Physics motivation and detector upgrades for the new era of the ATLAS experiment

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Abstract

The ATLAS experiment at CERN's Large Hadron Collider (LHC) will be upgraded in two stages to prepare first for the Run 3 data-taking campaign, during which the integrated luminosity will roughly double, and then for the High-Luminosity LHC program with an ultimate integrated luminosity of up to 4 ab^{-1}. These upgrades and high-statistics datasets will allow ATLAS to perform searches and precision measurements to constrain the Standard Model in yet-unexplored phase spaces and in the Higgs sector. This contribution summarizes the ATLAS detector upgrades and selected physics prospects for Run 3 and the HL-LHC.

1 Introduction

The luminosity upgrades for the Large Hadron Collider (LHC) at CERN are the evolution of the successful proton-proton physics program that has seen the discovery of the Higgs boson and a range of searches for physics beyond the Standard Model. To probe the properties of the Higgs boson and top quark with greater precision while improving sensitivity to low-cross-section processes, the Run 3 and High-Luminosity LHC phases will feature increases in integrated luminosity and center-of-mass energy. Run-3 is expected to double the size of the current LHC data, and the HL-LHC is expected to deliver up to 4000 fb^{-1} of integrated luminosity at $\sqrt{s} = 14$ GeV, with up to 200 pp pileup interactions per bunch crossing [1].

The ATLAS experiment [2] is also being upgraded to answer the experimental challenges introduced by the increased pileup density and higher radiation dose. These upgrades range from new muon spectrometer detectors and calorimeter electronics to improved trigger hardware and an ambitious all-silicon tracking detector. The motivating physics studies benefit from full detector simulation, extrapolated performance estimates, and the accumulated experience with the ATLAS experiment thus far.

2 Detector upgrades for Run 3

The ATLAS detector upgrades for Run 3 (also known as the "Phase 1 Upgrade") focus on three major components: the liquid argon calorimeter electronics, the forward muon detector, and the trigger/data acquisition system. These upgrades improve the precision of data flowing into the trigger system, allowing ATLAS to maintain low trigger thresholds and maximum physics sensitivity even as the average particle multiplicity per event increases. For example, Figure 1 highlights a new forward muon detector–the New Small Wheel (NSW)–in the overall context of the muon spectrometer. The NSW leverages several detector technologies to provide fast triggering data and precision hit positions in the forward region. The improved calorimeter electronics pass finer granularity data to the trigger, allowing for increased identification efficiency for electrons, photons, and tau leptons.

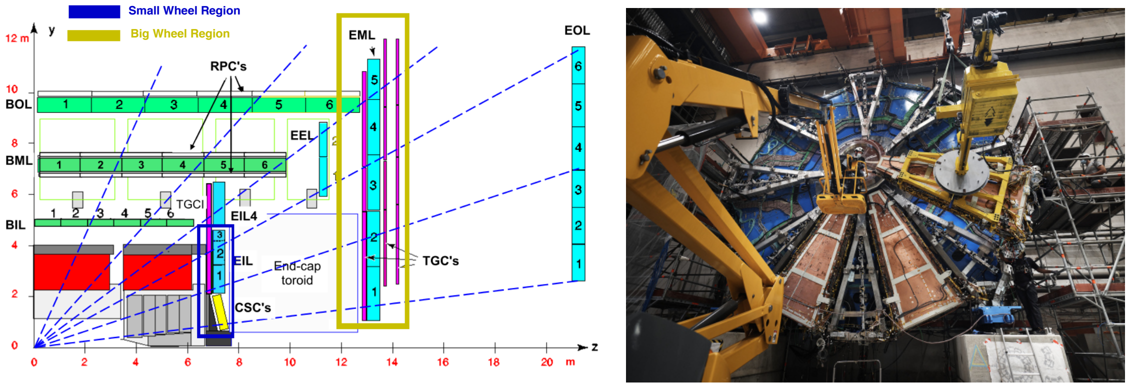

Figure 1: One of several detector systems in the ATLAS Muon Spectrometer (left), the New Small Wheel [3] is currently being assembled at CERN (right).

