High-mass Higgs searches at ATLAS and CMS

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Abstract. Several theories beyond the Standard Model, such as the two-Higgs doublet model, predict the existence of high-mass neutral and charged Higgs particles. The ATLAS and CMS experiments have completed an extensive program of searches for such particles using the $\sim 3 \text{ fb}^{-1}$ of $\sqrt{s} = 13 \text{ TeV}$ data recorded during 2015. This note summarizes a selection of these results.

1 Introduction

Since the first observations of the Higgs boson [1, 2], all measurements of its properties have been very consistent with expectations from the Standard Model (SM). There are, however, reasons to suspect that the known electroweak sector of the SM may not be complete, including the unnaturality of the observed Higgs boson mass and the possibility that new particles could constitute part of the inferred “dark matter” component of the universe. Therefore, both the ATLAS and CMS experiments have been searching for additional heavy Higgs-like scalars. The searches reported here mostly use the $\sim 3 \text{ fb}^{-1}$ of $\sqrt{s} = 13 \text{ TeV}$ data recorded by each experiment during 2015.

Some searches reported here are interpreted in the context of a simple extension to the SM, the two-Higgs doublet model (2HDM) [3]. In the 2HDM, an additional Higgs doublet is introduced, yielding five physical Higgs bosons: two CP-even scalars h, H ; one CP-odd scalar A ; and two charged scalars $H^\pm$. (In the following, the observed 125 GeV resonance is denoted h ; H is a putative heavier resonance.) Besides the particle masses ($m_h, m_H, m_A, m_{H^\pm}$), model parameters include the ratio of the vacuum expectation values of the two doublets $\tan\beta$; the mixing angle between h and H α ; and the potential parameter mixing the two doublets m_{12}^2 . There are many ways in which the doublets can be coupled to other particles. The most studied classes of models are “Type-I,” in which all quarks couple to only one doublet, and “Type-II,” in which up-type quarks couple to one doublet and down-type quarks to the other. The minimal supersymmetric standard model (MSSM) is a subset of 2HDM, and results are often reported in the context of a set of defined benchmark models [4, 5].

2 Higgs boson decays to ZZ

This section covers decays of a high-mass Higgs boson to two Z bosons, at least one of which decays into a lepton pair. Other diboson decay modes, including $Z\gamma$, are covered in [6].

The $H \rightarrow ZZ \rightarrow 4\ell$ channel is notable for having a very low background, though the branching ratio is also small. The high-mass analysis for both experiments is based on the analyses for

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$m_h = 125$ GeV. Selected events must have two same-flavor, opposite-sign lepton pairs. The CMS analysis [7] requires one pair with $40 < m_{\ell\ell} < 120$ GeV and the other with $12 < m_{\ell\ell} < 120$ GeV. Backgrounds are further reduced by requirements on lepton momenta, angular separation, and on track isolation and impact parameter. The resulting background is quite small and consists mostly of ZZ production, which is estimated from Monte Carlo (MC) simulation. Results are shown in Figure 1, including exclusion limits in $\sigma \times \text{BR}$ for the case of a narrow resonance over the range 200–1000 GeV, and also limits for several larger widths as well as an interpretation in terms of a Type-I 2HDM. The corresponding ATLAS analysis is described in [8].

Figure 1. Selected results of the CMS $H \rightarrow ZZ \rightarrow 4\ell$ search [7]. Left: distribution of four-lepton invariant mass $m_{4\ell}$. Center: 95% CL exclusion in $\sigma \times \text{BR}$ as a function of $m_{4\ell}$ for the narrow-width approximation and several larger widths. Right: 95% CL exclusions in $\tan\beta/m_h$ for a Type-I 2HDM.

The ATLAS search in the $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ channel [8] requires a $Z \rightarrow \ell\ell$ decay, $E_T^{\text{miss}} > 120$ GeV not pointing along a jet, and no b -tags. The discriminating variable is $m_T^{ZZ} = m_T(\ell\ell, E_T^{\text{miss}})$. There are additional requirements on p_T^Z , angular separations, and event transverse momentum balance. The major backgrounds are SM diboson production, which is estimated from MC simulations with the WZ background normalized to data, and Z + jets, which is estimated from data. Selected results are shown in Figure 2. The corresponding CMS analysis is described in [9].

Figure 2. Selected results of the ATLAS $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ search [8]. Left: m_T^{ZZ} distribution. Right: 95% $\sigma \times \text{BR}$ limit for a narrow-width Higgs boson produced via gluon-gluon fusion.

