Search for Heavy Higgs Bosons with the ATLAS Detector

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The ATLAS experiment at the Large Hadron Collider performed searches for heavy Higgs bosons, whose presence would establish the existence of new physics. Searches for charged and neutral Higgs bosons are carried out using 8 or 13 TeV data for various production modes and in many different final states. No deviations from Standard Model expectations are observed. Exclusion limits are set on the production cross section and on parameters in various benchmark models.

Keywords: LHC, ATLAS; Higgs boson; BSM.

1. Introduction

The discovery of the Standard Model (SM) Higgs boson of about 125 GeV mass by ATLAS^{1,3} and CMS² marks a historical success for high energy physics. But many arguments support the notion of new physics, such as the abundance of dark matter and dark energy, the hierarchy problem, the asymmetry of matter over antimatter, and many more.

Additional Higgs bosons, with a mass larger than 125 GeV, appear in many SM extensions and therefore are a powerful probe of physics beyond the SM. ATLAS carried out searches for heavy Higgs bosons with 8 TeV during Run-1, and with 13 TeV using up to 37 fb⁻¹ of integrated luminosity collected during Run-2. These proceedings summarize these searches and results.

2. Charged Higgs Bosons Decaying to Fermions

ATLAS used 36 fb⁻¹ of 13 TeV data to search for doubly charged Higgs bosons⁴, $H^{\pm\pm}$, that decay to same-signed pairs of either left or right-handed leptons (electrons or muons). $H^{\pm\pm}$ are produced in pairs through the Drell Yan process. Signal

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regions are required to contain either two, three or four leptons with each having a transverse momentum $p_T > 30$ GeV. Background processes such as VV (V is either W or Z), ttH and ttV are estimated from simulation. Backgrounds due to wrongly identified charges (eg. $Z \rightarrow \ell^+\ell^-$ that is detected as $\ell^+\ell^+$) are estimated from data and validated in dedicated signal-depleted regions. Upper limits using a 95% confidence interval are set on the $H^{\pm\pm}$ mass. These vary between 770 and 870 GeV for the mass of a Higgs boson coupling only to left-handed leptons, $H_L^{\pm\pm}$, and for a branching ratio $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm)=100\%$, and are above 450 GeV for $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm)>10\%$. The observed limits on the mass of a Higgs boson that only couples to right-handed leptons, $H_R^{\pm\pm}$, vary from 660 to 760 GeV for $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm)=100\%$ and are above 320 GeV for $\text{BR}(H^{\pm\pm} \rightarrow \ell^\pm\ell^\pm)>10\%$. An example of these results is displayed in Fig. 1 (left), for the case where the $H^{\pm\pm}$ exclusively decays to electron pairs.

Heavy singly charged Higgs bosons, $H^\pm$, are produced in association with a single top. The $\tau\nu$ search⁵, which uses 14.7 fb^{-1} of 13 TeV data, starts from a missing transverse energy trigger. Events are selected that have at least three jets and no electrons or muons. The largest background is that where jets fake the presence of hadronic τ , which is estimated from data. A signal would form a peak in the spectrum of the transverse mass. Upper limits are placed on the production cross section times $\text{BR}(H^\pm \rightarrow \tau^\pm\nu)$ between 2.0 and 0.008 pb for the $H^\pm$ mass range of 200 to 2000 GeV. In the hMSSM scenario⁸, values of $\tan\beta$ in the range 42 to 60 are excluded for an $H^\pm$ with mass of 200 GeV. The $H^\pm$ mass range from 200 to 540 GeV is excluded at $\tan\beta$ of 60.

The $t\bar{b}$ channel⁷ is searched for in 13.2 fb^{-1} of 13 TeV data, exploiting four signal-enriched categories with exactly five or at least six jets where exactly three or at least four of them are b -tagged^a. The largest background is that of $t\bar{t}$ production with one or two additional b -jets, which is estimated from simulation, yet the normalization is a floating fit parameter. Boosted decision trees (BDT) are trained in each signal region using kinematic information for each signal mass hypothesis, and the BDT score is used as final discriminant. Upper limits are set on the production cross section times the $\text{BR}(H^\pm \rightarrow t\bar{b})$, which range from 1.09 pb at 300 GeV to 0.18 pb at 1000 GeV. In the $m_h^{\text{mod-}}$ scenario⁶, some values of $\tan\beta$ in the range 0.5 to 1.7 are excluded for $H^\pm$ masses of 300 to 855 GeV. For masses between 300 to 366 GeV high values of $\tan\beta$ are excluded, ie. $\tan\beta > 44$ is excluded at 300 GeV, and $\tan\beta > 60$ at 366 GeV, which is depicted in Fig. 1 (right).

