PROCEEDINGS OF SCIENCE

ATLAS Higgs Physics Prospects at the High Luminosity LHC

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A highly successful Run 1 for the ATLAS experiment at the LHC brought the discovery of the Higgs boson and provided initial measurements of its properties. To fully verify the Standard Model nature of the Higgs boson or search for beyond the Standard Model properties in the Higgs sector will require a larger dataset, delivered by the High Luminosity LHC. This document outlines studies on simulated data into the prospects of future measurements on Higgs boson couplings, Higgs self-couplings and constraints on discovering further Higgs bosons at the High Luminosity LHC with a total integrated luminosity of 3000 fb^{-1} and collisions at $\sqrt{s} = 14$ TeV.

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1. Introduction

The first run of the Large Hadron Collider (LHC) from 2010 - 2012, using proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV, was highly successful. The highlight was the discovery of a new particle with a mass of 125 GeV compatible with the Standard Model (SM) prediction of the Higgs boson. ATLAS [1] has performed initial measurements of the Higgs properties such as spin/CP, differential cross sections and its couplings to SM particles [2, 3, 4]. In future LHC runs with a collision energy of $\sqrt{s} = 14$ TeV ATLAS will pursue precision measurements of the Higgs boson properties as well as performing Beyond the Standard Model searches in the Higgs sector. The present LHC programme is expected to deliver a total integrated luminosity of about 300 fb^{-1} by the year 2022. The peak instantaneous luminosity will be in the range from 2 to $3 \cdot 10^{34}\text{cm}^2\text{s}^{-1}$. This dataset is forseen to have an average number of pile-up events per bunch crossing, denoted by PU, of 50 - 60. A planned upgrade of the LHC to the High Luminosity LHC (HL-LHC) is needed to fully explore rare decay processes. The LHC will provide 3000 fb^{-1} by 2030, with a peak luminosity of $5{\cdot}10^{34}\text{cm}^2\text{s}^{-1}$ and a value of PU = 140. The increase in PU with instantaneous luminosity is the primary challenge for detector operation at the HL-LHC, degrading the experimental environment, primarily the primary vertex and track reconstruction efficiencies. To mitigate the effect of PU, as well as addressing the issue of radiation damage to the silicon sensors, the ATLAS detector will undergo an extensive upgrade program prior to the HL-LHC running [5]. Some highlights of the future physics potential of the ATLAS detectors at the HL-LHC are summarised in the context of measurements of the SM Higgs boson properties. The outlined sensitivity studies are performed using particle level simulated data, to which detector response functions are applied. These functions are derived from full Geant 4 simulations and are based on an upgraded ATLAS detector, taking into account the impact of future PU scenarios on the detector efficiencies [6, 7]. At high luminosity the theory uncertainties increasingly become the dominant contribution to the total uncertainty. It can be assumed that the theory uncertainties will improve with time, but it is unknown to what extent. For that reason, the results of the sensitivity studies are quoted for two scenarios: one in which all systematic uncertainties are considered, including the current understanding of the theory uncertainties, and another where no theory uncertainties are included.

2. Standard Model Higgs Couplings

The prospects to measure the SM Higgs couplings are presented for various decay channels, including the yet to be observed $b\bar{b}$ and $\mu\mu$ states. H$\rightarrow b\bar{b}$ suffers from a large background and is expected to be observed in Run 2 [8], while a $\text{H} \rightarrow \mu\mu$ observation will require the HL-LHC data, due to the low branching ratio of the process [9]. The expected precision on the couplings is obtained from a fit for each channel using a leading-order tree-level motivated framework [10], under the assumption of a single resonance Higgs boson of mass $m_\text{H} = 125$ GeV within a narrow width approximation. Results are quoted as the sensitivity to any deviation from the SM prediction $\Delta\mu/\mu$, where μ is the ratio of the observed cross section times branching ratio over the SM prediction, which is assumed to be $\mu = 1$. An overview is given in Figure 1 for the 300 and 3000 fb^{-1}

estimates. The expected precision at which the SM nature of the couplings can be probed with 3000 fb^{-1} is in the 2 - 15 % range depending on the decay channel.