In the $H \rightarrow ZZ \rightarrow \ell\ell qq$ channel, both Z bosons are reconstructed; however, there is a large background from Z + jets. For large m_H , the decay products become boosted, and the jets from the $Z \rightarrow qq$ tend to merge into a single jet. Therefore, the ATLAS $H \rightarrow ZZ \rightarrow \ell\ell qq$ search [10] is divided into “merged” and “resolved” analyses. Besides the $Z \rightarrow \ell\ell$ decay, the merged analysis requires the presence of a large- R jet with $p_T > 200$ GeV that is consistent with originating from Z boson decay, as well as $p_T(\ell\ell) > 0.3m_{\ell\ell}$. The resolved analysis requires two jets with $70 < m_{jj} < 105$ GeV and $\sqrt{p_T^2(\ell\ell) + p_T^2(jj)} > 0.5m_{\ell\ell jj}$. This analysis is further divided into tagged (with 2 b -tagged jets) and untagged categories. The dominant backgrounds are Z + jets and $t\bar{t}$, both of which are evaluated from data. Selected results are shown in Figure 3.

Figure 3. Selected results of the ATLAS $H \rightarrow ZZ \rightarrow \ell\ell qq$ search [10]. Left, middle: Observed $m_{\ell\ell qq}$ distribution compared to background expectations for the (left) merged analysis and (middle) tagged category of the resolved analysis. Right: 95% CL $\sigma \times \text{BR}$ limit for the production of a heavy scalar with narrow width.

3 Higgs boson decays to other Higgs particles

This section covers searches involving the CP-odd scalar A . Searches for a heavy scalar decaying into two SM Higgs bosons are covered in [11, 12].

CMS has searched for the process $H \rightarrow ZA \rightarrow \ell\ell bb$ [13]. The event selection requires a $Z \rightarrow \ell\ell$ decay (with $75 < m_{\ell\ell} < 105$ GeV) and two b -tagged jets. The analysis proceeds by choosing a set of hypothesized m_H/m_A pairs. For each specific pair, $\mathcal{H}_A^H$, a signal region $\mathcal{S}_A^H$ is defined in the $m_{bb}/m_{\ell\ell bb}$ plane as a rectangle centered on $\mathcal{H}_A^H$ with sizes given by three times the experimental resolution. The dominant backgrounds are Z + jets and $t\bar{t}$; the background is evaluated by fitting simulated samples to the control region defined by the area of the $m_{bb}/m_{\ell\ell bb}$ plane outside the signal region. (The $m_{\ell\ell}$ invariant mass requirement is also relaxed to 60–120 GeV in the control region.) The 95% CL limit on $\sigma \times \text{BR}$ is found for each $\mathcal{H}_A^H$; selected results are shown in Figure 4.

ATLAS has also searched for the process $A \rightarrow Zh$, with $h \rightarrow bb$ and either $Z \rightarrow \ell\ell$ or $Z \rightarrow \nu\nu$ [14]. Events must have at least one b -tagged jet, and are categorized as having either one or two tagged jets. If $p_T^Z < 500$ GeV (where p_T^Z is either E_T^{miss} or $m_{\ell\ell}$), then the analysis requires two jets with $110 < m_{jj} < 140$ GeV (“low- p_T^Z ”); otherwise, it requires a single large- R jet consistent with Z boson decay with $75 < m_J < 145$ GeV (“high- p_T^Z ”). If the event has two leptons, then there must be a $Z \rightarrow \ell\ell$ decay with $70 < m_{\ell\ell} < 110$ GeV (widened to 55–125 GeV for the high- p_T^Z case with muons), and in the low- p_T^Z case $E_T^{\text{miss}}/\sqrt{H_T} < 3.5\sqrt{\text{GeV}}$ (to suppress $t\bar{t}$ background). The final discriminant in this case is the overall invariant mass $m(Zh)$. If the event has no leptons, then the analysis requires

Figure 4. Selected results from the CMS $H \rightarrow ZA \rightarrow \ell\ell bb$ search [13]. Left/middle: $m_{bb}/m_{\ell\ell bb}$ distributions. Right: Resulting $\sigma \times \text{BR}$ limit as a function of m_A for $m_H = 500$ GeV. Expectations for a Type-II 2HDM model are also shown for two different values of $\tan\beta$.

