ATLAS Higgs and Supersymmetry Physics Prospects at the High-Luminosity LHC

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In the second half of 2026, after a shutdown period of two and one half years for a major upgrade of the accelerators infrastructure, the Large Hadron Collider (LHC) will enter the high-luminosity phase reaching an instantaneous luminosity of $7.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the centre-of-mass energy of 14 TeV. To cope with those unprecedented luminosities and to be able to fully exploit the physics discovery potential, the ATLAS detector will be upgraded as well. A total of 3000 fb^{-1} of *pp* collision data should be collected over about ten years of high luminosity LHC running. In this document, simulated data studies on the ultimate precision attainable on the couplings measurements of the 125 GeV Higgs boson, the prospect on the sensitivities for Higgs boson rare decays as well as perspectives on the measurement of the Standard Model di-Higgs production, are presented. Moreover, an overview of the expected sensitivities of the upgraded ATLAS detector to the discovery of several supersymmetric particles production are discussed.

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1. Introduction

The High-Luminosity LHC (HL-LHC)[1] phase is scheduled to start mid 2026 and after 10 years of run about 3000 fb^{-1} of pp collision data will be collected at the centre-of-mass energy of 14 TeV. The peak instantaneous luminosity will reach an unprecedented value of 7.5×10^{34}cm^{-2}s^{-1} which implies an average number of inelastic collisions per bunch crossing (pile-up) of $< \mu_{PU} > \approx 200$. To be able to cope with that unprecedented instantaneous luminosity and pile-up conditions and to replace radiation damaged subdetectors, the ATLAS detector [2] will undergo a major upgrade [3]. In particular, the inner tracking detector will be replaced with a new all-silicon trackers with higher granularity and extended coverage in pseudorapidity, η, up to $|\eta| \approx 4$, the innermost muon barrel detector will be upgraded for increasing triggering capabilities and the readout electronics of the trigger and data acquisition system will be replaced to achieve recording data rates up to 10 kHz. In order to maximise the physics performance and discovery potential of ATLAS and to probe different detector upgrade layouts, several benchmark simulated analyses have been performed. The physics analyses are mainly carried out using generator-level Monte-Carlo (MC) samples for which the detector response is simulated with smearing and efficiency functions. Those are derived from limited fully-simulated samples using different possible ATLAS HL-LHC detector layouts and high pile-up conditions and are applied as a function of the p_T and η of the reconstructed physics object. A second approach to avoid too computing-intense MC samples generation, is the extrapolation of the Run-1 and Run-2 results assuming similar detector performances and analysis approaches as the current ones but scaling the signal and background level to the higher luminosity and the increased centre-of-mass energy.

2. Higgs boson physics prospects at HL-LHC

The data collected at the end of the HL-LHC will allow for more accurate and detailed studies of the Higgs boson reaching the sensitivity for di-Higgs processes. All the Higgs boson prospect results presented in this section assume a Standard Model (SM) Higgs boson with a mass of 125 GeV.

2.1 Higgs boson couplings

The measurements of the cross sections times branching ratios are expressed as signal strengths $\mu = \sigma/\sigma_{SM}$ reflecting deviation from the SM predictions. The prospect on the signal strength precision measurements [5] are given in terms of relative uncertainties on μ and are summarised in figure 1 for 300 fb^{-1}, the amount of data expected before the Phase-II ATLAS upgrade, and 3000 fb^{-1} with a pile up of $< \mu_{PU} > \approx 140$. The improvements at high luminosity are as large as a factor of 2-3. Those results are then interpreted in terms of Higgs boson couplings to the elementary particles using a leading order motivated framework [4] within a narrow width approximation. Assuming a model with no new Higgs boson decay modes, the mass dependence of the reduced coupling constants of several SM particles and their expected precisions are shown in figure 1 and range from 3-4% for the W,Z bosons to 8-12% for the top, b quark and tau lepton.

