removal						🟥																						
New ID services preparation							🟩	🟩	🟩	🟩	🟩																	
New ID installation (as a mono block)												🟥																
ID connection, survey and qualification													🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩						
End cap Calorimeters in mid. Position																🟥												
Activities on Calorimers (electronics)																	🟦	🟦	🟦	🟦	🟦	🟦						
Activities on barrel muon chambers																	🟩	🟩	🟩	🟩	🟩	🟩						
Close calorimeters and SWs																							🟥	🟥				
Big wheels activities																								🟧	🟧	🟧	🟧	
Close detector side C																											🟥	
Close detector side A																												🟥

Figure 7: Installation schedule for various activities over the 27-month period.

The LHC project is scheduling a shutdown in 2022-2023 to allow the detectors and the accelerator to prepare for the HL-LHC conditions with beam operations starting in 2024. The ATLAS cavern will be accessible for about 27 months starting December 2021. The mechanical operations required by the Phase II upgrade are mainly driven by the insertion of the new inner tracker. The current schedule for opening and closing the detectors and the main installation schedule drivers is shown in Figure 7.

5. Current U.S. R&D Efforts toward Phase II Upgrade

The goal of the US ATLAS Upgrade R&D program for Phase II is to design the components for the Upgrade that require a long development time. This R&D effort will reduce the risk and the contingency required during construction. It further allows for a rapid construction schedule of about 5 years for the longest duration detector systems. The R&D program will not only allow the U.S. to develop and maintain its unique expertise in detector development but also position it to take on leadership roles in the upgrade of the ATLAS experiment. The current U.S. R&D efforts for the Phase II upgrade, supported by the U.S. ATLAS Operations Program and the DOE Generic R&D program, are being carried out by 15 U.S. institutes. They focus on two major activities: (a) The inner tracker and (b) the readout electronics for the calorimeter. Future areas of U.S. R&D efforts will include upgrades to the readout electronics for the Muon Drift Tubes and the new proposed TDAQ architecture.

5.1 Phase II R&D for Silicon Pixel and Strip Detector

The requirement of an affordable, low-mass and radiation-hard silicon tracker drives this R&D efforts. Those efforts focus on developing the individual sensors and ASICs (including those needed for a track trigger), mechanical support elements and powering components aimed at minimizing the mass in the tracking volume. Thus the required small feature size ASICs are being developed in 65 nm technology for the inner pixels and 130 nm technology for the outer strips. The silicon strip work is making progress in a number of areas including stave assembly; mechanical cores, foams and tapes; readout and controller chips and test readouts. In addition, an important concern being addressed by the U.S. is to minimize the cost of the individual sensors. This has led to the development of n-on-p sensors as well as large individual pixel sensors and large pixel chips to economize on bump bonding.

5.2 Phase II R&D for Calorimeter Readout Electronics

The second focus area has been to develop the ability to read out the calorimeter (LAr and Tile calorimeter) data for every crossing and consequently make use of the full calorimeter granularity information for Level-1 triggering. This requires replacement of the front-end electronics as well as development of high-speed data transmission elements. It should be noted that the existing calorimeter front-end electronics are not sufficiently radiation resistant to last through the Phase II data taking operations. The development of the new ASICs that will be required has been a primary focus. This includes front-end chips (for both LAr and Tile calorimeter detectors), ADCs, and very high-speed serialization and transmission chips. The Phase I upgrade also offers an opportunity to utilize some of the new chips (for LAr) and to instrument demonstrators within the detector that can be used over time to perform tests and increase confidence in specific technical solutions. Development of more economical powering systems is also an important part of the calorimeter program.

6. Conclusion

The ATLAS Phase II upgrade, providing a window to unique physics opportunities, is absolutely central to the U.S. High Energy Physics program. The successes of the current ATLAS program and the discovery of a new particle point the way to a rich physics program for the next decade and beyond. The proposed ATLAS Phase II upgrade program is a natural path to assure the full exploitation of the large U.S. and worldwide investment in the LHC and the experiments. The U.S. ATLAS groups, with unique expertise in several areas, are well positioned to play leading roles in future upgrades of the ATLAS detector. We have seen this in preparing for the Phase I Upgrade, where the investment in Upgrade R&D has had a dramatic payoff. We anticipate the same central role for the U.S. in the ATLAS Phase II upgrade, as we continue to invest in the critical R&D activities necessary to be ready for Phase II Upgrade construction.

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