Search for neutral and charged BSM Higgs bosons with ATLAS detector

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Abstract. Several theories beyond the Standard Model, like the EWS or 2HDM models, predict the existence of high mass neutral or charged Higgs particles. In this presentation the latest ATLAS results on searches for these particles will be discussed.

1 Introduction

The current Standard Model (SM) was completed with the discovery of the Higgs boson particle with a mass of $m_h \sim 125$ GeV in 2012 [1, 2]. However the theory lacks satisfactory explanation for several phenomena of nature and suffers from naturalness problems such as the hierarchy or fine-tuning. In order to solve these issues, several theories beyond the SM (BSM) have been proposed. These theories extend the SM, trying to accommodate the current experimental results while providing with an explanation for the different phenomena. Some of these models predict the appearance of additional Higgs bosons which might be found in the range of energy that the LHC has access to. Therefore, many searches are developed to find these hypothetical particles, which would be solid evidence of the models beyond the SM.

This contribution reviews different searches for additional Higgs bosons, both charged and neutral, which have been developed within the ATLAS Experiment [3]. The analyses use the data of the Run 2 of the LHC, collected at $\sqrt{s} = 13$ GeV, mainly for the full 2015 (3.2 fb$^{-1}$) and the first dataset of 2016, which correspond to additional 10 – 12 fb$^{-1}$. No excess over the SM is found in any of the analyses reported.

2 BSM Higgs models

Different models have been proposed to address the issues concerning the current SM. Several of them predict that the Higgs mechanism is mediated by a set of different Higgs bosons, rather than an unique particle. The boson particle found at $m_h \sim 125$ GeV would be one of them (usually the lightest one, labelled as $h$), and thus, additional Higgs bosons can be found, which would be evidence of the modified Higgs mechanism. A brief summary of the main BSM models with additional Higgs bosons is covered here.

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Electroweak Singlet (EWS)

The simplest extension of the SM is the addition of a single real scalar $S$ that is a gauge singlet \[4\]. The Higgs mechanism results then in two neutral bosons, $h$ and $H$. After the symmetry breaking, the two boson mix and the resulting state couples with quarks, leptons and gauge bosons proportionally to the SM couplings. The only new parameters that are needed to characterize most of the phenomenology of this model are the mixing angle between the bosons, $\alpha$, the mass of the new light scalar particle, $m_h$, and the branching ratio (BR) for the decay of the heavier Higgs scalar to a pair of the lighter ones.

Two-Higgs-Doublet Model (2HDM)

The Two-Higgs-Doublet Model \[5–7\] is an extension of the SM where a second Higgs doublet is added. Its simplest implementation, conserving CP symmetry and suppressing Flavour Changing Neutral Currents, leads to the appearance of four additional Higgs bosons, in addition to $h$: CP-even $H$, CP-odd $A$ and $H^\pm$. The model, and specifically the couplings of the different Higgs bosons to the SM particles, can be characterized by two parameters: the ratio between the vacuum expectation value of the two Higgs doublets, $\tan \beta \equiv v_1/v_2$ and the mixing angle of the two CP-even neutral bosons, $\alpha$. How the two doublets couple with the different fermions allows to define several types of 2HDM models.

Minimal Supersymmetric Standard Model (MSSM)

The Minimal Supersymmetric Standard Model \[8–12\] is the minimum implementation of the Super Symmetry theory (SUSY) \[13\] as an extension of the SM, which states that there is a higher symmetry between fermions and bosons and so, each particle would have a super-partner of the complementary type at large mass. The MSSM implements SUSY by adding the minimum additions that accommodate for the observed phenomena. In particular, for the Higgs mechanism, the MSSM implements the Type-II 2HDM model, which has five Higgs bosons: $h, H, A$ and $H^\pm$. At three level, the MSSM can be characterized by two parameters, the mass of the CP-odd boson, $m_A$ and the aforementioned $\tan \beta$. Furthermore, the high-order corrections can be purposely fixed to address certain phenomenological scenarios \[14–17\], accessible by the LHC experiments. Examples of these scenarios are: the hMSSM, where the MSSM parameters are tuned so that the lightest Higgs boson $h$ is exactly the observed particle; the $m_h^\text{max}$ scenario, where the values are chosen such that the mass of the light CP-even Higgs boson is maximized for a fixed $\tan \beta$ and large $m_A$; the $m_h^\text{mod}$, a modification of the $m_h^\text{max}$ scenario where the stop mixing parameter is modified in positive or negative direction, etc. Some of the different analyses performed at ATLAS are focused in setting limits for particular MSSM scenarios.