2.2 Higgs boson self-coupling

Of particular interest at the HL-LHC is the measurement of the Higgs boson pair production from which one can test the trilinear Higgs boson self coupling, λ_{HHH} and hence probe
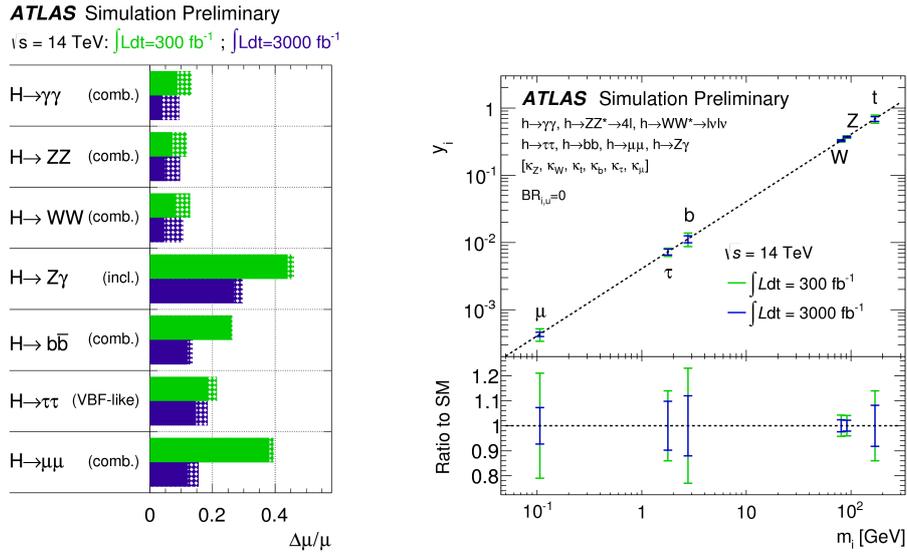
Figure 1: Right: Expected relative uncertainty on the signal strength μ for several Higgs boson final states expected with 300 and 3000 fb^{-1} of pp data. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties [5]. Left: expected fit results for the reduced coupling scale factors (y-axis) for SM fermions and bosons masses (x-axis) compared to the predicted mass dependence for the SM Higgs boson (dashed line) [5].

the form of the Higgs potential. There are two processes interfering destructively generating the di-Higgs boson final state, one of them depending on the Higgs boson triple-linear self coupling giving an expected NNLO total production cross section of 41 fb^{-1} at 14 TeV [6]. Due to their high branching ratios the decay channels involving b-quarks are of great importance. With the upgraded inner detector and the extension in pseudorapidity coverage, it will be possible to achieve a b-tag efficiency compatible with the actual one even under extreme pile-up condition as those of the HL-LHC [7]. Among the most promising signature there is the $HH \to b\bar{b}\gamma\gamma$ with 9.5 expected events in the signal region giving a 1.05σ statistical significance. This channel will set a constraint in the deviation of the Higgs self coupling from the SM in the range of $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$ at 95% C.L. neglecting all systematics [8]. From the $HH \to b\bar{b}b\bar{b}$ decay channel the constraint will be $0.2 < \lambda_{HHH}/\lambda_{SM} < 7.0$ at 95% C.L. (without systematic uncertainties) and $-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$ if current systematics are assumed [9]. Further decay channels that are exploited are $HH \to bb\tau\tau$ [10] with an expected significance of 0.60σ and constraining the self coupling to $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ and $t\bar{t}HH \to WbWbb\bar{b}b\bar{b}$ with a statistical significance of 0.35σ [11]. To achieve the maximal sensitivity to the Higgs boson self-coupling all measurable channels will be statistically combined.

2.3 Vector Boson Fusion Higgs boson production and Higgs boson rare decays

The large data sample available after the HL-LHC phase will allow to probe the couplings to the second generation of fermions. The expected statistical significance of the $H \to \mu\mu$ decay channel will improve from 2.3σ with 300 fb^{-1} to 7.0σ with 3000 fb^{-1} assuming a pile-up of $<\mu_{PU}>\approx 140$ with a relative precision on the signal strength of $\delta\mu/\mu = 0.2$ [7]. This channel will

also benefit from the improved mass resolution of around 25% offered by the fully-silicon inner detector upgrade contributing to the precise determination of the Higgs boson mass. Projections for the measurement of $H \rightarrow J/\Psi\gamma$ decay have also been performed [12]. The expected yields are 3 signal and 1700 background events setting the upper limit on the branching ratio to $44^{+19}_{-22} \, 10^{-6}$ at 95% C.L. (SM prediction is $2.9 \pm 0.2 \, 10^{-6}$). The extended pseudorapidity coverage of the new inner tracker will also allow an efficient pile-up suppression from about 200 pile-up jets per event down to 0.2 which is particular beneficial for the vector boson fusion (VBF) Higgs boson production topologies characterised by two hard forward jets [7]. This efficient pile-up mitigation will allow to measure the cross-section of the $H \rightarrow WW^*$ with an expected precision of 12% whereas $H \rightarrow ZZ^*$ decay mode measurement will have a statistical significance of 7.7σ and an expected signal strength precision of $\Delta\mu/\mu = 0.17$.

