Physics prospects for ATLAS at the HL-LHC

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Abstract. The ATLAS experiment at CERN will undergo a series of detector upgrades over the next few years to prepare for the the High-Luminosity Large Hadron Collider (HL-LHC) project. The upgrades are designed to maintain or improve detector performance, even with the instantaneous luminosity needed to deliver a total of 3000 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 14$ TeV to ATLAS. This contribution provides details of the broad and deep program of measurements and searches planned by ATLAS for the HL-LHC. The higher centre-of-mass energy and increased integrated luminosity will allow ATLAS not only to improve the precision of Higgs boson, electroweak boson, and top quark measurements, but also to extend the sensitivity of searches for beyond-the-Standard-Model processes with small cross sections. Many of the projections use detailed detector simulations to model the performance of the proposed ATLAS detector upgrades.

1. Introduction

The High-Luminosity Large Hadron Collider (HL-LHC) project at CERN is the evolution of the successful LHC program. To probe particle properties with greater precision and improve sensitivity to low-cross-section processes, the HL-LHC is designed to collide protons at $\sqrt{s} = 14$ TeV and deliver 3000 fb$^{-1}$ of integrated luminosity [1]. Achieving this goal over a dozen years will require an instantaneous luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, which implies in turn approximately 200 pp collisions per bunch crossing.

The ATLAS experiment [2] will be upgraded to maintain or improve detector performance even in this challenging environment of high charged particle multiplicity and high radiation dose [3]. With these upgrades, the ATLAS Collaboration has planned a wide-ranging HL-LHC physics program of precision measurements and searches for physics beyond the Standard Model. This contribution highlights a few studies of expected ATLAS results in the areas of Higgs boson measurements, electroweak boson measurements, and searches for supersymmetry. These studies have been performed either with a full simulation of the ATLAS detector upgrades or with extrapolation from results obtained from Run 2 LHC data.

2. Measurements of electroweak bosons, Higgs bosons, and top quarks

Precision measurements of electroweak bosons and their Higgs boson couplings are expected to be an important component of the ATLAS HL-LHC physics program. Vector boson scattering, including $WW$, $WZ$, and $ZZ$ scattering, can be measured precisely with the full HL-LHC dataset. The main event signatures are $VVjj$ with leptonic decays of the bosons, so the ATLAS detector upgrades that improve forward tracking and jet-finding capabilities are important for
increasing the event selection acceptance. ATLAS expects to measure \(WW\) scattering with 6% precision, as shown in figure 1 (a), and \(WZ\) scattering at the same level [4,5]. \(ZZ\) scattering can be measured with a significance in the 1–8\(\sigma\) range, depending on the theory uncertainties [6]. Even though these inclusive scattering cross sections can be measured with good precision, the measurement of longitudinal \(W\) boson scattering is still expected to be a challenge. When all uncertainties are taken into account, ATLAS expects to measure \(L^-W^+L^-\) scattering with 2\(\sigma\) significance, as shown in figure 1 (b). More detailed studies of experimental and theory uncertainties will be needed to improve the sensitivity.

Measurements of the \(W\) boson mass and the electroweak mixing angle \(\sin\theta_W\) are also expected to improve at the HL-LHC. In the case of the \(W\) boson mass, the improvement comes not from the increased luminosity – in fact, a low-luminosity run will be required – but rather from the improved lepton acceptance at high \(|\eta|\). Studies suggest that a precision of 10 MeV is achievable [8]. In the case of the \(\sin\theta_W\) measurement through a study of the \(Z\) boson forward-backward asymmetry, both the improved lepton acceptance and the large electron data sample result in substantial improvements over existing ATLAS measurements [9].

The measurements of Higgs boson couplings are a pillar of the HL-LHC program. With a dataset approximately 20 times the size of the Run 2 dataset, ATLAS expects to measure the Higgs boson production cross sections with between 2.4% and 7.7% precision [10], as shown in figure 2 (a). The \(WH\) associated production cross section is projected to be the most challenging measurement, due to both statistical and systematic uncertainties that are larger than corresponding uncertainties in other channels. By reinterpreting the Higgs boson production and decay measurements in the coupling modifier framework (including effective couplings to photons and gluons), the Higgs boson couplings can be constrained at the 2–7% level, even the \(H\mu\mu\) coupling, as shown in figure 2 (b). Nearly all of the measurements are dominated by systematic uncertainties, even though the baseline scenario assumes that the uncertainties will be halved by the end of the HL-LHC program.

