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Searches for non-SM heavy Higgses at a 100 TeV *pp* collider

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In this write-up, we summarize the production of non-SM Higgses in the Type II Two Higgs Doublet Model at a 100 TeV *pp* collider, as well as their decays. We present the reach for $pp \to bbH^0/A \to bbtt$, $bb\tau\tau$ as well as $pp \to tbH^\pm \to tbtb$, $tb\tau\nu$ at the 100 TeV *pp* collider and outline the possible search channels via Higgs exotic decays. We point out that a combination of these conventional channels potentially yields full coverage for $\tan\beta$ and pushes the exclusion limits from the $\mathcal{O}(1)$ TeV at the LHC to the $\mathcal{O}(10)$ TeV at a 100 TeV *pp* collider, whereas the exotic decays of a heavy Higgs into two light Higgses or one light Higgs plus one SM gauge boson provide alternative discovery channels.

1. Introduction

The discovery of the Standard Model (SM)-like Higgs boson at the Large Hadron Collider (LHC) is one of the greatest triumphs in particle physics.[1–4] Stabilization of the observed Higgs mass of 126 GeV, however, provides strong motivation of physics beyond the SM. In addition, there are puzzles facing particle physics which can not be explained in the SM, for example, the particle candidate for dark matter or the generation of neutrino mass. Solutions to those problems typically lead to models with an extended Higgs sector. Well known examples include the Minimal Sypersymmetric Standard Model (MSSM),[5–7] Next-to-Minimal Supersymmetric Standard Model (NMSSM),[8,9] and Two Higgs Doublet Models (2HDM),[10–13] etc. In addition to a SM-like Higgs boson in these models, the low energy spectrum typically includes extra neutral CP-even and CP-odd Higgses, as well as charged ones.

The discovery of the non-SM Higgses would provide unambiguous evidence for new physics beyond the SM. The search for these extra Higgses, however, is typically challenging at the LHC. For the extra neutral Higgses, most of the current searches at the LHC focus on the conventional Higgs search channels of WW, ZZ, $\gamma\gamma$, $\tau\tau$ and bb channel.[14–20] The production of the extra Higgses is usually suppressed compared to that of the SM Higgs, either due to its larger mass or its suppressed couplings to the SM particles. The decay of the heavy neutral Higgses to the WW and ZZ is absent for the CP-odd Higgs, and could be highly suppressed for the non-SM like CP-even Higgs. The decay modes of $\tau\tau$ or bb suffer from either suppressed signal or large SM backgrounds, and are therefore only relevant for regions of the parameter space with an enhanced bb or $\tau\tau$ coupling. The search for the charged Higgs at the LHC is even more difficult. For $m_{H^\pm} > m_t$, the cross section for the dominant production channel of $tbH^\pm$ is typically small. The dominant decay mode $H^\pm \to tb$ is hard to identify given the large tt and $ttbb$ background, while the subdominant decay of $H^\pm \to \tau\nu$ has suppressed branching fraction. In the MSSM, even at the end of the LHC running, there is a "wedge region" in the $m_A - \tan\beta$ plane for $\tan\beta \sim 7$ and $m_A \gtrsim 300$ GeV in which only the SM-like Higgs can be covered at the LHC. Similarly, the reach for the non-SM Higgses is limited in models with an extended Higgs sector.

In addition to their decays to the SM particles, non-SM Higgses can decay via exotic modes, i.e., heavier Higgs decays into two light Higgses, or one light Higgs plus one SM gauge boson. Examples include $H^0 \to H^+H^-$, $H^0 \to AA$, $H^0 \to AZ$, $A \to H^\pm W^\mp$, and $H^\pm \to AW$, etc. These channels typically dominate once they are kinematically open. The current limits on the beyond the SM Higgs searches are therefore weakened, given the suppressed decay branching fractions into SM final states. Furthermore, these additional decay modes could provide new search channels for the non-SM Higgs, complementary to the conventional search modes. Recent study on exotic Higgs decays can be found in Refs. 21–32. Latest searches from ATLAS and CMS have shown certain sensitivity in $A/H \to HZ/AZ$ channel.[33–36]