Higgs Triplet Model (HTM)

The Higgs Triple Model \[18\] is an extension of the SM where a Higgs triplet in the form $\vec{\phi} = (\phi^{++}, \phi^+, \phi^0)$ is added. Among other effects, the breaking of the symmetry raises seven Higgs bosons: $h, H, A, H^\pm$ and $H^{\pm\pm}$. The doubly-charged Higgs bosons are the main feature of the phenomenology of this model.

Other models

Finally, two more models will be described, whose Higgs phenomenology is similar to one of the aforementioned models. First the Next-to Minimal Supersymmetric Model (NMSSM) \[19\], which is an extension of the MSSM that introduces a single scalar field $S$ to the superpotential of the MSSM. The Higgs sector is composed by three CP-even scalars ($H_1, H_2, H_3$), two CP-odd scalars ($A_1, A_2$) and two charged scalars ($H^\pm$). Last, the Left-Right Symmetric Models \[20, 21\] are a set of extensions of
the SM whose aim is the symmetrization of the left and right chiral components of the fermions. Some of these models have an extended Higgs sector, composed by additional neutral or charged bosons, as the ones mentioned above.

**Current status of the search for BSM models**

After the Run 1 of the LHC was completed, a summary of the status of the current searches for BSM models was done [22]. The analysis combines the exclusion limits in the space of the parameters for different models, which is shown in Figure 1, and establishes the current status of the searches in preparation for the Run 2.

![Figure 1: Exclusion limits for the (a) hMSSM scenario and (b) Type-II 2HDM for the combination of all channels at the end of the Run 1 of the LHC [22].](image)

### 3 Neutral Higgs to bosonic final states

$H \to \gamma\gamma$

The $H \to \gamma\gamma$ analysis received attention at the end of 2015 due to a local $4 \sigma$ excess around $m_{\gamma\gamma} = 750\,\text{GeV}$, which was reported by ATLAS and CMS after the analysis of the first data of the Run 2, which accounted for a luminosity of $3.2\,\text{fb}^{-1}$ collected at $\sqrt{s} = 13\,\text{GeV}$. The first analysis adding the 2016 data shown here [23], which accounts for a total of $15.4\,\text{fb}^{-1}$, showed no excess over the SM expectation in the mentioned region, with an statistical significance of less than 1 $\sigma$.

This updated analysis was limited to the spin-0 resonance and the main event selection required two photons with a transverse energy conditions, for the leading one, $E_T^\gamma > 0.4m_{\gamma\gamma}$ and $E_T^\gamma > 0.3m_{\gamma\gamma}$ for the subleading photon. In addition, the di-photon invariant mass is required to be larger than $m_{\gamma\gamma} > 150\,\text{GeV}$. Two approaches are done when interpreting the results: first, the narrow width approximation (NWA), where the width of the particle is assumed to be much smaller than detector resolution; in contrast, several widths are tested. The distributions of the signal region (SR) and the exclusion limits on the cross-section times branching ratio are shown in Figure 2.
$H \rightarrow WW \rightarrow ℓνℓν$

The $H \rightarrow WW \rightarrow ℓνℓν$ analysis [24] updates the previous result adding the first data of 2016, to account for a total luminosity of 13.2 fb$^{-1}$ at $\sqrt{s} = 13$ GeV. The analysis updates the extended search of the leptonic decay of the $WW$ analysis in the high-mass region ($m_{WW} > 300$ GeV). Three categories compose the analysis, according to the number of jets: a 0-jet category, oriented to events produced by gluon-fusion (ggF), and two categories oriented to the vector boson fusion (VBF) production mode, with only 1-jet and with 2 or more jets. Due to the presence of several neutrinos, the discriminant variable is the transverse mass, defined as: $m_T = \sqrt{(E_{ℓℓ}^{miss} + E_{miss}^T)^2 - (p_{ℓℓ}^T + E_{miss}^T)^2}$. A second definition is used for the $W$ boson system, which is defined as: $m_W^T = \sqrt{2p_{ℓ}^{miss}E_{miss}^T(1 - \cos(\phi_ℓ - \phi(E_{miss}^T)))}$.

The main event selection requires two opposite-sign (OS) different-flavour (DF) leptons with $p_T > 45, 30$ GeV respectively. In addition, the invariant mass of the di-lepton system is required to be $m_{ℓℓ} > 55$ GeV while the transverse mass of the $W$ system has to be $m_W^T > 50$ GeV. A $b$-jet veto is required and the leptons must satisfy $\Delta η_{ℓℓ} < 1.8$. The distribution in the SR and the exclusion limits on the cross-section times branching ratio for the NWA are shown in Figure 3. No excess over the SM is observed.