One of the most anticipated measurements at the HL-LHC is the measurement of the Higgs boson self coupling \(\lambda_{HHH}\), which is accessible through tree-level Higgs boson pair production.
Many studies have been performed of the sensitivity to flavour-changing neutral currents (FCNC) in top quark decays. In the Standard Model, the branching ratio for $t \rightarrow qZ$ is $10^{-4}$, but this value can be enhanced significantly in some models. For example, the quark singlet model predicts FCNC branching ratios as high as $10^{-2}$. Using the three-lepton final state and kinematic fits to test the $t\bar{t}t\bar{t}$ hypothesis, ATLAS projects a sensitivity of $6.9 \times 10^{-5}$ for the branching ratio of $t \rightarrow uZ$ and $8.1 \times 10^{-5}$ for $t \rightarrow cZ$.

The large HL-LHC dataset offers an excellent testbench for electroweak supersymmetry searches. Studies demonstrate the ability to reach near the TeV mass scale for charginos and neutralinos, even though the production cross sections are small. Figure 3 (a) shows the dramatic improvement in sensitivity to chargino pair production in the dilepton final state, compared to the current ATLAS exclusions [17]. For neutralino–chargino production, followed by decay to

and loop-induced single Higgs production. ATLAS has studied $HH$ production at the HL-LHC in three main event signatures: $bb\gamma \gamma$, $bb\tau \tau$, and $bbbb$ [11]. Of these, the first is most sensitive, while the last suffers from large systematic uncertainties. Combined results from the three final states achieve a 3.0σ significance when all systematic uncertainties are included. When these results are further combined with similar $HH$ production studies from the CMS Collaboration, an overall significance of 4.0σ can be reached with the HL-LHC dataset [12].

Another rare process that is expected to be measured with the HL-LHC dataset is the production of four top quarks. ATLAS has recently provided evidence for four-top-quark production in the multilepton final state using the full Run 2 data, with a cross-section measurement of $2\pm1$ fb [13]. The expected $t\bar{t}t\bar{t}$ cross section at $\sqrt{s} = 14$ TeV is 16 fb, and the large HL-LHC dataset will make it possible to measure this production to a precision of 11% [14]. Because $t\bar{t}t\bar{t}$ production is sensitive to changes in the top quark Yukawa coupling and to additional mediator particles from theories beyond the Standard Model, the measurement can also be cast as a search for new particles [15].

3. Searches for physics beyond the Standard Model

ATLAS anticipates a wide range of searches for new physics at the HL-LHC, from top quark couplings to supersymmetry and dark matter.

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the lightest Higgs boson $h$, a search that reconstructs the $h \rightarrow b\bar{b}$ decay yields a sensitivity to $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses well above 1 TeV, as shown in figure 3 (b) [17]. This projection includes a full flavour-tagging simulation and associated flavour-tagging uncertainties.

**Figure 3.** Exclusion limit and discovery potential for $\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow W^+\chi^0$ production, assuming $\tilde{\chi}_1^+$ decays to $W^+\chi^0$ (a), and for $\tilde{\chi}_1^-\tilde{\chi}_2^0$ production, assuming $\tilde{\chi}_2^0$ decays to $h\chi^0$ (b) [17]. The baseline uncertainty scenario assumes the systematic uncertainties in the background estimates will be halved relative to the Run 2 uncertainties.

If the supersymmetric particle mass spectrum is compressed so that the mass splitting between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ is small, then the leptons from $\tilde{\chi}_2^0$ decay will have low transverse momentum. Projections for a search for low-momentum leptons ($p_T \geq 3$ GeV) demonstrate sensitivity to $\tilde{\chi}_2^0$ masses around 350 GeV with the HL-LHC dataset, well beyond the exclusions of LEP2 and ATLAS. If instead the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ mass splitting is small, then the $\tilde{\chi}_1^\pm$ lifetime is extended, and the chargino can produce a visible disappearing track in the inner tracking layers. A search for
such disappearing tracks in conjunction with large missing transverse energy results in a broad mass exclusion at small mass splittings, as shown in figure 4 (a) [18]. The combined result of the soft lepton and disappearing track searches is shown in figure 4 (b).

Searches for dark matter in signatures of missing energy, such as jet + missing transverse energy, benefit from the increase in the centre-of-mass energy and in integrated luminosity. The projections for these searches with the 3000 fb$^{-1}$ indicate sensitivity to dark matter particles coupling to mediators with masses up to 2.7 TeV [19,20].

4. Summary
ATLAS projects a broad and deep HL-LHC physics program. It includes precision measurements of Higgs bosons and electroweak bosons, probing the nature of the electroweak sector. It also includes improved top quark measurements and proton structure function measurements at 14 TeV. Searches for small cross section processes in models of supersymmetry and dark matter will see extended sensitivity as the result of the 3000 fb$^{-1}$ dataset. Many more studies are reported in detail in Ref. [21], as part of the joint HL-LHC/HE-LHC study.

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