1 Introduction

The discovery of a neutral scalar particle with a mass of approximately 125 GeV at the Large Hadron Collider (LHC) in 2012\(^1,2\) has provided important insight into the mechanism of electroweak symmetry breaking. Experimental studies of the properties of this new particle have demonstrated consistency with the Standard Model (SM) predictions. However, it remains possible that the discovered particle is part of an extended Higgs sector, a scenario which is favoured by a number of theoretical models. The existence of such an extended sector would be confirmed by the observation of additional scalars, thus motivating the wide variety of searches carried out by ATLAS\(^3\), and presented in this document. All analyses are performed using the 2015 LHC \(pp\) collision data at 13 TeV centre-of-mass energy, corresponding to an integrated luminosity of 3.2 \(fb^{-1}\) recorded with the ATLAS detector.

2 Searches for heavy neutral Higgs bosons decaying to SM vector bosons

Many BSM models predict the existence of a heavy neutral scalar decaying to a pair of SM electroweak bosons. An important probe into physics beyond the SM is thus represented by analyses searching for a heavy Higgs decaying via \(WW\), \(ZZ\) and \(Z\gamma\).

2.1 Search for \(H \rightarrow Z\gamma \rightarrow (\ell\ell/J)\gamma\)

To improve the sensitivity of the search, both the leptonic and hadronic decay modes of the \(Z\) boson are studied, which are sensitive to complementary mass ranges. The leptonic analysis looks for an electron or muon pair consistent with a \(Z\) decay, while the hadronic analysis identifies boosted \(Z\) bosons from the merged di-jet cluster reconstructed as a single, large-radius, jet \(J\). In both cases, the invariant mass distribution of the background is parameterized by a smooth function with free parameters, which are adjusted to the data. No significant signal excess in the invariant mass distribution of the final state particles is found, and limits are set on the production cross section times branching ratio (see Fig 1a)\(^4\).
2.2 Search for $H \rightarrow WW \rightarrow \ell\ell\nu\nu$

As for the $Z\gamma$ search, different $WW$ final states are considered: $H \rightarrow WW \rightarrow \ell\ell\nu\nu$ and $H \rightarrow WW \rightarrow \ell\nu J$, where again $\ell = e, \mu$ and $J$ is a single large jet. The transverse mass $m_T$ of the system is used as discriminating variable in the $\ell\ell\nu\nu$ analysis, while the semi-leptonic analysis considers the reconstructed $WW$ invariant mass, $m_{\ell\nu J}$. The main backgrounds, arising from top-quark and $WW$ production processes and from $W/Z+jets$ production in the $\ell\ell\nu\nu$ and in the $\ell\nu J$ channels, respectively, are estimated from a simultaneous fit to the signal and control regions. No evidence of a high mass Higgs has been found, and limits are set on $\sigma \times BR(H \rightarrow WW)$ in the mass range between 600 and 3000 GeV, as shown in Fig.1b.

2.3 Search for $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$

A search for high-mass resonances in events with large missing transverse momentum and a $Z$ boson decaying into $e^+e^-$ or $\mu^+\mu^-$ is also performed by ATLAS. After applying the selection requirements, aimed at significantly reducing the background contamination, the dominant source of background is $ZZ$ production, followed by $WZ$ production, both estimated using simulation, with the $WZ$ normalisation taken from data. The remaining backgrounds are predicted using data driven methods. No significant deviation is found in the distribution of the transverse mass with respect to the SM prediction, and upper limits are set on $\sigma \times BR(H \rightarrow ZZ)$ for high-mass narrow-width Higgs bosons (see Fig.2a).

![Figure 1: Limits on the production cross section times the branching ratio for a heavy resonance decaying to (a) a $Z$ boson and a photon (leptonic and hadronic results overlaid) and (b) a pair of $W$ bosons (leptonic and hadronic analyses combined).

![Figure 2: Limits on $\sigma \times BR(H \rightarrow ZZ)$ at 95% CL for a narrow-width, heavy-Higgs boson in the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ (b) and in the $H \rightarrow ZZ \rightarrow \ell\ellqq$ (b) searches. Results for three different values of the width are also shown in (b).]
2.4 Search for $H \rightarrow ZZ \rightarrow \ell\ell qq$

The search is performed in the final state in which one $Z$ boson decays to a pair of electrons or muons, and the other $Z$ boson decays hadronically. The hadronic $Z$ boson candidate is reconstructed either as a pair of small-radius jets (resolved analysis) or as one large-radius jet (merged or boosted analysis). The two analyses are mutually exclusive, with the $Z \rightarrow \ell\ell$ candidates first passed to the merged analysis, and if they fail, to the resolved analysis. Background contributions from $Z+\text{jets}$ and top-quarks are evaluated from a simultaneous fit to both signal and control regions, whereas diboson production is estimated from MC. As no deviation is observed in the invariant mass distributions, limits are set on $\sigma \times \text{BR}(H \rightarrow ZZ)$ for a narrow resonance, as well as for a resonance with a 5, 10, or 15% width, as shown in Fig.2b\textsuperscript{7}.