$E_T^{\text{miss}} > 150$ GeV and, for the low- p_T^Z category, that the scalar p_T sum of the highest three p_T jets be > 150 GeV (or > 120 GeV if there are only two jets). Additional requirements are made on the track-based missing momentum and on the angular separation between objects to reduce backgrounds due to mismeasured E_T^{miss} . The final discriminant for this case is the transverse mass $m_T(Zh)$. The dominant backgrounds are $Z + \text{jets}$ and $t\bar{t}$ and are studied by defining background-enriched control samples. For the $Z + \text{jets}$ background, the m_{jj} (or m_j) requirement is inverted. A two-lepton low- p_T^Z $t\bar{t}$ control sample is also defined by requiring that the two leptons have different flavor with $m_{e\mu} > 40$ GeV. Backgrounds are estimated from MC simulations, constrained by including the control regions in the final fit. Selected results are shown in Figure 5, including $\sigma \times \text{BR}$ limits as a function of m_A and limits in the $\tan\beta/\cos(\beta - \alpha)$ plane in the context of the MSSM.

4 Higgs boson decays to fermions

As mentioned earlier, models with two Higgs doublets include charged Higgs bosons. For $m_{H^\pm} > m_t$, production is dominantly in association with a top quark, $pp \rightarrow t(b)H^\pm$. Decay is mostly $H^\pm \rightarrow tb$, but $H^\pm \rightarrow \tau\nu$ is significant for large $\tan\beta$. Both experiments have reported searches for a charged Higgs boson, and also for a heavy H or A scalar decaying to a pair of tau leptons.

CMS has searched for $H^\pm \rightarrow tb$ and $H^\pm \rightarrow \tau\nu$ produced via $pp \rightarrow t(b)H^\pm$ using 8 TeV data from 2012 [15]. The hadronic channel is also sensitive to $t\bar{t} \rightarrow bH^\pm\bar{b}H^\pm$ and $t\bar{t} \rightarrow bH^\pm\bar{b}W$. This search is performed in four separate channels.

The first channel is $\tau_{\text{had}} + \text{jets}$, which is sensitive to the $\tau\nu$ decay mode. This requires a hadronic tau decay, at least three jets, at least one b -tagged jet, $E_T^{\text{miss}} > 60$ GeV, and no leptons. Additional requirements are made on the azimuthal separations between objects. The discriminating variable used is $m_T(\tau_{\text{had}}, E_T^{\text{miss}})$. The dominant backgrounds include SM diboson processes, $W/Z + \text{jets}$, and top quark decays into tau leptons; these are evaluated by replacing the muon in $\mu + \text{jets}$ data with a simulated tau lepton. The QCD multijet background is estimated by measuring the rate for a jet to be misidentified as a tau lepton and applying that to multijet data.

The second channel is $\ell\ell$, which is sensitive to both decay modes. This channel requires two opposite-charge leptons not consistent with Z boson decay, at least two jets, $E_T^{\text{miss}} > 40$ GeV, and at least two b -tagged jets. The final discriminating variable is the number of b -tagged jets. The dominant

Figure 5. Selected results from ATLAS searches involving a CP-odd scalar A [14]. Top left: $m_T(Zh)$ for the 0-lepton, 1-tag, high- p_T^Z category. Top middle: $m(Zh)$ for the 2-lepton, 2-tag, low- p_T^Z category. Top right: 95% $\sigma \times \text{BR}$ limit for $A \rightarrow Zh \rightarrow Zb\bar{b}$ as a function of m_A , for production via the gluon-gluon fusion process. Bottom left: Same, for production with associated b quarks. Bottom middle: Interpretation of the $A \rightarrow Zh \rightarrow Zb\bar{b}$ search in terms of a Type-I 2HDM. Bottom right: Same for Type-II.

background is $t\bar{t}$ decay with two leptons; backgrounds are evaluated from MC simulations. The third channel is the same except that instead of two leptons, a muon and a tau lepton are required, and only one b -tagged jet is required. Backgrounds are again evaluated from MC, convoluted with the probability for a jet to be misidentified as a tau lepton, which is measured from data.

The fourth channel is $\ell + \text{jets}$, which is sensitive to the $t\bar{b}$ decay mode. Events must have one lepton, $E_T^{\text{miss}} > 20$ GeV, at least two jets, and at least one b -tagged jet. Events are categorized based on whether they have one or two b -tagged jets. Background shapes are taken from MC simulations and normalized by fitting to data in both the signal and several control regions.

Selected results from this search are shown in Figure 6.

ATLAS has also searched for $H^\pm \rightarrow \tau\nu$ using 13 TeV data [16]. (The ATLAS $H^\pm \rightarrow t\bar{b}$ search using 8 TeV data [17] is not covered here.) To select the final state $(t \rightarrow jjb)b\tau_{\text{had}}\nu$, events must contain a hadronically-decaying tau lepton, no other leptons, at least three jets with at least one b -tagged jet, and $E_T^{\text{miss}} > 150$ GeV. The final discriminant is the transverse mass $m_T(\tau_{\text{had}}, E_T^{\text{miss}})$, which must be > 50 GeV. The dominant backgrounds are those with a real τ_{had} , including $W \rightarrow \tau\nu$ and $t\bar{t}$; these are estimated with MC simulation and validated with data. Backgrounds with jets misidentified as tau leptons are estimated using data, while backgrounds with other leptons misidentified as tau leptons are small and are also estimated with MC simulation. Selected results are shown in Figure 7.

