Search for Beyond SM Higgs Bosons

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This article summarizes the latest results within the context of searches for Higgs boson production and properties beyond the Standard Model obtained with ATLAS and CMS experiments in summer 2017.

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1. Introduction

Recent studies of the Higgs boson\textsuperscript{1,2} with the ATLAS\textsuperscript{3} and CMS\textsuperscript{4} experiments suggest the existence of a spontaneous symmetry breaking phenomena in the electroweak sector. The observation of couplings of Higgs boson to fermions\textsuperscript{5,6} indeed proved the existence of the mass generation mechanism through the scalar Higgs field. However, the nature of this mechanism has not yet been precisely established. Several underlying questions like the hierarchy problem, unification of the forces, mystery of the asymmetry of the matter and anti-matter in universe, dark matter and the origin of the dark energy in universe are not explained by the Standard Model (SM). To answer such fundamental questions a new theory, beyond the SM, is required. The quest to discover new particles beyond those predicted by the SM is therefore a primary task of the LHC experiments in addition to performing precise measurements of the Higgs boson.

This article summarizes the latest results within the context of the searches for additional Higgs bosons, beyond that predicted by the SM, presented by the ATLAS and CMS experiments in summer 2017. An overview of the searches for MSSM Higgs bosons is discussed in Sec. 2, a summary of the use of the Higgs boson as a tool in searches for new physics is presented in Sec. 3, searches for anomalous Higgs couplings and rare decays are presented in Sec. 4, and the summary is given in Sec. 5.

2. Searches for MSSM Higgs bosons

2.1. Overview

The Minimal Supersymmetric Standard Model (MSSM)\textsuperscript{7–9} is an extension of the SM inducing the supersymmetric partners of the SM particles. The MSSM requires two Higgs doublets with opposite hypercharge which results in one CP-odd ($A$), two CP-even ($h, H$) neutral Higgs bosons and two charged Higgs bosons ($H^\pm$) with
two additional mixing parameters, $\alpha$ the mixing angle of $h$ and $H$, and $\tan \beta$ the ratio of the vacuum expectation values of the up-type and down-type fermions in the two Higgs doublets.

Extensive searches for these Higgs bosons have been carried out over the years. For example, Fig. 1 summarizes the 95% CL exclusion contours in the MSSM $m^{\text{mod}+}_h$ scenario (with $\mu=+200$ GeV), obtained from selected CMS analyses that have been performed with the LHC Run 1 dataset. The $m^{\text{mod}+}_h$ scenario is chosen to be the mass of the lightest CP-even Higgs boson, $m_h$, is close to the measured mass of the Higgs boson that was discovered at the LHC. The colored filled areas correspond to the excluded regions in $m_A$ and $\tan \beta$. In the Fig. 1 on the right in addition to the direct exclusion contours, the constraint that is obtained from the compatibility of the scenario with the couplings of the SM Higgs boson when interpreted as the $h$ is also displayed.

The couplings of the Higgs bosons to down-type fermions are enhanced for large $\tan \beta$, which results in a large production rate for the Higgs bosons with couplings to $\tau$ leptons and $b$-quarks. Therefore, direct searches for the heavy $H/A$ bosons decaying to $\tau$ leptons$^{12,13}$ and $b$-quarks$^{14}$ are appropriate approaches to high $\tan \beta$ region, while searches for Higgs bosons coupled to the up-type fermions explore the low $\tan \beta$ region. Since almost all Higgs boson measurements so far indicate the obtained parameters are consistent with the SM, that is, low $\tan \beta$ region is preferred, the number of analyses searching in the low $\tan \beta$ region has rapidly grown during Run 2 of the LHC. The charged Higgs boson $H^\pm$ with couplings to the $t$- and $b$-quark$^{15,16}$ is one channel which can explore the low $\tan \beta$ region. Searches for the decays of a heavy Higgs boson, $A$, to a light Higgs boson, $h$, and the SM weak boson $Z$ also provides indirect constraints. Analyses may also search for interference effects in the top-pair production process caused by the decay $H \rightarrow tt$ in high mass region$^{19}$. Finally, searches for charged Higgs bosons decaying to $\tau \nu$ and $tb$ provide global constraints ranging from the low to high $m_A$ regions.

In the following, only the selected physics analyses, $H/A \rightarrow \tau \tau$ and $H^\pm \rightarrow \tau \nu/tb$, which represent the most powerful channels in constraining the MSSM parameter space of $\tan \beta$ as a function of Higgs mass, are presented as benchmark searches.