A 100 TeV pp collider offers great opportunity for probing non-SM Higgses. The production cross sections can be enhanced by about a factor of 30–50 for gluon fusion and bb associated production, and about a factor of 90 for the charged Higgs for Higgs mass of about 500 GeV, and even more for heavier Higgses. In the new mass domain accessible to the machine, the decays of $H^0/A \to tt$ and $H^\pm \to tb$ are easily allowed kinematically. In the former case, the branching fraction becomes sizable for intermediate $\tan\beta$ and dominant for low $\tan\beta$. The channels of $pp \to ttH^0/A$, bbH^0/A with $H^0/A \to \tau\tau$, bb, tt potentially provide full coverage of the $\tan\beta$ domain. In the latter case, $H^\pm \to tb$ becomes dominant over the whole $\tan\beta$ domain if exotic decay modes are not present. New kinematics of these signal events at a 100 TeV pp collider also bring new handles. For example, the top quark appearing in the decay could be highly boosted. Looking into its internal structure (though a finer granularity of both ECAL and HCAL is typically required) or requiring an extremely hard lepton in top decays can efficiently suppress the relevant backgrounds. In addition, exotic Higgs decays can provide alternative search channels at the 100 TeV pp collider when the conventional decays are suppressed.

In this paper, we summarize the production and decay of heavy non-SM Higgses at a 100 TeV pp collider, and highlight the main search channels for H^0, A^0 and $H^\pm$ and its reach potential. Note that while it is a viable possibility for the light CP-even Higgs h^0 being non-SM like, and the heavy CP-even Higgs H^0 being SM-like (the so-called H^0-125 case with $\sin(\beta-\alpha) \sim 0$),[37] in this paper we focus on the conventional case of h^0 being the SM-like Higgs of 125 GeV with a heavy non-SM H^0. For simplicity, the results presented in the following sections are for the alignment limit of $\cos(\beta-\alpha) = 0$, even though regions of $\cos(\beta-\alpha)$ away from zero can still be accommodated by the current experimental Higgs search results.[37]

The paper is organized as follows. In Sec. 2, we briefly introduce the Type II 2HDM with its particle content and relevant couplings. In Sec. 3, we present the dominant production cross sections for H^0, A^0 and $H^\pm$ at the 100 TeV pp collider. In Sec. 4, we discuss the decay modes for heavy Higgses. In Sec. 5, we present the reach for heavy Higgses at a 100 TeV pp collider using the conventional decay modes into SM fermions. In Sec. 6, we discuss the prospect for heavy Higgs discovery via exotic decay modes to light Higgses or one light Higgs plus a SM gauge boson. In Sec. 7, we conclude.

2. Type II 2HDM

In the 2HDM,[a] we introduce two SU(2) doublets Φ_i, $i = 1, 2$:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}, \tag{1}$$

where v_1 and v_2 are the vacuum expectation values of the neutral components which satisfy the relation: $v = \sqrt{v_1^2 + v_2^2} = 246$ GeV after electroweak symmetry breaking. Assuming a discrete $\mathcal{Z}_2$ symmetry imposed on the Lagrangian, we are left with six free parameters, which can be chosen as four Higgs masses (m_h, m_{H^0}, m_A, $m_{H^\pm}$), the mixing angle α between the two CP-even Higgses, and the ratio of the two vacuum expectation values, $\tan\beta = v_2/v_1$. In the case in which a soft breaking of the $\mathcal{Z}_2$ symmetry is allowed, there is an additional parameter m_{12}^2.

[a] For more details about the 2HDM, see Ref. 10.

The mass eigenstates contain a pair of CP-even Higgses: h^0, H^0, one CP-odd Higgs A and a pair of charged Higgses $H^\pm$:

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \qquad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \,, \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \,. \end{aligned} \tag{2}$$

Two types of couplings that are of particular interest are the couplings of a Higgs to two gauge bosons, as well as the couplings of a SM gauge boson to a pair of Higgses. Both are determined by the gauge coupling structure and the mixing angles. The H^0VV and h^0VV couplings are:[38]

$$g_{H^0VV} = \frac{m_V^2}{v} \cos(\beta - \alpha) \,, \quad g_{h^0VV} = \frac{m_V^2}{v} \sin(\beta - \alpha) \,. \tag{3}$$