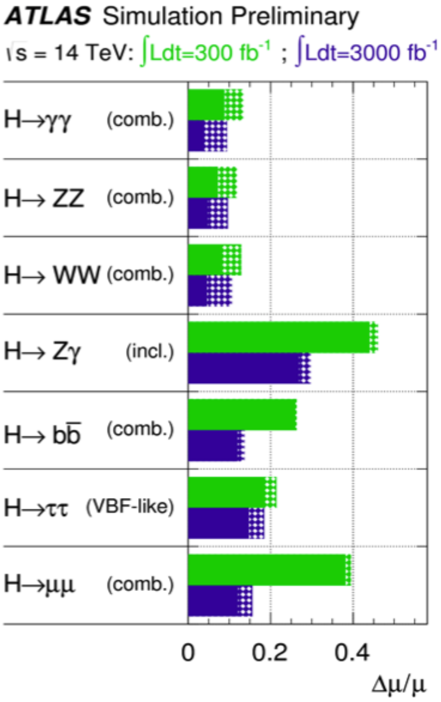
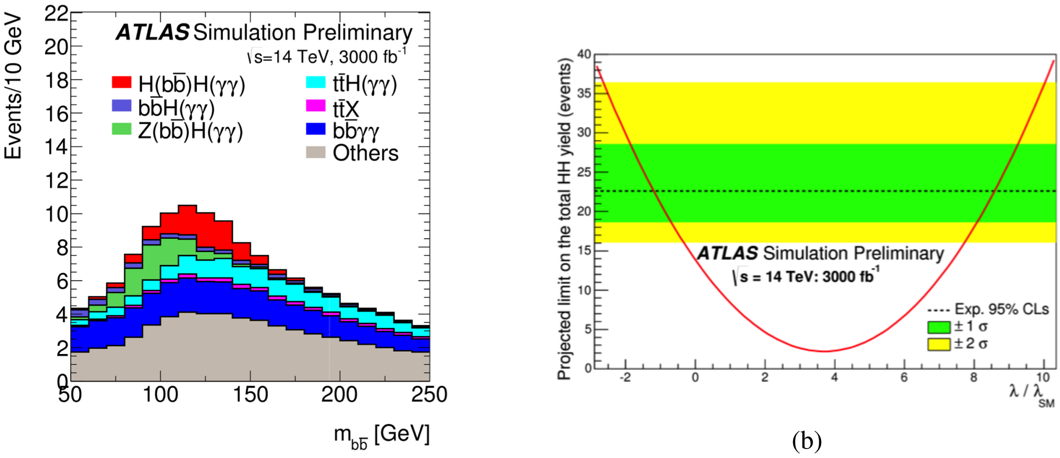


Figure 1: Relative signal strength errors $\Delta\mu/\mu$ in units of SM expectation, taken from Ref. [11], for 300 and 3000 fb^{-1}. The hashed areas indicate current theory uncertainty.

3. Higgs Self-Coupling

An exciting goal of the HL-LHC is observing di-Higgs boson production, which is sensitive to the Higgs self-coupling. Measuring the self-coupling, λ, will provide the strongest test of assessing the SM nature of the Higgs boson. The expected NNLO cross section is 41 fb for $\sqrt{s}$ = 14 TeV [12]. For this challenging measurement, the most promising signatures come from the final states HH $\rightarrow b\bar{b}\gamma\gamma$ with only 320 expected events for 3000 fb^{-1} but an experimentally clean signature and HH $\rightarrow$ WW$\gamma\gamma$ with 30,000 expected events but subject to large backgrounds. Further, the $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ final states are also of interest [13]. Results for HH$\rightarrow b\bar{b}\gamma\gamma$ are shown in Figure 2a. A strong seperation of signal and background is achieved through angular and mass cuts. In the case of the HH$\rightarrow b\bar{b}\gamma\gamma$ channel alone, 8.4 signal and 47 background events are selected, assuming a SM coupling λ_{SM}. As shown in Figure 2b, just HH$\rightarrow b\bar{b}\gamma\gamma$ will not be sensitive at the 5 σ discovery level to λ_{SM}, but will be able to rule out large deviations from the SM, namely $-1.3 < \lambda/\lambda_{SM} < 8.7$. A combination of all available channels from both ATLAS and CMS experiments is likely to be sensitive at the 5 σ discovery level to SM Higgs self-coupling by the end of the HL-LHC run.