3 Physics prospects for Run 3

The ATLAS physics prospects for Run 3 rely not only on the dataset increase of a factor of two, but also on improved lepton, photon, and missing energy trigger performance. Analysis of Higgs boson properties, especially measurements of production rates and Higgs couplings, will constrain even the most challenging Hbb and $H\mu\mu$ couplings at the 20% level. Searches for new physics, including supersymmetric and exotic particles, will see dramatic increases in sensitivity, translating in up to 1 TeV of increased mass reach relative to Run 2 results. Studies of vector boson scattering, a key test of the Higgs mechanism in the Standard Model, will be possible with the Run 3 dataset. The expected significance for WV scattering in semileptonic signatures should reach the observation level of 5σ, as shown in Figure 2, even if the ultimate measurements of longitudinal WW scattering will require the much larger HL-LHC dataset of $4000\,\mathrm{fb}^{-1}$.

4 Detector upgrades for HL-LHC

The ATLAS detector upgrades for HL-LHC (also known as the “Phase 2 Upgrade”) are needed to maintain the current performance capabilities in the face of increased particle multiplicity due to increased beam intensities. The higher hit occupancy in the detectors complicates tracking algorithms and tends to degrade calorimeter resolution. These detector systems also need to withstand increased radiation doses, up to 1 Grad in the innermost silicon tracker layers.

The upgrades will increase the detector acceptance in the forward regions, improve trigger resolution and efficiency, and introduce precision timing information to reject the effects of additional pp “pileup” interactions. The ATLAS inner tracker will be replaced with an all-silicon tracker [6, 7] composed of pixel and strip layers covering $|\eta| < 4.0$ in a optimized layout of

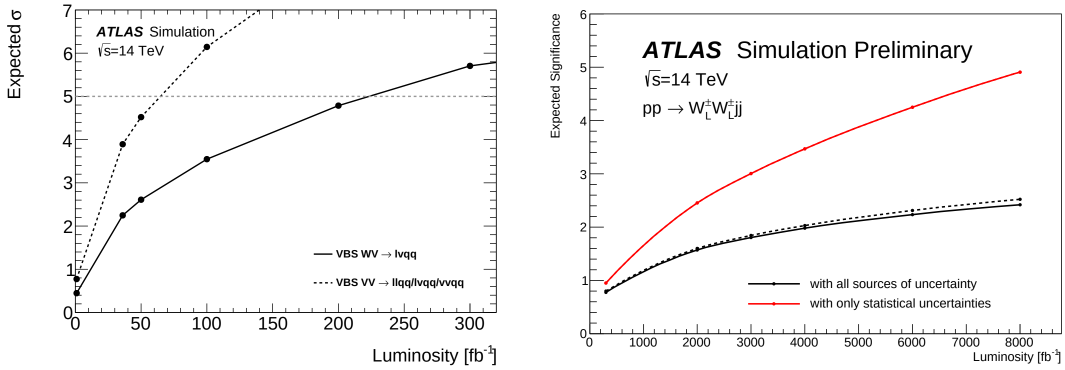

Figure 2: Vector boson scattering projections include observation potential for inclusive production in Run 3 (left) [4] and sensitivity to longitudinal WW scattering with the much larger HL-LHC dataset (right) [5].

barrel staves, inclined regions, and ring structures (Figure 3). Reduced pixel size and extended acceptance will improve the b-jet tagging performance even beyond the current Run 2 benchmarks. The first-level trigger system will make use of the full granularity of detector data from the calorimeters and muon spectrometer in the decision hardware, and the event filter output will increase from 1 kHz to 10 kHz [8]. In the forward region ($|\eta| > 2.5$), a high-granularity timing detector will be based on the new low-gain avalanche detector technology [9].