Both CMS and ATLAS have also searched for a heavy scalar decaying into two tau leptons. This is particularly interesting in the context of the MSSM, where the couplings of Higgs bosons

Figure 6. Selected results from the CMS charged Higgs boson search [15]. Top: observed data compared to MC simulations in the (left) $\tau_{\text{had}} + \text{jets}$, (middle) $e\mu$, and (right) $\mu\tau_{\text{had}}$ channels. Bottom: 95% $\sigma \times \text{BR}$ limit as a function of $m_{H^\pm}$ for the (left) $\tau_{\text{had}} + \text{jets}$ channel and (middle) the other three channels. Bottom right: 95% CL exclusion in $\tan\beta/m_{H^\pm}$ for the MSSM benchmark model $m_h^{\text{mod}^-}$.

to tau leptons may be enhanced for large $\tan\beta$. The CMS search [18] is divided into four channels: $\tau_e\tau_{\text{had}}$, $\tau_\mu\tau_{\text{had}}$, $\tau_e\tau_\mu$, and $\tau_{\text{had}}\tau_{\text{had}}$. The two tau lepton candidates must have opposite sign and be well-separated in ΔR (> 0.3 for $\tau_e\tau_\mu$ and > 0.5 for other channels). In the $\tau_e\tau_{\text{had}}$ and $\tau_\mu\tau_{\text{had}}$ channels, there must be no opposite-sign ee or $\mu\mu$ pairs and also $m_T(\ell, E_T^{\text{miss}}) < 40$ GeV (e) or < 30 GeV (μ). An additional topological requirement is applied in the $\tau_e\tau_\mu$ channel to reject $t\bar{t}$ events, and events are then categorized as having either 0 or ≥ 1 b -tagged jets. The final discriminant is the $\tau\tau$ transverse mass $m_{T,\tau\tau}$, computed using the likelihood technique described in [19]. The dominant $Z \rightarrow \tau\tau$ background is evaluated using MC simulations and cross-checked with $Z \rightarrow \mu\mu$ data. Other backgrounds include $t\bar{t}$, also evaluated using MC and checked against data, and $W + \text{jets}$ and multijets, which are evaluated using same-sign τ_{had} candidates and high- m_T control regions. Selected results are shown in Figure 8.

The ATLAS $H/A \rightarrow \tau\tau$ search [20] is divided into two channels. The first requires exactly one electron or muon along with a τ_{had} candidate. Additional requirements include $\Delta\phi(\tau_{\text{had}}, \ell) > 2.4$, $m_T(\ell, E_T^{\text{miss}}) < 40$ GeV, and for electrons, $m(e, \tau_{\text{had}})$ must be outside the range 80–110 GeV, to reduce background from $Z \rightarrow ee$. The second channel requires two τ_{had} candidates with opposite charge, leading/subleading $p_T > 110/55$ GeV, and $\Delta\phi(\tau_{\text{had}}, \tau_{\text{had}}) > 2.7$. For both channels, events are categorized as either b -veto (no b -tagged jets) or b -tagged (at least one b -tagged jet). The final discriminant is $(m_T^{\text{tot}})^2 = m_T^2(E_T^{\text{miss}}, \tau_1) + m_T^2(E_T^{\text{miss}}, \tau_2) + m_T^2(\tau_1, \tau_2)$. The dominant background for the $\tau_e\tau_{\text{had}}$ channel is $Z \rightarrow \tau\tau$, while that for the $\tau_{\text{had}}\tau_{\text{had}}$ channel is multijets. Backgrounds containing real τ_{had} are estimated from MC simulations. Those with misidentified τ_{had} are estimated using a “fake-factor” method

Figure 7. Selected results from the ATLAS charged Higgs boson search [16]. Left: m_T distribution after event selection. Middle: 95% $\sigma \times \text{BR}$ limit for charged Higgs boson production. Right: 95% exclusion limits in $\tan\beta/m_{H^\pm}$ for the hMSSM scenario.