$H \rightarrow WW \rightarrow ℓνqq’$

This analysis [25] covers the search of the $WW$ di-boson resonance where one $W$ decays leptonically (into $e$ or $μ$ plus neutrino) and the other hadronically, using the 13.2 fb$^{-1}$ collected during Run 2 at $\sqrt{s} = 13$ GeV. The analysis aims for the boosted topology, assuming the two jets produced by the quarks are boosted in the same direction and thus, they can be reconstructed as a single large jet, $J$.

The main event selection requires one lepton, an elevated missing energy ($E_{miss}^T > 100$ GeV) and the $p_T$ of the leptonic $W$ system satisfying $p_T(ℓν) > 200$ GeV. Regarding the large jet, it is required that its invariant mass be within 15 GeV of the mass of the $W$ boson. The $p_T$ of both systems has to satisfy $p_T^ℓ, p_T^{ν} > 0.4m_H$. Finally, a $b$-jet veto is applied, in addition to several sub-jet structure checks, which defines two categories: high-purity and low-purity. The distributions in the high-purity category of the SR and the exclusion limits on the cross-section times branching ratio for the NWA are shown in Figure 4. No excess over the SM is observed.
Figure 3: Distribution of the (a) transverse mass in the ggF Signal Region and (b) upper limits on the Higgs production cross-section times branching ratio in the analysis for the ggF category in the narrow width approximation [24].

Figure 4: Distributions of the (a) invariant mass for the high-purity category in the Signal Region and (b) upper limits on the cross-section times branching ratio for a heavy Higgs boson in the NW A approximation [25]. The theoretical curves corresponding to the expectation for a scalar singlet, in the naive dimensional analysis (red) and unsuppressed (blue) hypotheses are also overlaid.

\[ H \rightarrow ZZ \rightarrow 4\ell \]

The \( H \rightarrow ZZ \rightarrow 4\ell \) analysis [26] updates the extended search of ZZ analysis to the high-mass region (\( m_{4\ell} > 140 \text{ GeV} \)) in the NWA and in the large width approximation (LWA, where the width is assumed to be higher than detector resolution), using 15.8 fb\(^{-1}\) of data collected at \( \sqrt{s} = 13 \text{ GeV} \) during the Run 2. In the NWA assumption, the dataset is divided in two categories, aimed to different production modes: the VBF, asking for 2 jets with an invariant mass \( m_{jj} > 400 \text{ GeV} \) and a \( \Delta\eta > 3.3 \); and a ggF category, collecting the events rejected by the VBF. Due to the lack of fine sensitivity, for the LWA no categorization was done.

The main selection requires two pairs of OS same-flavour (SF) leptons with \( p_T > (20, 15, 10, 10 \text{ GeV}) \) respectively. In addition, the invariant mass of both pairs must be
around the mass of the $Z$ boson. In particular, the leading pair must satisfy $50 \text{ GeV} < m_{12} < 106 \text{ GeV}$ while for the subleading the range is relaxed to $12 \text{ GeV} < m_{34} < 115 \text{ GeV}$. The distributions of the inclusive SR and the exclusion limits on the cross-section times branching ratio for ggF category of the NWA approximation are shown in Figure 5. No excess over the SM is observed.

Other bosonic channels

Additional searches using bosonic channels are performed at ATLAS. The three reported here use ~13.3 fb$^{-1}$ of the data collected during Run 2 at $\sqrt{s} = 13 \text{ GeV}$.

The $H \to ZV$ search [27], where $V$ refers to a generic vector boson, is studied using two semi-leptonic decaying channels, the $\ell \ell qq$ and the $\nu \nu qq$. In the former, the SR is analyzed in two topologies, the boosted, where the two quark-jets are reconstructed as a single one jet, $J$, and the resolved analysis, for two separated low-$p_T$ jets. The latter is analyzed only in the boosted topology, using the transverse mass as discriminant, due to the presence of two neutrinos. Upper limits on the cross-section times branching ratio are shown in Figure 6 for the two analyses. No excess over the SM is observed.

The $H \to Z(\to \ell \ell) + E_T^{\text{miss}}$ analysis [28], where the search is focused in a $Z$ boson and large $E_T^{\text{miss}}$ in the mass range from 300 GeV to 1000 GeV. Two OS SF leptons are required, in addition to high $E_T^{\text{miss}}$ requirements. Figure 7 (a) shows the upper limits on the cross-section times branching ratio where no excess over the SM is observed. Finally the $H \to Z\gamma$ analysis [29], where the search is focused in the decay of a heavy Higgs into a $Z$ boson and a photon $\gamma$. The analysis ranges from 250 to 2400 GeV and is focused only in the light leptonic decays of the $Z (e, \mu)$. Figure 7 (b) shows the upper limits on the cross-section times branching ratio where no excess over the SM is observed.