3. Neutral Higgs Bosons Decaying to Fermions

ATLAS used 36.1 fb^{-1} of 13 TeV data to search for a heavy neutral scalar H or pseudoscalar A in the decay mode $A/H \rightarrow \tau\tau$ ⁹, where one τ candidate decays

^aA b -tagged jet, or short b -jet, means a jet that is identified to originate from the decay of a b -hadron.

Fig. 1. Exclusion limits for $H^\pm \rightarrow e^\pm e^\pm$ (left) and $H^\pm \rightarrow tb$ in the m_h^{mod-} scenario (right).

hadronically, and the other τ decays either hadronically or to an electron or muon. The A/H is produced either in association with b -quarks or via gluon fusion. Categories are defined by either requiring the presence of a b -jet or a b -veto. The largely irreducible $Z \rightarrow \tau\tau$ background is estimated from simulation, while processes where jets fake hadronic τ s are estimated from data. The transverse mass is the final discriminant. Upper limits on the production times $\text{BR}(A/H \rightarrow \tau\tau)$ are obtained, they yield 0.78 to 0.0058 pb (0.70 to 0.0037 pb) for gluon fusion (b -associated) production of A/H with masses of 0.2 to 2.25 TeV. In the hMSSM scenario, the most stringent limits exclude $\tan\beta > 1.0$ for a mass of 0.25 TeV and $\tan\beta > 42$ for a mass of 1.5 TeV, displayed in Fig. 2 (left).

Heavy Higgs bosons A/H decaying to $t\bar{t}$ are searched for using 20.3 fb^{-1} of 8 TeV data¹⁰. Events are selected that contain one lepton and four jets. The mass is reconstructed using a χ^2 algorithm to match the identified objects to the decay products of the $t\bar{t}$ system. The treatment of the sizable interference of the signal with the SM $t\bar{t}$ production is very challenging and has been carefully considered in this analysis. The interference alters the signal shape from a peak to a structure consisting of a peak followed by a dip. Exclusion limits are explored for the 2HDM type II¹¹ in the mass range between 500 to 750 GeV and for $0.4 < \tan\beta < 2.0$. The strongest exclusions are obtained at 500 GeV, where $\tan\beta < 1.5$ is excluded for the case that A and H are mass-degenerate, which is displayed in Fig. 2 (right).

The decay of heavy Higgs bosons to $t\bar{t}$ is also explored in $t\bar{t}H$ and $b\bar{b}H$ production using 13.2 fb^{-1} of 13 TeV data¹². Despite the much smaller production cross section, these channels do not suffer from the large interference that is the case for gluon fusion production mentioned above. Events are categorized by, amongst other variables, the number of jets and b -jets, and the final discriminant is the scalar sum of the transverse momenta of the lepton, the jets and the missing transverse energy. Upper limits are obtained for the 2HDM type I or type II for both production modes in the range between 400 to 1000 GeV, where $t\bar{t}H(\rightarrow t\bar{t})$ production is excluded for $\tan\beta < 0.1$.

Fig. 2. Exclusion limits $A/H \rightarrow \tau\tau^9$ in the hMSSM scenario (left) and the results for $A/H \rightarrow tt^{10}$ in the 2HDM type II (right).

4. Neutral Higgs Bosons Decaying to Bosons

The decay mode $H \rightarrow Z\gamma$ was searched for with 36.1 fb $^{-1}$ of 13 TeV data¹³. The Z boson decays to either ee or $\mu\mu$. The background and signal shapes are modelled analytically with parametric functions. The function describing the background is chosen such as to minimize a potential bias in absence of a real signal. The remaining bias is treated as a systematic uncertainty. Upper limits are set on the production cross section times BR, varying between 88 fb and 2.8 fb for the mass range from 250 GeV to 2.4 TeV. A moderate excess is observed at 960 GeV, the global significance is 0.9 standard deviations.

The search for heavy $H \rightarrow \gamma\gamma$ ¹⁴ is carried out in 13 TeV with 36.7 fb $^{-1}$. The signal and background shapes are modelled with parametric functions. Various signal width hypotheses are tested, and the mass range explored is 200 to 2700 GeV. An excess is observed in the 2015 dataset (3.2 fb $^{-1}$) at 750 GeV, which is not confirmed in the much larger dataset of 2016, the global significance is null. Upper limits on the cross section times BR are set for a narrow-width signal ranging from 11.4 fb at 200 GeV to about 0.1 fb at 2700 GeV.