### 2.2. Search for $H/A \rightarrow \tau \tau$

The analysis$^{12}$ is performed with 36.1 fb$^{-1}$ data at a centre-of-mass energy of 13 TeV collected with the ATLAS detector in 2015 and 2016. Figure 2 shows the typical lowest order Feynman diagrams for gluon-gluon fusion production (a), $b$-quark associated production with 4 flavor scheme (b) and 5 flavor scheme (c) of a neutral MSSM Higgs boson. The $b$-quark associated production mode is enhanced in the high $\tan \beta$ region. The search is therefore split according to the presence or absence of jets originating from $b$-quarks in the final state as well as the decay mode of the
Fig. 1. 95% CL exclusion contours, in the MSSM $m_A^{mod+}$ scenario (with $\mu=+200$ GeV), which is obtained by selected CMS analyses that have been performed with the LHC Run 1 dataset. The colored filled areas correspond to the excluded regions in $m_A$ and $\tan \beta$. The colored (slightly darker shaded) lines with indicated hatches to the regions that were expected to be excluded, based on the null-hypothesis assumption of a SM-like Higgs sector. In the figure on the right in addition to the direct exclusion contours, the constraint is also displayed that is obtained from the compatibility of the scenario with the couplings of the SM Higgs boson when interpreted as the $h$.

The final discriminant is $m_T^{tot}$, defined as

$$m_T^{tot} = \sqrt{\left(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss}\right)^2 - \left(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss}\right)^2}$$

where $p_T^{\tau_1/2}$ is the transverse momentum of the visible component of the $\tau$ decay products, $E_T^{miss}$ is the opposite direction of the transverse vector sum of all detected particles from the collision events, which represents the direction in transverse plane of the sum of the momenta of all neutrinos produced in $\tau$ decays. The dominant backgrounds are $W+\text{jets}$, $t\bar{t}$ and multi-jet processes where a jet is mis-identified as a hadronically decaying $\tau$-lepton. They are estimated from data. The dominant experimental uncertainty is associated with the modeling of high-$p_T$ hadronic $\tau$ decays which cannot be verified in data due to the lack of a sufficiently large control sample of $Z \to \tau\tau$ events. To address this, hadronic $\tau$ identification is studied in a sample of high-$p_T$ di-jet events, where the modeling of the detector response to such events is assumed to be the same as for high-$p_T$ hadronic $\tau$ events. An additional uncertainty of $\sim 20\%$ is assigned for high-$p_T$ hadronic $\tau$ events.

Figure 3 presents the $m_T^{tot}$ distribution in the $b$-tagged category (a) and the observed and expected 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the MSSM $m_A^{mod+}$ scenario (b). Comparing with Fig. 1, the exclusion limit is largely expanded in Run 2, mostly owing to the increased production cross section from $\nu\tau \to \pm H$.
8 TeV to 13 TeV. The region \( \tan \beta > 25 \) at \( m_A = 1 \) TeV is excluded. Model independent limits of \( \sigma \times \text{Br}(\phi \to \tau\tau) = 0.0058 - 0.85 \text{ pb} \) for gluon-gluon fusion and 0.0041 - 0.95 pb for \( b \)-quark associated processes in the mass range of 0.2-2.25 TeV are also obtained.

(a) gluon-gluon fusion (b) 4FS associated production (c) 5FS associated production

Fig. 2. Lowest order Feynman diagrams for gluon-gluon fusion production (a), \( b \)-quark associated production with 4 flavor scheme (b) and 5 flavor scheme (c) of a neutral MSSM Higgs boson.

\[ \phi = h/A/H \]

2.3. Search for \( H^\pm \to \tau\nu \) and \( tb \)

The main production mode of the charged Higgs boson at high mass (\( m_{H^\pm} > m_{\text{top}} (=172.5 \text{ GeV}) \)) is through the associated production of \( tbH \), as shown in Fig. 4. The \( H^\pm \) predominantly decays into \( \tau\nu \) or \( tb \) final state depending on \( m_{H^\pm} \) and \( \tan \beta \). In both case, the \( t \)- and \( b \)-quarks in the final state are associated with the \( H^\pm \), so that the analyses\(^{15,16,20}\) require at least one \( b \)-quark jet and high jet...
multiplicity. The dominant background is from the $t\bar{t}$+jets process as well as a jet faking the hadronic $\tau$-lepton from $W$+jets and multi-jet events. For fully hadronic events without containing $e$ or $\mu$ in the final state, the $E_T^{\text{miss}}$ trigger is used in combination with the hadronic $\tau$ trigger. The final discriminant is the distribution of the transverse mass between hadronic $\tau$ and missing transverse energy for the $H \to \tau\nu$ mode,

$$m_T = \sqrt{2 \cdot p_T^{\tau} |E_T^{\text{miss}}| (1 - \cos \Delta \phi(p_T^{\tau}, E_T^{\text{miss}})).}$$