4 Neutral Higgs to fermionic final states

$A/H \to \tau\tau$

The analysis for an additional scalar boson $A/H$ decaying to a pair of $\tau$ fermions [30] is preliminary released with the first 13.3 fb$^{-1}$ of data of the Run 2. The study searches for additional heavy resonances
in di-τ events in the range between 200 GeV and 1200 GeV and the results are interpreted in different MSSM scenarios. Two main categories are defined according to the presence of $b$-jets, focused in the ggF production mode and the $b$-associated production mode (bbH), respectively, the latter enhanced by the MSSM for high $\tan\beta$ values. The analysis is further divided in two channels, according to the type of decay of the $\tau$: the fully hadronic ($\tau_{\text{had}}\tau_{\text{had}}$), which requires the firing of a hadronic $\tau$ trigger and two candidates with high $p_T$, 110 and 55 GeV respectively; and the semi-leptonic ($\tau_{\text{lep}}\tau_{\text{had}}$), with has a combination of single-lepton trigger and requires large $E_T^{\text{miss}}$. This channel adds a further category aimed for the high-$E_T^{\text{miss}}$ phase space. The discriminant variable is the total transverse Mass of the system. Figure 8 shows examples of the SR of the different categories and channels.

The exclusion limits are set in two interpretations: a model-independent approach, which sets limits on the cross-section times branching ratio of the two production modes and the model-dependent approach, which set limits for different MSSM scenarios. Both of them are shown in Figure 9. No excess over the SM is found.
**Figure 8:** Pre-fit distributions of the total transverse Mass in the signal region of the $A/H \to \tau\tau$ analysis for the (a) $\tau_{\text{had}}\tau_{\text{had}}$ $b$-veto category, (b) $\tau_{\text{lep}}\tau_{\text{had}}$ $b$-tag category and (c) $\tau_{\text{lep}}\tau_{\text{had}}$ high-$E_T\text{miss}$ category [30].

**Figure 9:** Upper limits on the (a) cross-section times branching ratio for the model-independent approach showing the exclusion in the ggF production mode and (b) the $m_A - \tan\beta$ phase space for the model-dependent approach, showing the exclusion for the hMSSM scenario [30]. In (b), the result of the Run 1 search is shown for comparison.

$A/H \to t\bar{t}$

The $A/H \to t\bar{t}$ analysis [31] updates the Run 1 study $(20.3 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ GeV})$ by adding the inference of signal with the SM $t\bar{t}$ background in the mass range $400 - 800 \text{ GeV}$. The signal is consider to be the process $A/H \to t\bar{t}$ $\to b\bar{b}W(\to q\bar{q})W(\to \ell\nu)$ and the analysis aims for the resolved topology with two separated jets at low $p_T$. The main event selection requires two leptons with $p_T$ higher than 25 GeV, an $E_{\text{miss}}^T$ higher than 20 GeV and that $E_{\text{miss}}^T + m_W > 60 \text{ GeV}$. In addition, the event is required a minimum of four jets, where at least one is tagged as a $b$-jet. The rank in $p_T$ of the $b$-tagged jet defines three categories. Figure 10 shows the interference between the signal and the SM $t\bar{t}$ background and the exclusion limits on the cross-section times branching ratio of the analysis interpreted in the Type-II 2HDM scenario, where no excess over the SM is found.
5 Neutral Higgs to di-higgs final states

If the heavy Higgs boson is massive enough, it can decay in pairs of the observed boson $h$ at $m_h = 125$ GeV, which is studied by several analyses.

One of these analyses is the $H \rightarrow hh \rightarrow WW\gamma\gamma$ [32], performed using 13.3 fb$^{-1}$ of the Run 2. This analysis takes advantage of the clean signature of the $\gamma\gamma$, the easy detection of one energetic lepton and the large BR of the $WW$ decay. However, the BR of the $\gamma\gamma$ pair constrains the analyses to the range $260 – 500$ GeV. The analysis requires 2 photons whose invariant mass is around the Higgs boson mass, $105 – 160$ GeV, and two non-$b$-jets. Figure 11 shows the SR of the analyses and the upper limits on the cross-section times branching ratio extracted, although no excess over the SM was found.