The couplings for a SM gauge boson with a pair of Higgses are:[38]

$$\begin{aligned} g_{AH^0Z} &= -\frac{g \sin(\beta - \alpha)}{2 \cos\theta_w} (p_{H^0} - p_A)^\mu \,, \\ g_{Ah^0Z} &= \frac{g \cos(\beta - \alpha)}{2 \cos\theta_w} (p_{h^0} - p_A)^\mu \,, \end{aligned} \tag{4}$$

$$\begin{aligned} g_{H^\pm H^0 W^\mp} &= \frac{g \sin(\beta - \alpha)}{2} (p_{H^0} - p_{H^\pm})^\mu \,, \\ g_{H^\pm h^0 W^\mp} &= \frac{g \cos(\beta - \alpha)}{2} (p_{h^0} - p_{H^\pm})^\mu \,, \end{aligned} \tag{5}$$

$$g_{H^\pm A W^\mp} = \frac{g}{2} (p_A - p_{H^\pm})^\mu \,, \tag{6}$$

with g being the SU(2) coupling, θ_w being the Weinberg angle and p_μ being the incoming momentum of the corresponding particle. Note that A and $H^\pm$ always couple to the non-SM-like Higgs more strongly, while the $H^\pm AW^\mp$ coupling is independent of the mixing parameters.

In the Type II 2HDM, one Higgs doublet Φ_1 provides masses for the down-type quarks and charged leptons, while the other Higgs doublet Φ_2 provides masses for the up-type quarks. The couplings of the CP-even Higgses h^0, H^0 and the CP-odd Higgs A to the SM gauge bosons and fermions are scaled by a factor ξ relative to the SM value, as presented in Table 1.

Table 1. The multiplicative factors ξ by which the couplings of the CP-even Higgses and the CP-odd Higgs to the gauge bosons and fermions scale with respect to the SM value. The superscripts u, d, l and VV refer to the up-type quarks, down-type quarks, leptons, and WW/ZZ respectively.

$\xi_{h^0}^{VV}$	$\sin(\beta - \alpha)$	$\xi_{H^0}^{VV}$	$\cos(\beta - \alpha)$	ξ_A^{VV}	0
$\xi_{h^0}^{u}$	$\cos\alpha / \sin\beta$	$\xi_{H^0}^{u}$	$\sin\alpha / \sin\beta$	ξ_A^{u}	$\cot\beta$
$\xi_{h^0}^{d,l}$	$-\sin\alpha / \cos\beta$	$\xi_{H^0}^{d,l}$	$\cos\alpha / \cos\beta$	$\xi_A^{d,l}$	$\tan\beta$