On the other hand, for the $H \to tb$ decay mode, the reconstruction of the invariant mass of the final state is non-trivial and the analysis relies instead on a fit to a multivariate discriminant. The dominant experimental uncertainties are the jet energy scale uncertainty and $E_T^{\text{miss}}$ as well as the modeling of the hadronic $\tau$ events. For the multivariate analysis, the theory uncertainty is large, at around 50%, due to the uncertainty in estimating the number of additional jets produced in $t\bar{t}$ events.

Figure 5 shows the observed and expected 95% CL upper limits on $\tan \beta$ as a function of $m_{H^\pm}$ of the $H^\pm \to \tau\nu$ (a) and $H^\pm \to tb$ (b) analyses, respectively. The $H^\pm \to \tau\nu$ analysis is sensitive to the high $\tan \beta$ region while the $H^\pm \to tb$ is sensitive to the low $\tan \beta$ region. These analyses extend the constraints on the MSSM parameter space using Run 2 data.

3. The Higgs boson as a probe of new physics

3.1. Overview

The observation of the Higgs boson opens up the possibility of its use as a tool to probe new physics. Many theories beyond the SM predict new particles decaying into Higgs bosons. If such a particle has a mass larger than that of the Higgs boson (125 GeV), the decay products can become highly boosted leading a collimated shower of final state particles. The SM Higgs boson decays into a $b$-quark pair around 60% of the time. In this case, the two $b$-quark jets are reconstructed as a merged single jet object with a mass close to the Higgs boson mass. Other decay
Fig. 5. The observed and expected 95% CL upper limits on $\tan \beta$ as a function of $m_{H^\pm}$ of the $H^\pm \to \tau \nu$ (a) and $H^\pm \to t\bar{b}$ (b) analyses, respectively.

3.2. Search for $X \to Vh$

A new particle $X$ can decay into a Higgs boson, $h$, and SM $W$ or $Z$ boson, where the $h$ is required to decay to a $b$-quark pair and the $W$ or $Z$ bosons are required to decay leptonically or hadronically into $\ell \ell, \ell \nu, \nu \nu, jj^{24}$. The resonance mass $m_{Vh}$ is well-reconstructed from the 4-vectors from the measured objects in both the merged and resolved categories. When a neutrino is in the final state, the $m^{\text{tot}}_T$ variable is used instead. Figure 6 shows the $m_{Vh}$ distribution in the resolved (a) and merged (b) categories for a particular analysis channel with leptons and $b$-quark jets in the final state. The signal events with $m_X = 1.5$ TeV are also overlaid as 10 times of the predicted cross section for a benchmark model. The resolution for the $m^{\text{tot}}_T$ is about 30-40% at $m_X = 1.5$ TeV.

The 95% CL upper limits on the production cross section of the $A$ multiplied by its branching ratio into the $Zh$ final state and the branching ratio of $h \to b\bar{b}$ are obtained as a function of resonance mass in Fig. 7 for gluon-fusion (a) and $b$-quark
associated (b) production processes, respectively. The data are also interpreted in terms of limits at 95% CL on the 2HDM parameters of $\tan\beta$ and $\cos(\beta - \alpha)$ for several benchmark models.

![Graph A](image1.png)

(a) Resolved category

(b) Merged category

Fig. 6. The resonance mass $m_{Vh}$ in the resolved (a) and merged (b) categories for a particular analysis channel with leptons and $b$-quark jets in the final state. The signal events with $m_X=1.5$ TeV are also overlaid as 10 times of the predicted cross section for a benchmark model.

![Graph B](image2.png)

(a) gluon-fusion production

(b) $b$-quark associated production

Fig. 7. Upper limits at the 95% CL on the product of the production cross-section for $pp \rightarrow A$ and the branching ratios for $A \rightarrow Zh$ and $h \rightarrow b\bar{b}$. The possible signal components of the data are interpreted assuming (a) pure gluon-fusion production, and (b) pure $b$-quark associated production.
3.3. Search for $X \to hh$