Figure 11: Distributions of the (a) signal region and (b) upper limits on the cross-section times branching ratio for the $H \rightarrow hh \rightarrow WW\gamma\gamma$ analysis [32].
Another similar di-Higgs analysis is the $H \rightarrow hh \rightarrow bb\gamma\gamma$ [33], which was preliminarily rel with the first 3.2 fb$^{-1}$ of 2015 at $\sqrt{s} = 13$ GeV. The analysis takes advantage of the large BR of the $bb$ pair and clear signature of the $\gamma\gamma$ pair. However, the latter limits the range of search to $300 – 1000$ GeV. The event selection requires two $b$-jets and that the di-photon pair is within the range of the SM Higgs boson, $105 – 160$ GeV. Figure 12 (a) shows the exclusion limit on the cross-section times branching ratio of the decay.

Finally, the last di-Higgs analysis reported is the $H \rightarrow bbb\bar{b}$ [34], which was preliminarily released using 13.2 fb$^{-1}$ of data of the Run 2. The analysis is divided in two approaches, a resolved one, where four jets are required, with a condition that the invariant mass of each pair candidate is around the SM Higgs boson; and a boosted one, searching for two large jets with $m_J > 50$ GeV, a $p_T$ higher than 450 and 250 GeV, respectively and $|\Delta \eta| < 2.0$. Figure 12 (b) shows the phase-space of the analysis, highlighting the signal and control regions. No excess over the SM was found.

![Figure 12: Distributions of the (a) upper limits on the cross-section times branching ratio for the $H \rightarrow hh \rightarrow bb\gamma\gamma$ analysis [33] and (b) phase-space of the signal and control regions of the $H \rightarrow bbb\bar{b}$ analysis [34]. In (b) the SR is the region within the red circle, while the CR is the area within the orange circle, excluding the SR; finally, the area within the yellow contour is the side-band region.](image)

### 6 Charged and doubly-charged Higgs bosons

Three analysis involving charged Higgs bosons are reported. First, the $H^\pm \rightarrow \tau \nu$ [35], which was released using 13.2 fb$^{-1}$ of data of the Run 2. The analysis searches for events containing one $\tau$, large $E_T^{\text{miss}}$ and a top quark, in the mass range 200 – 2000 GeV and the results are interpreted in different MSSM scenarios. Only the fully-hadronic decays of the top and $\tau$ are considered while for the signal the $tbH^\pm$ and $tH^\pm$ modes are taken into account. The main event selection requires one hadronic $\tau$, large $E_T^{\text{miss}}$ and three jets, where at least one is $b$-tagged. Figure 13 shows the discriminant variable (transverse mass) and the exclusion limits on the hMSSM scenario. No excess over the SM is observed.

A second analysis is the $H^\pm \rightarrow tb$ [36], was released with 13.9 fb$^{-1}$ of data of the Run 2. The analysis searches for a final state consisting of one lepton and several ($b$-) jets in the mass range between 300 – 1000 GeV. The same signal modes as the previous analysis are considered. The analysis implements an MVA technique, a BDT, and the results are interpreted in the $m_h^{\text{mod}}$ MSSM scenario. In addition to the lepton, a minimum of four jets are required, where at least two have to be $b$-tagged. The
distribution of the jets and $b$-jets defines the categories of the analysis. Figure 14 shows the BDT output for one of the SR and the exclusion limits on the $m_{h}^{\text{mod-h}}$ scenario. No excess over the SM is observed.

Finally, the search of the doubly-charged Higgs boson into a pair of Same Sign (SS) electrons $H^{\pm\pm} \rightarrow ee$ [37] was released with 13.9 fb$^{-1}$ of data of the Run 2. The main selection requires at least one SS pair of $e$ with $m_{ee} > 300$ GeV. Pairs of OS electrons and pairs of low energetic SS electrons with $m_{ee} < 200$ GeV are used for control and validation Regions, respectively. Figure 15 shows the SR of the analysis and the upper limits on the cross-section times branching ratio. No excess over the SM is observed.
7 Conclusions

Several theories beyond the SM model predict additional Higgs bosons, which are searched by ATLAS in different analyses. The first results of the 2016 data-taking period have been shown, which account for around $13 \text{ fb}^{-1}$ of data collected at $\sqrt{s} = 13 \text{ GeV}$ during the Run 2 of the LHC. The analyses include searches for a neutral boson decaying to bosons, fermions or pairs of SM Higgs bosons and decays of a charged Higgs boson (singly or doubly charged). No excess over the SM has been observed in any of the analyses with the current luminosity collected. The analysis are ongoing and they will be updated with further data.

References