Figure 8. Selected results from the CMS $H/A \rightarrow \tau\tau$ search [18]. Top: Distributions of $m_{T,\tau\tau}$ for data and expected background for the (left) untagged $\tau_\mu\tau_{\text{had}}$, (middle) untagged τ_e, τ_μ , and (right) tagged $\tau_{\text{had}}\tau_{\text{had}}$ channels. Bottom left, middle: 95% $\sigma \times \text{BR}$ limits as a function of m_ϕ (where ϕ denotes either H or A) for (left) production via gluon-gluon fusion and (middle) associated production with b quarks. Bottom right: 95% exclusions in $\tan\beta/m_A$ for the hMSSM scenario.

in which a control sample, not selected for tau leptons, is convoluted with the measured probability for a jet to be misidentified as a tau lepton. Selected results are shown in Figure 9.

Figure 9. Selected results from the ATLAS $H/A \rightarrow \tau\tau$ search [20]. Left, middle: Distributions of m_T^{tot} for the (left) $\tau\ell\tau_{\text{had}}$ and (right) $\tau_{\text{had}}\tau_{\text{had}}$ channels for the (top) b -veto and (bottom) b -tag categories. Top right: 95% $\sigma \times \text{BR}$ limit for $H/A \rightarrow \tau\tau$ as a function of the scalar mass, assuming production via gluon-gluon fusion. Bottom right: 95% limits in $\tan\beta/m_A$ for the MSSM $m_h^{\text{mod}+}$ scenario.

5 Higgs boson decays to invisible particles

There is good evidence from astrophysics that so-called “dark matter” makes up a substantial fraction of the universe. If some portion of this is composed of a new, massive particle, then it should couple with the Higgs sector and, depending on its mass, may have a significant decay branching ratio. In fact, some models such as supersymmetry [21] and large extra dimensions [22, 23], naturally include heavy scalars coupling to invisible particles.

CMS has searched for a heavy scalar decaying to undetected particles, in both cases assuming that the heavy scalar decays exclusively to such particles. Two strategies are used to tag such decays. In the first, CMS searches for an invisibly-decaying scalar produced in association with a Z boson that decays into two leptons [24]. This search requires a $Z \rightarrow \ell\ell$ decay with $m_{\ell\ell}$ within 15 GeV of the nominal Z boson mass, $E_T^{\text{miss}} > 100$ GeV, no more than one jet with $p_T > 30$ GeV, and no b -tagged jets or additional leptons. Additional requirements are $\Delta\phi(\ell\ell, E_T^{\text{miss}}) > 2.8$ and $|E_T^{\text{miss}} - p_T^{\ell\ell}|/p_T^{\ell\ell} < 0.4$. Events are split into zero- and one-jet categories. The final discriminating variable is $m_T(\ell\ell, E_T^{\text{miss}})$, which is required to be above 200 GeV. The dominant background is Z + jets, which is estimated using a control sample of γ + jets events. Other backgrounds are estimated from a control sample in which the two leptons are different flavors. Results are shown in Figure 10; $\sigma \times \text{BR}$ limits are given for the heavy scalar mass range 125–600 GeV.

The second CMS search is for an invisibly-decaying heavy scalar produced via vector boson fusion (VBF) [25]. This search requires the presence of a VBF jet pair consisting of two forward jets with $\Delta\eta_{jj} > 3.6$ and $m_{jj} > 1100$ GeV. In addition, there must be no leptons, $E_T^{\text{miss}} > 200$ GeV, and $\Delta\phi(j, E_T^{\text{miss}}) > 2.3$. The dominant W/Z + jets background is evaluated using four control regions. One of these requires the presence of a $Z \rightarrow \mu\mu$ decay, and the other three require the presence of a single electron, muon, or tau lepton, respectively. The QCD multijet background is addressed with a fifth control region defined by inverting the $\Delta\phi$ requirement. The data are fit to simulated backgrounds in all five control regions simultaneously along with the signal region and the result found by counting the number of data and fit background events in the signal region. Results are shown in Figure 10.

Figure 10. Selected results from the CMS searches for a heavy scalar decaying to invisible particles. Top row: Associated production with $Z \rightarrow \ell\ell$ [24]. Left/middle: $m_T(\ell\ell, E_T^{\text{miss}})$ for the 0- and 1-jet categories. Right: 95% $\sigma \times \text{BR}$ limits. Bottom row: Production via vector boson fusion [25]. Left/middle: Distributions of $\Delta\eta_{jj}$ and m_{jj} for the VBF pair. Right: 95% $\sigma \times \text{BR}$ limits.

6 Summary

ATLAS and CMS have completed an extensive set of searches for new heavy scalars using the $\sim 3 \text{ fb}^{-1}$ of $\sqrt{s} = 13 \text{ TeV}$ data recorded in 2015. No significant excesses above SM expectations have been found so far. However, the LHC continues to perform exceptionally well, and the searches will continue with future data.

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