RESULTS ON BSM HIGGS BOSON SEARCHES AT ATLAS

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Many beyond the SM theories (BSM) foresee a complex Higgs sector and hence additional Higgs bosons. These new scalar particles could appear as excesses in events containing two bosons or two fermions. Direct searches for BSM Higgs bosons in final states with tau leptons, heavy quarks or vector bosons have been performed by the ATLAS experiment at the LHC. Recent results of these searches are reviewed in this article.

1 Introduction

The discovery of a neutral scalar particle by the ATLAS\textsuperscript{1,2} and CMS\textsuperscript{3} experiments at the LHC has opened a new era of measurements and motivated searches to investigate whether the new particle is the Standard Model (SM) Higgs boson or a part of a more complex Higgs sector which would reveal physics beyond the Standard Model (BSM).

All measurements of the production and decay rates of the Higgs particle, $h$, with mass at around 125 GeV, are so far compatible with the SM Higgs boson with $J^P = 0^+$ spin-parity\textsuperscript{4,5}. The width of the Higgs boson particle is sensitive to potential invisible BSM decay modes. An upper limit of 0.34 on the branching ratio of possible BSM decays is obtained at 95\% confidence level (CL) by means of a global fit on the measurements of the accessible decay modes\textsuperscript{6}.

Many BSM theories predict an extended Higgs sector, which would reveal for example an additional electroweak singlet (EWS) or a second Higgs doublet, as for the two Higgs doublet Model (2HDM)\textsuperscript{7}. While the first theory predicts the existence of another scalar particle, heavier than the SM-like Higgs boson, the latter class of models increase the number of total Higgs bosons up to five: $h$, SM-like Higgs; $H$, heavy CP-even boson whose mixing with the state $h$ is parametrised by the mixing angle $\alpha$; a CP-odd state $A$; and two charged Higgs bosons, $H^{\pm}$, with the same mass. In addition to the four Higgs boson masses and the mixing angle $\alpha$, a sixth free parameter characterises the theory: the ratio of the vacuum expectation value of the two doublets, $\tan \beta$. The models belonging to the 2HDM are categorised in four types. They differ in the way the two doublets couple to particles: Type-II models, for example, predict different couplings for up-type versus down-type fermions.
The most famous Type-II 2HDM is the Minimal Supersymmetric Standard Model (MSSM). Although at tree level the masses and the mixings of the five Higgs states depend only on two parameters, chosen to be $\tan \beta$ and one of the heavy Higgs masses, at higher orders they depend on many more parameters like the masses of the top and bottom scalar partners and their mixing parameters. Hence, benchmark models are employed to interpret the outcome of experimental searches. After the discovery of the SM-like Higgs, the $m_{h_\text{mod+/-}}$ and hMSSM$^9$ scenarios have been proposed, which incorporate the observed $h$ mass of 125 GeV as a constraint, leading to the reduction of the MSSM parameter space. The higher the $\tan \beta$, the more likely the neutral heavy scalar bosons will decay into down-type fermions. Moreover, the coupling of each fermion to the BSM Higgs bosons is proportional to its fermion mass. The $H/A \rightarrow \tau \tau$, $H^\pm \rightarrow tb$ and $H^\pm \rightarrow \tau \nu$ final states would be experimentally accessible at the LHC. The searches for these decay modes in ATLAS are discussed in the following sections.

Other theories question the fundamental nature of the Higgs boson, like composite Higgs models, or predict additional doubly charged Higgs bosons in triplet models. Results within these models are not discussed in this article.

2 Charged Higgs Searches

ATLAS has searched for the MSSM charged Higgs, $H^+$, in various final states, depending on the mass range under investigation. If a charged Higgs with mass heavier than the top quark is looked for, the channels with the highest expected significance are the $H^+ \rightarrow tb$ and $H^+ \rightarrow \tau \nu$ decay modes with the associated production of a top quark.

The first channel is characterised by events with a top pair and at least one $b$-quark. The $H^+ \rightarrow tb$ decay mode has been searched for by ATLAS$^{10}$ using proton-proton collision data taken at a centre-of-mass energy of $\sqrt{s} = 8$ TeV in the final state with one top quark decaying hadronically and the other decaying semi-leptonically. The requirement of three $b$-tagged jets reduces most of the SM background. The associated production of a top quark pair with additional partons is the main background. A multivariate technique is employed to discriminate the $H^+$ signal from the background process containing a top quark pair associated with a $b$-flavoured particle jet. An excess of data events with respect to the background-only hypothesis is observed over the whole $H^+$ mass hypotheses, and additional studies suggest a systematic background mis-modelling to be the cause of this excess. No signal is found and upper limits at 95% CL on cross section times the branching ratio with respect to signal hypotheses with $\tan \beta \leq 0.6$ in the $H^+$ mass range of 200–300 GeV and for $\tan \beta \approx 0.5$ in the $H^+$ mass range of 350–400 GeV.