3. Supersymmetry prospects at HL-LHC

Supersymmetry (SUSY) [13, 14, 15, 16, 17, 18] is an appealing possible extension of the SM which predicts the existence of a scalar partner to the SM fermion and a fermionic partner to the SM boson. The discovery or more stringent limits on the weak-scale SUSY particles is one of the priorities for the future HL-LHC physics program as the sensitivities will be strongly enhanced at the LHC design centre-of-mass energy. Discovery and exclusion projections have been studied for several benchmark SUSY scenarios at the HL-LHC with pile up condition of $<\mu_{PU}> \approx 200$ using a total integrated luminosity of 3000 fb^{-1} of data. The analyses presented assume a systematic uncertainty of 30% on the background estimation.
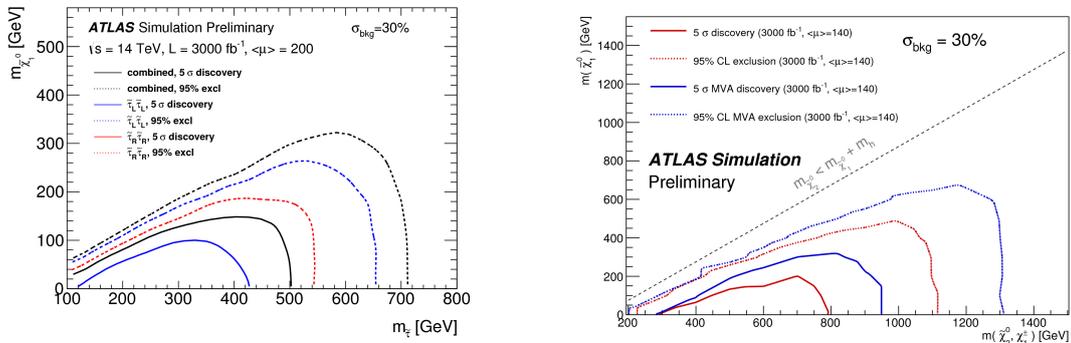

Figure 2: Right: 95% C.L. exclusion limits and 5σ discovery contours on pure $\tilde{\tau}_L, \tilde{\tau}_L$, pure $\tilde{\tau}_R, \tilde{\tau}_R$ and combined tau slepton production mode [20]. Left: 95% C.L. exclusion limits and 5σ discovery contours in the lightest neutralino $\tilde{\chi}_1^0$ versus charginos $\tilde{\chi}_2^\pm$ and neutralino $\tilde{\chi}_2^0$ mass plane for the cut and count and the multivariate analysis approaches [21].

3.1 Scalar top quark pair production

The on-going searches at the LHC have limited sensitivity to the scalar top quark production for the case in which its mass difference with the neutralino is the SM top quark mass. The semi-leptonic final state is very similar to the SM $t\bar{t}$ with enhanced missing transverse energy coming from the stable neutralinos. The discovery projection at the HL-LHC will be up to 450 GeV and the exclusion limit will be increased up to 700 GeV for the stop mass eigenstate [19].

3.2 Scalar tau lepton pair production

Electro-weak SUSY production of scalar tau lepton is an important channel for testing the reconstruction and identification of tau's with the upgraded ATLAS detector. Also, in many SUSY scenarios, light scalar taus can affect the decay rate of the Higgs boson into di-photons. The final state considered here involves two hadronically decaying taus, low jet activity and large missing transverse energy. The 5σ discovery potential and 95% C.L. exclusion is shown in figure 2 for the pure left and right handed mass scalar tau production and for their combinations [20]. For the latter case, the exclusion range reaches 700 GeV and the discovery ranges from 100 up to 500 GeV in scalar tau mass.

3.3 Direct chargino and neutralino pair production

Several SUSY models predict charginos and neutralino to have masses of hundreds of GeV so within the discovery reach of the LHC. One of those model, simplified with several assumptions on the masses of scalar leptons and scalar neutrinos and assuming equal masses for the charginos $\tilde{\chi}_2^\pm$, and neutralino $\tilde{\chi}_2^0$, has been studies. The very challenging final state consists of leptons, missing transverse energy and b-jets allowing also to test the future detector performances under pile-up condition of $<\mu_{PU}>\approx 140$. The expected 95% C.L. exclusion and the 5σ discovery contours for the cut based analysis and the multivariate analysis can be seen in figure 2. For a massless lightest neutralino $\tilde{\chi}_1^0$ the discovery contour is extended up to 950 GeV and the exclusion limit up to 1350 GeV in charginos and neutralino masses [21].

4. Conclusions

The HL-LHC phase will deliver 3000 fb^{-1} of data at the centre-of-mass energy of 14 TeV reaching an unprecedented instantaneous luminosity of 7.5×10^{34}cm^{-2}s^{-1} with about 200 pile-up interactions per bunch-crossing. The ATLAS detector will undergo a major upgrade to maintain the current optimal performances hence allowing the full exploitation of the physics potential of the HL-LHC data. Several prospect physics analyses and performance studies have been performed for the Phase-II detector upgrade assuming different detector geometries and designs and pile-up conditions. In particular, the precision measurements of the SM Higgs boson couplings to SM particles (from 2% to 15%), the expected sensitivity of the Higgs boson self-coupling measurement and to rare Higgs boson decay channels have been explored. Moreover, the discovery potential of several SUSY particles such as scalar top quark, scalar tau lepton, charginos and neutralinos has been explored. All the analyses performed so far in the context of the physics prospects at the HL-LHC will greatly benefit from the Phase-II ATLAS upgrade and the large dataset collected.

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