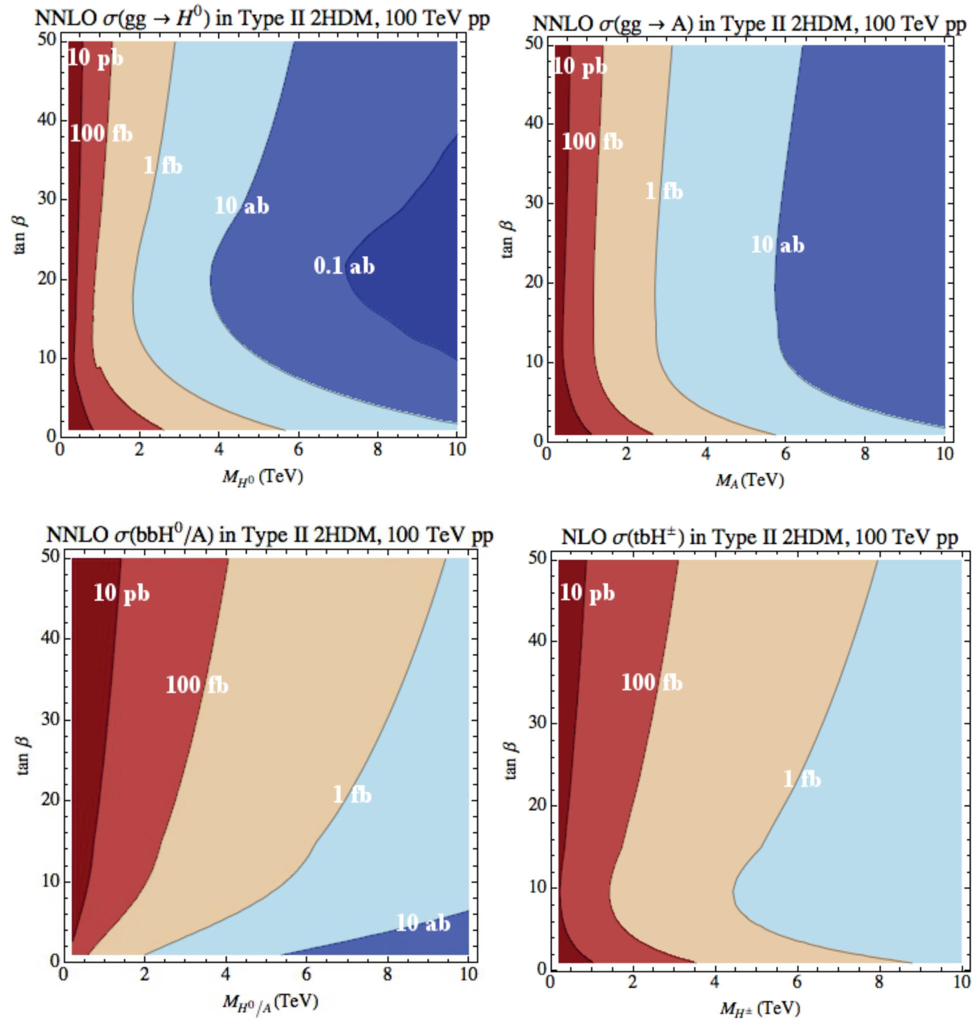

Fig. 1. Dominant production cross sections for non-SM like Higgses in the type II 2HDM at the 100 TeV pp collider: NNLO cross section for $gg \to H^0$ or A (top left and top right panel, calculated using HIGLU[39] with the NNPDF2.3 parton distribution functions[40]), NNLO cross section for bottom-associated production bbH^0/A (lower left panel, calculated using SusHi.[41–43] bbH^0 and bbA cross sections are the same in the alignment limit), NLO cross section for $tbH^\pm$ (lower right panel, calculated in Prospino[44,45]).

In addition, the $H^\pm tb$ coupling is

$$g_{H^\pm tb} = \frac{g}{2\sqrt{2}m_W}\left[(m_b \tan\beta + m_t \cot\beta) \pm (m_b \tan\beta - m_t \cot\beta)\gamma_5\right], \tag{7}$$

which is enhanced at both small and large $\tan\beta$. The $H^\pm \tau\nu$ has similar enhancement at large $\tan\beta$ as well.

3. Production Cross Sections

The dominant production processes for the neutral Higgses are gluon fusion $gg \to H^0/A$ with dominant top and bottom (for large $\tan\beta$) loops, as well as bbH^0/A associated production. ttH^0/A associated production could be important as well.[46] The dominant production process for the charged Higgses is $tbH^\pm$ associated production. Production cross sections at 100 TeV pp collider for A^0, H^0 and $H^\pm$ are shown in Fig. 1. For H^0, we have assumed the alignment limit of $\cos(\beta-\alpha)=0$ in which the light CP-even Higgs is the SM-like one, and the couplings of the heavy CP-even Higgs H^0 to the SM particles is the same in amplitude as that of the CP-odd Higgs A, but differs in the relative sign of the couplings to the up type quarks comparing to that of the down type quarks. For charged Higgs production, corrections from resumming top logarithms may play a role at 100 TeV,[47,48] but are not expected to significantly affect the general features of the results.[48,49] For neutral Higgses, gluon fusion production and ttH^0/A dominates at low $\tan\beta$ [46] while bbH^0/A associated production dominates at large $\tan\beta$. The $tbH^\pm$ production cross section gets enhanced at both small and large $\tan\beta$.

Comparing to the 14 TeV LHC, the production rates can be enhanced by about a factor of 30–50 for gluon fusion and bb associated production, and about a factor of 90 for the charged Higgs for Higgs mass if about 500 GeV, and even more for heavier Higgses, resulting in great discovery potential for heavy Higgses at a 100 TeV pp colliders.

4. Heavy Higgs Decays

Conventional decay modes for heavy Higgses are $H^0 \to tt/bb/\tau\tau/WW/ZZ/\gamma\gamma$, $A \to tt/bb/\tau\tau$ and $H^\pm \to tb/\tau\nu/cs$. Note that for h^0 being SM-like, H^0 decays to WW and ZZ are highly suppressed given that $\cos(\beta-\alpha)\sim 0$ is preferred. The branching fractions for a heavy H^0, A, and $H^\pm$ are shown in the dashed curves in Fig. 2, assuming exotic decay modes are kinematically forbidden.

Five main exotic decay categories for Higgses of the Type II 2HDM are shown in Table 2. Once these decay modes are kinematically open, they typically dominate over the conventional decay channels, as shown in Fig. 2 for H^0 (left panel),

Table 2. Exotic Decay modes for Higgses in the 2HDM. H in column two refers to any of the neutral Higgs h^0, H^0 or A.