3 Search for heavy neutral Higgs bosons decaying to di-Higgs

While the production cross section for Higgs-boson pairs is extremely small in the SM, it is enhanced in many BSM models. Searches for a heavy neutral scalar decaying into a pair of SM Higgs thus offer great potential in the search for new phenomena.

3.1 Search for $H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$

This search is performed in the $b\bar{b}\gamma\gamma$ final state, and profits both from the large BR of the $h \rightarrow b\bar{b}$ decay and from the clean signal of the $h \rightarrow \gamma\gamma$ decay. A counting approach is adopted in order to estimate the number of signal and background events within $m_{b\bar{b}\gamma\gamma}$ windows, defined to contain 95% of simulated di-Higgs events for each mass hypothesis. The signal region is required to have 2 $b$-tagged jets, while a control region with 0 $b$-tagged jets is used to provide a data-driven estimate of the continuum background. No excess was found with respect to the background-only hypothesis, and limits are set on the cross section times branching ratio in the mass range of 280-400 GeV, as shown in Fig.3a\textsuperscript{8}.

![Graph](image1)

(a)

![Graph](image2)

(b)

Figure 3: Limits on the production cross section times the branching ratio for a heavy resonance decaying to di-Higgs, in the $b\bar{b}\gamma\gamma$ a\textsuperscript{8} and in the $b\bar{b}b\bar{b}$ b\textsuperscript{9} final states.

3.2 Search for $H \rightarrow hh \rightarrow b\bar{b}b\bar{b}$

The dominant $h \rightarrow b\bar{b}$ decay mode is exploited in this search, with the four $b$-jets either reconstructed as distinct jets, or as a pair of large-radius jets. The resolved analysis is used up to resonance masses of 1.1 TeV (where its expected sensitivity is higher), while the boosted analysis is used above 1.1 TeV. The analysis sensitivity is increased by including in the boosted analysis a channel with only three $b$-tagged jets, in addition to the channel with four $b$-tagged jets. The dominant multijet background source, as well as the contribution from $t\bar{t}$ events, are modelled using data. No significant data excess is observed above the estimated background, and limits are set on the cross section times branching ratio to the $b\bar{b}b\bar{b}$ final state (see Fig.3b)\textsuperscript{9}.

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4 Search for charged Higgs boson decaying via $H^\pm \to \tau \nu$

Charged Higgs bosons produced in association with a top quark and decaying via $H^\pm \to \tau \nu$ are searched for in this analysis. The final state is characterised by the presence of a hadronic $\tau$ decay and missing transverse momentum, as well as a hadronically-decaying top quark, resulting in the absence of electrons or muons. The backgrounds are categorized based on what object is identified as the hadronically-decaying $\tau$ (a jet, an electron or muon, or a true $\tau$), and different data-driven techniques are used for their evaluation. Limits are set on $\sigma(pp\to[bt]H^\pm) \times \text{BR}(H^\pm \to \tau \nu)$ between 1.9 pb$^{-1}$ and 15 fb$^{-1}$, for charged Higgs boson masses ranging from 200 to 2000 GeV$^{10}$.

5 Search for heavy neutral Higgs bosons decaying to $\tau$ leptons

The search for neutral Higgs bosons decaying to a pair of $\tau$ leptons is performed in the mass range of 200 GeV – 1.2 TeV. Both the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels are considered, where $\tau_{\text{lep}}$ and $\tau_{\text{had}}$ represents the leptonic and hadronic decays of the $\tau$ candidates, respectively. The background processes for the $\tau_{\text{lep}}\tau_{\text{had}}$ channel are split depending on whether the lepton and/or $\tau_{\text{had}}$ are correctly identified or not. Simulated events are used to estimate the contribution from the former category, while data-driven methods are employed if the objects are misidentified. The dominant multi-jet background in the $\tau_{\text{had}}\tau_{\text{had}}$ channel is also evaluated from data. The data are found to be in good agreement with the SM expectations, hence results are given in terms of limits on the production cross section times branching fraction. The results are also interpreted in a range of MSSM scenarios$^{11}$.

6 Search for a heavy neutral CP-odd Higgs boson decaying to $Zh$

The final states considered for this search include cases where $h$ decays to a pair of $b$ quarks, and the $Z$ boson decays either to two electrons, two muons, or two neutrinos. As already seen for other analyses, both the resolved and merged regime are considered, and the division between the two categories is defined by $p_T^Z$ greater than (merged) or less than (resolved) 500 GeV. The events are further split depending on the number of $b$-tagged jets. The main backgrounds, arising from $Z$+jets and $t\bar{t}$ events, are constrained in control regions included in the final likelihood fit. No significant excess beyond the expectation from background studies is observed in the data. The data are thus used to set limits on the production cross sections times branching fractions in the range of $[4.0, 0.017] \text{pb}^{-1}$ ($[6.9, 0.026] \text{pb}^{-1}$) for $m_A = [220, 2000]$ GeV, assuming gluon-fusion ($b$-quark-associated) exclusive production$^{12}$.

References