Given the unique topology of the $h$ decay, backgrounds can be well suppressed when a new resonance decays into $hh$. The considered decay modes are $b\bar{b}b\bar{b}$, $b\ell\nu\ell\nu$, and $b\gamma\gamma$. Figure 8 (a) shows the di-jet invariant mass distribution $m_{jj}^{\text{red}}$ in the $b\bar{b}b\bar{b}$ channel, where the invariant mass of two small-jets inside the merged object (jet) is required to be $105 < m_{\text{small}}^{jj} < 135$ GeV. The signal cross section is assumed to be 20 pb for all the mass hypotheses at 1400, 1800 and 2500 GeV for illustration purposes. Only a very small background contribution is present in the large resonance mass region ($m_X > 1.5$ TeV). Figure 8 (b) presents the observed and expected 95% CL upper limits on the product of cross section and the branching ratio $\sigma(gg \to X) \times B(X \to hh)$ obtained by different analyses assuming spin-0 hypothesis in an extended mass range beyond 1 TeV.

4. Anomalous Higgs couplings and rare decays

4.1. Overview

Unlike the case of the SM gauge bosons, the fermion couplings in the Higgs sector is not universal across fermion flavors. Although the Yukawa couplings are predicted to be proportional to the mass of the fermion, the detailed structure of the Yukawa couplings has not yet been determined. This inspires the possibility of flavor violating decays through off-diagonal elements of the Yukawa mass matrix or rare decays.
involving new particles beyond the SM.

In this section, searches for rare and exotic decays of the Higgs boson are discussed.

4.2. Search for flavor-violating decay modes

The flavor-changing neutral current process is strictly forbidden in the framework of the SM, however searches for such processes in the decay of the Higgs boson represent important tests of flavor violation in the Higgs sector. High energy colliders provide many opportunities to study the Yukawa couplings of the third generation fermions. A search for lepton flavor violating decays of the 125 GeV Higgs boson in the $\mu\tau$ and $e\tau$ decay mode, $H \rightarrow \mu\tau, e\tau$, has been carried out. No significant excess over the SM background expectation is observed. The observed (expected) upper limits on the branching ratio of the Higgs boson are set to be $\text{Br}(H \rightarrow \mu\tau) < 0.25\%(0.25)\%$ and $\text{Br}(H \rightarrow e\tau) < 0.61\%(0.37)\%$ at 95% CL. Constraints on the flavor violating Yukawa couplings, $|y_{\mu\tau}|, |y_{\tau\mu}|$, are obtained from these results as shown in Fig. 9 (a) for $\mu\tau$ mode. The flavor diagonal Yukawa couplings are approximated by their SM values. The green (yellow) band indicates the range that is expected to contain 68% (95%) of all observed limit excursions from the expected limit. The shaded regions are constraints derived from null searches for $\tau \rightarrow 3\mu$ (dark green) and $\tau \rightarrow \mu\gamma$ (lighter green). The purple diagonal line is the theoretical naturalness limit $y_{ij}y_{ji} \leq m_i m_j / v^2$, where $v$ is the vacuum expectation value.

Flavor violation in the quark sector is also tested using the $t$-quark decay, $t \rightarrow qH$, where $q$ is an up-type quark, $c$ or $u$. The $H \rightarrow \gamma\gamma$ decay mode is used since it offers optimal sensitivity. The SM prediction is $\text{Br}_{\text{SM}}(t \rightarrow qH) = 3 \times 10^{-15}$. Figure 9 (b) shows the invariant mass distribution of the two selected photons and a jet from the decay of the $t$-quark. The signal distributions are normalized assuming a branching ratio of 5%. The limit is obtained to be $\text{Br}(t \rightarrow qH) < 2.4 \times 10^{-3}$ at 95% CL.

4.3. Search for exclusive decay mode

The Higgs boson can also decay into hadrons exclusively through loop diagrams as illustrated in Fig. 10. According to the SM, the branching ratios for the exclusive decays of the Higgs boson to a meson and photon, $J/\psi\gamma, \phi\gamma$ and $\rho\gamma$, are $2.95 \times 10^{-6}$, $2.31 \times 10^{-6}$, and $1.68 \times 10^{-7}$, respectively. The mesons are experimentally identified using the decay modes of $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$ and $\rho \rightarrow \pi^+\pi^-$. Figure 11 shows the invariant masses $m_{K^+K^-}$ (a) and $m_{K^+K^-\gamma}$ (b) for the selected $\phi\gamma$ candidates. The reconstructed mass resolution of $m_{K^+K^-}$ is about 4 MeV. The $m_{K^+K^-}$ distribution exhibits a clear phi mass peak over the combinatoric
Fig. 9. (a) Constraints on the flavor violating Yukawa couplings, $|y_{\mu\tau}|$ and $|y_{\tau\mu}|$. The expected (red solid line) and observed (black solid line) limits are derived from the limit on $\text{Br}(H \rightarrow \mu\tau)$. The flavor diagonal Yukawa couplings are approximated by their SM values. The green (yellow) band indicates the range that is expected to contain 68% (95%) of all observed limit excursions from the expected limit. The shaded regions are derived constraints from null searches for $\tau \rightarrow 3\mu$ (dark green) and $\tau \rightarrow \mu\gamma$ (lighter green). The purple diagonal line is the theoretical naturalness limit $y_{ij}y_{ji} \leq m_i m_j/v^2$. (b) Invariant mass distribution of the two selected photons and a jet from $t$-quark. The signal distributions are normalized assuming a branching ratio of 5%.