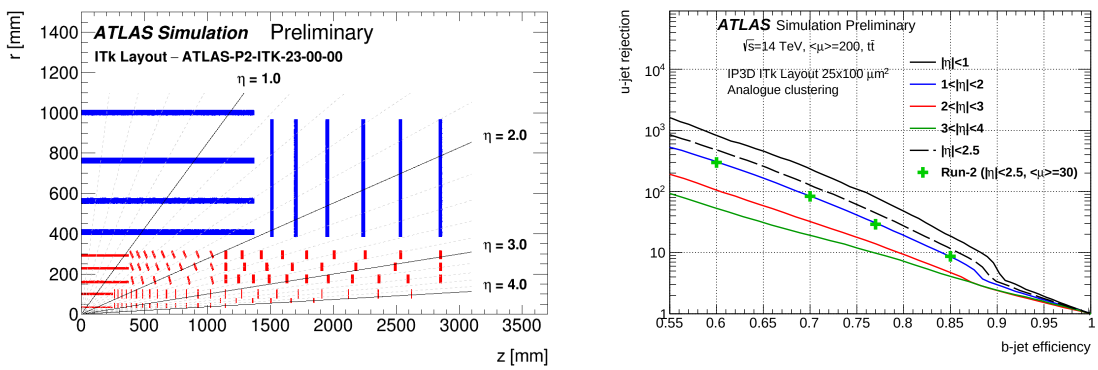

Figure 3: The all-silicon ITk tracker provides full coverage up to $|\eta| = 4.0$ with strip and pixel detectors (left) [10], resulting in improved b-jet tagging efficiency relative to the current ATLAS detector (right) [11].

5 Physics prospects for HL-LHC

The measurements of Higgs boson couplings are a primary component of the HL-LHC physics program. Precision measurements both test the Standard Model and constrain possible contributions from new physics, under the assumption that the new particles couple to the Higgs boson. With the HL-LHC dataset, ATLAS expects to measure Higgs boson production cross sections with precisions between 2.4 and 7.7%, depending on the production mode and decay signature [12]. The results for the different modes and the corresponding coupling constraints are shown in Figure 4. Perhaps the most anticipated measurement is the Higgs boson self coupling λ_{HHH}, which is accessible through loop-induced single Higgs boson production and tree-level Higgs pair production. ATLAS has studied projections for HH production in three main event signatures: $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, and $b\bar{b}b\bar{b}$. The latest projections show that a combination of ATLAS and CMS measurements can reach 3.5σ significance with the full HL-LHC dataset [13].

The large HL-LHC dataset provides an excellent opportunity for electroweak supersymmetry searches. Studies have demonstrated sensitivity near the TeV mass scale for charginos and neutralino, even for weak production modes with small cross sections. In fact, the most dramatic improvement occurs for searches that are currently limited by statistics because of tight selection requirements. Additional silicon tracking layers also enable searches for disappearing track signatures that arise in models with compressed SUSY mass spectra.

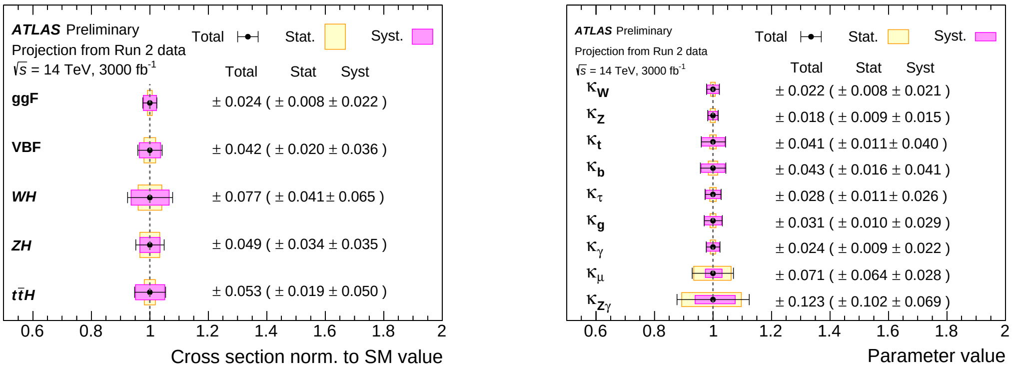

Figure 4: Higgs boson production mode measurements reach their ultimate sensitivity at the HL-LHC (left), allowing for precise measurements of the couplings relative to the Standard Model (right). In this scenario, the systematic uncertainties in the measurement are assumed to be half of the current Run 2 uncertainties [12].

6 Conclusion

The ATLAS collaboration projects a broad and deep physics program in the Run 3 and HL-LHC eras, taking advantage of the increased luminosity at the LHC. Detailed physics studies highlight the challenging experimental conditions that require new detector upgrades and improved reconstruction algorithms [14]. These studies and improvements also depend on continued progress in theoretical calculations and computational tools, especially for the ultimate sensitivity at the HL-LHC [15]. The ATLAS detector upgrades are well underway and will deliver the needed performance to satisfy the physics challenges described here.

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