Higgs bosons decaying to pairs of Z bosons, that subsequently decay to $llll$ or $ll\nu\nu$, are searched for in a dataset of 36.1 fb $^{-1}$ taken at 13 TeV¹⁵. These resonances are produced via gluon fusion or vector boson fusion. The interferences of the SM Higgs boson with the heavy Higgs boson, and that between $gg \rightarrow H \rightarrow ZZ$ and $gg \rightarrow ZZ$, are both taken into account. The signal mass shape is parametrized as a function of the mass. The best signal mass resolution is achieved in the $eeee$ channel, which ranges from 8 to 22 GeV for masses between 200 to 1400 GeV. The ZZ continuum background is estimated from simulation. Upper limits on the production times BR are set for both decays combined, ranging from 0.68 pb at

242 GeV to 11 fb at 1200 GeV for the gluon fusion production, and from 0.41 pb at 236 GeV to 13 fb at 1200 GeV for the vector boson fusion production. These results are also interpreted in the 2HDM. The exclusions for a mass of 200 GeV are displayed in Fig. 3 in the 2HDM type I and type II (at this mass only the $\ell\ell\ell\ell$ channel contributes).

Heavy Higgs bosons decaying to WW and resulting in a $\ell\nu qq$ final state¹⁶ are searched for in 36.1 fb^{-1} collected at 13 TeV. These Higgs bosons are produced via gluon fusion, vector boson fusion or quark-antiquark annihilation. A dedicated vector boson fusion category is defined by selecting events with a large dijet mass and well-separated jets that are not originating from the Higgs boson decay. Jet substructure analysis is carried out for those events where the two jets from the Higgs boson decay are merged into one jet with a large radius. The largest background contributions are W +jets and $t\bar{t}$, whose shapes are estimated from simulation, yet their normalizations are estimated with data-driven techniques. Limits on the production times BR are set in the mass range of 300 to 3000 GeV, ranging from 2 fb to 10 pb.

The channel $A \rightarrow Zh$, where h is the SM Higgs boson which decays to $b\bar{b}$, and the Z decays to $\nu\nu$ or $\ell\ell$, is explored in a dataset of 36.1 fb^{-1} taken at 13 TeV. Various categories are defined, with either no or two leptons, merged or resolved jets, and those with the presence of additional b -jets. The latter is used to enrich the selected dataset with b -associated A boson production ($b\bar{b}A$), which is enhanced in many BSM scenarios. Processes that constitute most of the background are Z +jets and $t\bar{t}$, while in the 0-lepton category also W +jets contributes. Upper limits are placed on the production times BR ranging between 5.5 to 240 fb for gluon fusion production and between 3.4 to 730 fb for $b\bar{b}A$ production in the mass range 220 GeV to 2 TeV. These limits are also interpreted in four types of the 2HDM.

Heavy scalars decaying to pairs of SM Higgs bosons are searched for in various final states using 13 TeV data: $bbbb$ ¹⁷ (3.2 fb^{-1}), $bb\gamma\gamma$ ¹⁸ (3.2 fb^{-1}) and $\gamma\gamma WW$ ¹⁹ (13.3 fb^{-1}). In the $bbbb$ analysis, the two jets forming a SM Higgs boson candidate are either resolved or in case of a boosted scalar merged into a single large-radius jet. The boosted (resolved) analysis is more sensitive for Higgs masses above (below) 1100 GeV. Multijet events dominate the background which is estimated from data. Upper limits on the production cross section times BR are obtained in the mass range of 500 to 3000 GeV and cover values between 35 to 250 fb. The $bbbb$ mode is the most sensitive channel at high mass. In contrast, the $bb\gamma\gamma$ channel is sensitive for resonances close to the kinematic threshold of twice the SM Higgs boson mass. The background is estimated by counting events in a mass window around 125 GeV, that is imposed on the invariant mass of the selected diphoton candidates. The upper limits on the production cross section times BR range between 7.0 to 4.0 pb for masses between 275 and 400 GeV. The $\gamma\gamma WW$ channel exploits final states where the WW decay to $\ell\nu qq$. This search is also based on event counting. The upper limits on the production cross section times BR range between 48 and 25 pb for masses of the resonance between 260 and 500 GeV.

Fig. 3. Exclusion limits for $H \rightarrow ZZ \rightarrow \ell\ell\ell$ ¹⁵ in the 2HDM type I (left) and type II (right).

5. Conclusion

Searches for heavy Higgs bosons were conducted using 8 and 13 TeV data collected until 2016 with the ATLAS experiment at the Large Hadron Collider. No significant deviation from the SM is observed in any channel. Exclusions limits are set in various scenarios of MSSM and for specific regions of the 2HDM, as well as in other models. Searches will continue and significant updates are expected for the final Run-2 analyses with a dataset of presumably 100 fb⁻¹.

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