background. Combining with the $\gamma$, the Higgs (and $Z$) boson mass is reconstructed with high precision. No significant excess of events is observed above the background, in agreement with the SM expectations. Upper limits at 95% CL on the branching ratios of the exclusive radiative Higgs boson decays to mesons are set as $\text{Br}(H \rightarrow \phi\gamma) < 4.8 \times 10^{-4}$ and $\text{Br}(H \rightarrow \rho\gamma) < 8.8 \times 10^{-4}$, respectively. The current limits on the branching fractions for such decays are two orders of magnitude higher than the SM prediction. However, assuming a dataset of 3000 fb$^{-1}$ at $\sqrt{s} = 14$ TeV, a limit of $\text{Br}(H \rightarrow J/\psi\gamma) = 5.5 \times 10^{-7}$ is expected.

(a) Direct contribution (b) Indirect contribution

Fig. 10. Feynman diagrams for direct (a) and indirect (b) contributions in the exclusive decay of $H \rightarrow V\gamma$. The crossed circle denotes the off-shell $H \rightarrow \gamma\gamma^*$ and $H \rightarrow \gamma Z^*$ amplitudes, which in the SM arise first at one-loop order.
4.4. Search for exotic decay mode

Several theories beyond the SM predict the existence of a dark sector that is weakly coupled with the SM particles. Due to the weakness of the coupling, the particles of the dark sector can have non-negligible lifetime which could decay beyond the beam-pipe or even outside the detector. The CMS experiment have searched for long lived particles which could decay inside the tracking detector volume ($c\tau \leq 100$ mm) \cite{36}, while the ATLAS experiment searches for decays within the region between the beam-pipe and the muon detectors ($3.8 \leq c\tau \leq 600$ mm) \cite{37}. Limits on models predicting Higgs boson decays to neutral long-lived particles (dark photons $\gamma_D$) are derived as a function of the decay length, $c\tau_{\gamma_D}$ as shown in Fig. 12.

5. Summary and prospects

In this article, three different topics are discussed within the context of the latest searches for Higgs boson production and decays beyond that predicted in the SM.

Searches for MSSM Higgs bosons explore both the low and high tan $\beta$ regions in term of the mass of $H/A$ boson. With current dataset of 36 fb$^{-1}$, an MSSM Higgs bosons are excluded up to 1 TeV at tan $\beta \sim 20$ with $m_{h_{\text{mod+}}}^+$ scenario. The HL-LHC will be sensitive to the region up to $m_{H/A} = 400$ GeV for the whole parameter space, but the region around tan $\beta \sim 10$ at high mass region is not excluded, and may require a future linear or circular collider to investigate.

The Higgs boson can be used as a tool to probe a new physics, where a new heavy particle may decay into Higgs bosons. When the mass of a particle is sufficiently larger than that of the 125 GeV Higgs boson, its decay products can be largely boosted and reconstructed as single object. By resolving the individual decay products or reconstructing them as a merged object, the good rejection of background
processes can be achieved, leading to almost model independent exclusion limits which extend up to 1 TeV.

The search for anomalous Higgs couplings and rare decays also represent important tests of the nature of the Higgs boson, since the detailed structure of the Yukawa coupling is not yet well established. Searches for flavor violating Higgs boson decays have been performed by the ATLAS and CMS experiments and already lead to very stringent limits. The exclusive radiative decays of the Higgs boson to light mesons are also searched for. To date, the limits on these decays are far from the SM prediction, but in HL-LHC era, such decays may offer the possibility to study the Yukawa couplings of the first and second generation quarks. Searches for exotic Higgs boson decay modes have also been performed, including decays to dark matter candidates. The results from the collider experiments are very complementary to the programme of underground direct detection experiments.

In conclusion, it should be emphasized that both the ATLAS and CMS experiments are very active in the area of Higgs boson studies, both in terms of production and coupling measurements and searches for phenomena beyond the SM.

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