	Decay	Final states	Channels
Neutral Higgs H^0, A	HH type	$(bb/\tau\tau/WW/ZZ/\gamma\gamma)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$	$H^0 \to AA, \ldots$
	HZ type	$(\ell\ell/qq/\nu\nu)(bb/\tau\tau/WW/ZZ/\gamma\gamma)$	$H^0 \to AZ,\ A \to H^0 Z, \ldots$
	H^+H^- type	$(tb/\tau\nu/cs)(tb/\tau\nu/cs)$	$H^0 \to H^+H^-, \ldots$
	$H^\pm W^\mp$ type	$(\ell\nu/qq')(tb/\tau\nu/cs)$	$H^0/A \to H^\pm W^\mp, \ldots$
Charged Higgs	$HW^\pm$ type	$(\ell\nu/qq')(bb/\tau\tau/WW/ZZ/\gamma\gamma)$	$H^\pm \to H^0 W,\ AW, \ldots$

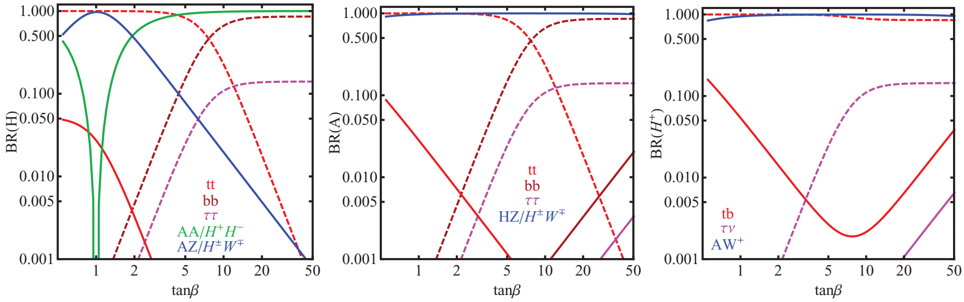

Fig. 2. Branching fractions for H^0 (left panel), A (middle panel) and $H^\pm$ (right panel). The parent and daughter Higgs masses are chosen to be 2 TeV and 800 GeV, respectively. Note that in the $H^0(A)$ decay, we have assumed either light A (H^0) *or* light $H^\pm$, but not both. Dashed curves are the branching fractions when exotic decay modes are kinematically forbidden. All decay branching fractions are calculated using the program 2HDMC.[50]

Table 3. Main conventional search channels for non-SM Higgses to cover various $\tan\beta$ regions[51] at a 100 TeV *pp* collider.

	$\tan\beta$	Channels
Neutral Higgs H^0, A	High	$pp \to bbH^0/A \to bb\tau\tau, bbbb$
	Intermediate	$pp \to bbH^0/A \to bbtt$
	Low	$pp \to H^0/A \to tt$, $pp \to ttH^0/A \to tttt$
Charged Higgs $H^\pm$	High	$pp \to tbH^\pm \to tbtb, tb\tau\nu_\tau$
	Low	$pp \to tbH^\pm \to tbtb$

A (middle panels), and $H^\pm$ (right panel). Note that in the alignment limit of $\cos(\beta - \alpha) = 0$, the branching fraction of $H^0 \to h^0h^0$ is zero. The branching fractions for heavy A are similar to those of H^0, except that the decay modes of H^0H^0 and H^+H^- are absent.

Note that the current experimental searches for the non-SM Higgs always assume the absence of exotic decay modes. Once there are light Higgs states such that these exotic modes are kinematically open, the current search bounds can be greatly relaxed.[22,24,26]

5. Conventional Search Channels

At a 100 TeV *pp* collider, new mass domains for both neutral and charged Higgs bosons become accessible, given the enhanced production cross sections and the dominance of decays to final states with top quarks (at small $\tan\beta$ for neutral Higgses and at both small and large $\tan\beta$ for charged Higgses), as well as novel kinematic features of the decay products. Combining production processes and decay channels, the main search channels to cover various $\tan\beta$ regions are summarized in Table 3.