The most recent search in ATLAS for $H^+ \rightarrow \tau \nu$ in association with a single top quark is performed at $\sqrt{s} = 13$ TeV$^{11}$. The studied final state consists of a hadronically decaying top quark, a neutrino, and a hadronic $\tau$ decay, characterised by the absence of muons or electrons in its decay products. The top quark is identified by requesting three jets, one of which is $b$-tagged. The neutrinos coming from the $H^+$ and $\tau$ decay leave a signature of missing transverse momentum in the event. A jet is identified as a hadronically decaying $\tau$ if one or three charged-particle tracks are found within a small cone in the jet and if it is tagged by means of multivariate techniques. The mass in the transverse plane obtained from the missing transverse momentum and the reconstructed $\tau$ is used to discriminate the signal from the background. The SM predictions are compatible with the data. Exclusion limits are set on the charged Higgs cross section times the $H^+ \rightarrow \tau \nu$ branching ratio with respect to signal hypotheses with $H^+$ mass ranging from 200 to 2000 GeV. The observed upper limits at 95% CL on the cross section times branching ratio range from 1.9 pb to 15 fb. The results are also interpreted in the hMSSM scenario as a function of $\tan \beta$ and $m_{H^+}$, see Figure 1(a). For $\tan \beta = 60$, models with $m_{H^+}$ in the range 200–340 GeV are excluded at 95% CL.
Figure 1 – (a) Exclusion limits at 95% CL in the \((\tan \beta, m_{H^\pm})\) parameter plane in the context of the hMSSM. The maximum value of \(\tan \beta = 60\), that can be tested, corresponds to the limit to which reliable theoretical calculations exist. (b) Observed and expected 95% CL exclusion limits on \(\tan \beta\) as a function of \(m_A\) in the hMSSM scenario.

3 Neutral Higgs Searches

The MSSM heavy Higgs boson couplings to down-type fermions are enhanced for large \(\tan \beta\) values with respect to the SM prediction. In this scenario the leading decay modes of the \(H\) and \(A\) heavy Higgses are \(H/A \rightarrow \tau \tau\) and \(H/A \rightarrow t \bar{t}\). The main production channel of \(H\) or \(A\) is via gluon-gluon fusion or in association with \(b\)-quarks. The search for \(H/A \rightarrow \tau \tau\) has been performed by ATLAS at \(\sqrt{s} = 13\) TeV with a data sample corresponding to an integrated luminosity of 3.2 fb\(^{-1}\). Final states with both taus decaying hadronically or with one tau decaying hadronically and the other leptonically are investigated. The visible part of each \(\tau\) decay is reconstructed, and the two \(\tau\) candidates are required to be roughly back-to-back. The undetected neutrino part of the \(\tau\) decay is estimated by means of missing transverse momentum. Each selected event is characterised by three masses in the transverse plane: the first one is calculated from the two reconstructed taus and two are calculated from the two taus each combined with the missing transverse momentum. The final discriminating variable is obtained by the sum in quadrature of these transverse masses. No excess with respect to the background-only hypothesis is found. Hence, the signal hypotheses of neutral heavy Higgs bosons in the \(m_{h_{\text{mod}}}^\text{mod}\) and hMSSM scenarios are tested for different values of \(\tan \beta\) and \(A\) boson mass. The upper limits at 95% CL in hMSSM are shown in Figure 1(b) after the two channel combination. Values of \(\tan \beta > 7.1\) and \(\tan \beta > 39\) are excluded for \(m_A = 200\) GeV and \(m_A = 1\) TeV, respectively.

In addition to the fermion pair final state, heavy neutral BSM Higgs particles decaying to bosons have been searched for. ATLAS has looked for final states with only charged leptons (4\(\ell\)), or charged leptons plus neutrinos (\(\ell \ell \nu \nu\)) coming from the decay of a \(Z\) boson pair, as reported in 13 and 14. No significant deviations with respect to the SM prediction have been observed. Upper limits at 95% CL are set on the cross section times branching ratio for heavy Higgs boson masses in the range 200-1000 GeV (\(ZZ \rightarrow 4\ell\)) and 300-1000 GeV (\(ZZ \rightarrow \ell \ell \nu \nu\)).

Moreover, the search for resonances in the final state with two vector bosons, \(ZZ\) or \(WW\), with at least one decaying hadronically, has been performed by ATLAS. The results are interpreted in the context of EWS models predicting an additional heavy CP-even scalar particle. Such a massive state would produce a pair of vector bosons with high transverse momentum.
Hence, the signature of these events is characterised by the presence of at least one jet with large distance parameter, $R$. This large-$R$ jet is likely to contain all the collimated final state particles originating from the hadronically decaying vector boson. The jet is then discriminated from QCD background by looking into its substructure composition. Channels where both vector bosons decay hadronically are combined with those with one boson decaying into a lepton pair ($\ell\ell, \ell\nu\nu$, with $\ell = e$ or $\mu$) and the other hadronically. The signal would appear as a resonant excess in the invariant mass distribution calculated from the objects reconstructed in the event, i.e. electrons, muons, large-$R$ jets or missing transverse momentum. No signal is observed and limits at 95% CL are set on the production cross-section times branching ratio of a narrow-width scalar resonance.

Searches with the SM-like Higgs boson involved in the final state have been performed by ATLAS. For example, the 2HDM CP-odd state, $A$, decaying to a $Z$ boson and $h$ have been searched for. No significant excess is observed in data and 95% CL upper limits are determined on the production cross section times branching ratio for $m_A$ in the range 220-2000 GeV. The data are also interpreted in the context of the Type-I and Type-II 2HDMs and 95% CL exclusion regions are defined in the plane of $\tan\beta$ and $\cos(\beta - \alpha)$.

4 Conclusions

Many scenarios beyond the Standard Model predicting an extended Higgs sector have been tested so far by ATLAS. Some of these searches have been reported in this article. No significant excess has been found so far. With the increasing recorded integrated luminosity and the increasing centre of mass energy, wider regions of the parameter space defined by new physics models can be tested.

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References