(a)

(b)

Figure 2: (a) Expected invariant mass distribution $m_{b\bar{b}}$ in the HH→ $b\bar{b}\gamma\gamma$ channel. Contributions are shown before a mass and angular cut is applied and are normalized to the number of expected events after the full event selection. The background component *Others* is the sum of $c\bar{c}\gamma\gamma$, $b\bar{b}\gamma j$, $b\bar{b}jj$ and $jj\gamma\gamma$, where j signifies a jet. (b) Number of signal events (red) as a functions of $\lambda/\lambda_{\mathrm{SM}}$ with projected 1 and 2σ sensitivity bands (green/yellow) of the 3000 fb^{-1} dataset, taken from Ref. [13].

4. High Mass Higgs Searches

In several theoretical extension to the SM further Higgs bosons are envisioned. For example, in the Two Higgs Doublet Model (2HDM) [14], an additional Higgs doublet is considered, resulting in a model with five Higgs bosons: one neutral-CP-odd A, two charged $\mathrm{H}^{\pm}$, two neutral CP-even h and H, where h_{125} would be the discovered 125 GeV Higgs boson. Indirect searches for the heavy H through precision measurements of the h_{125} couplings are possible, where the presence of H would be established from deviations of the h_{125} couplings from the SM expectations, in both the couplings to bosons and fermions. The relationship between h_{125} and H is determined by their mixing angle α and tanβ, the ratio of the vacuum expectation values of the two doublets. Likewise, $\cos(\beta-\alpha)$ is a measure of the relative coupling strength of H to vector bosons over the SM expectation, such that $\cos(\beta-\alpha)$=0 recovers the SM case. For a MSSM-like Type II 2HDM, in which one Higgs doublet couples to up-type quarks and the other to down-type quarks and charged leptons, the regions of the $\cos(\beta-\alpha)$ vs tanβ plane that are expected to be excluded are shown in Figure 3.

5. Summary

With the discovery of the Higgs boson at LHC Run 1 we have entered a new era of particle physics. The unprecedented collision energy of $\sqrt{s}$ =13 - 14 TeV in Run 2 will vastly increase the scope for precision Higgs physics studies and searches for New Physics, but it will be the HL-LHC with 10 times more luminosity that will offer unique opportunities to fully explore the Higgs

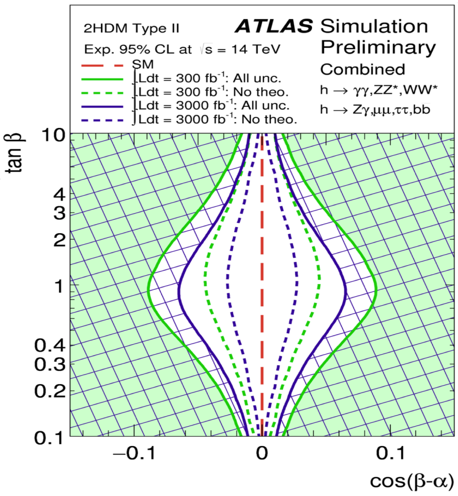


Figure 3: Excluded regions of the $\cos(\beta-\alpha)$ vs $\tan\beta$ of the Type II 2HDMs by fits to the measured rates of Higgs boson production and decays, taken from Ref. [15]. The confidence intervals account for a possible relative sign between different couplings. The expected likelihood contours of 95% CL (2σ) are indicated assuming the SM Higgs sector. The light shaded and hashed regions indicate the expected exclusions for 300 and 3000 fb^{-1}, with and without theory uncertainties.

sector, and probe for, and characterise high scale New Physics. Upgrades to the ATLAS detector are foreseen to ensure optimal performance in the harsh experimental environment of the HL-LHC. The prospects of future SM Higgs couplings measurements with a precision of 2 - 15% and the expected sensitivity to BSM physics such as Higgs self-coupling measurements and extra heavy Higgs boson searches were outlined in this note. ATLAS HL-LHC prospects studies not covered in this note include the Higgs boson decays to Dark Matter and SUSY couplings and Higgs boson compositeness. It should be noted that all prospect studies are a conservative projection based on current analysis techniques, which will most likely improve over the course of the LHC lifetime.

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