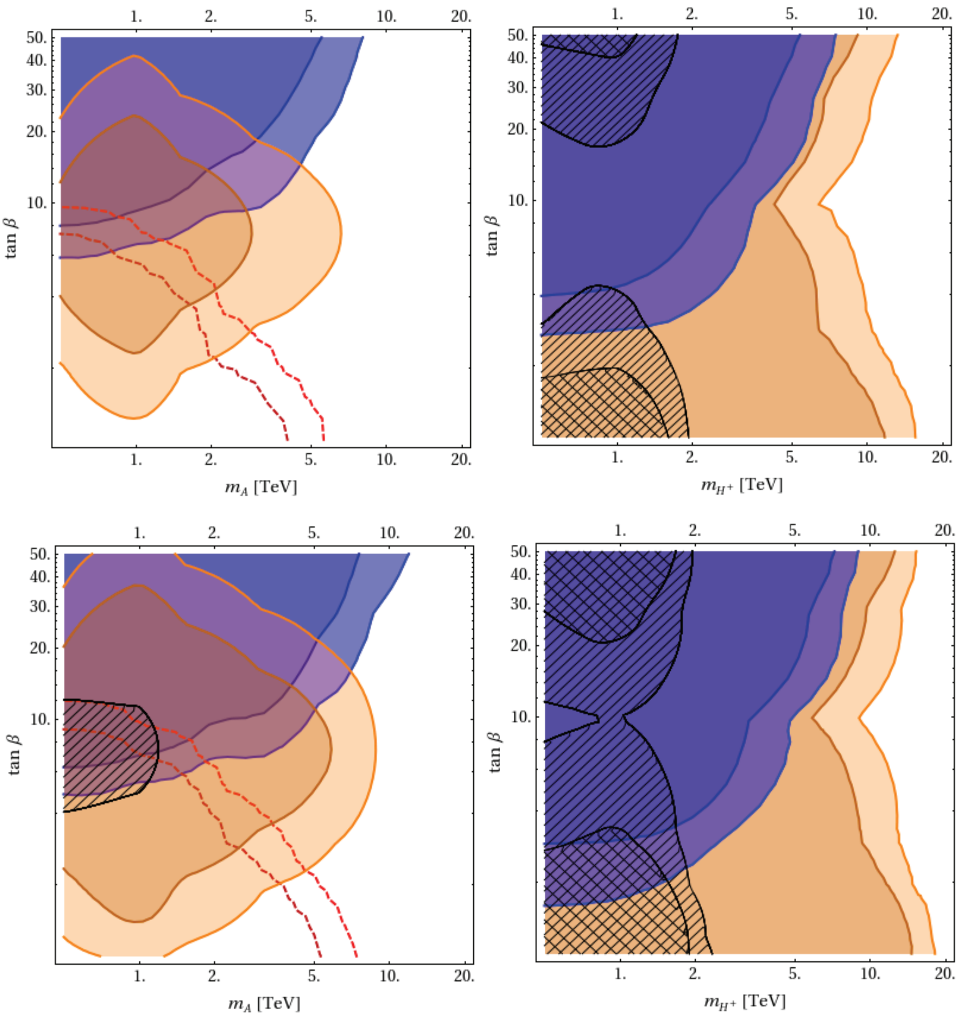

Fig. 3. Discovery reaches and exclusion limits for the MSSM Higgs bosons at a 100 TeV pp collider.[51] The two regions with the same color and different opacities are excluded by assuming a luminosity of 3 ab^{-1}, and 30 ab^{-1}, respectively. Left: neutral Higgs bosons (H^0/A). The blue and orange regions are excluded by the channels $pp \to bbH^0/A \to bb\tau_h\tau_l$, $pp \to bbH^0/A \to bbt_ht_l$ and $pp \to H^0/A \to t_ht_l$, respectively. Right: charged Higgs bosons ($H^{\pm}$). The blue and orange regions are excluded by the channels $pp \to tbH^{\pm} \to tb\tau_h\nu_\tau$ and $pp \to tbH^{\pm} \to t_hbt_lb$, respectively. The cross-hatched and diagonally hatched regions are the predicted discovery contours (or exclusion contours) for associated Higgs production at the LHC for 0.3 ab^{-1}, and 3 ab^{-1}, respectively.

The top quarks from the heavy Higgs can decay either hadronically or leptonically. The hard leptons produced from top decay products, together with the boosted top jets, can efficiently suppress the backgrounds, including the irreducible backgrounds of tt and $ttbb$. For final states with taus, either large transverse mass for the signal events or hard leptons from tau decays can efficiently distinguish the signal and backgrounds. The choices made in the illustrative analyses below (see caption of Fig. 3) also benefit the reconstruction of the heavy Higgs resonance. In addition, the large rapidity of the two non-top b-jets in $pp \to bbH^0/A \to bbtt$ and $pp \to tbH^\pm \to tbtb$ can be used to further suppress the backgrounds; this kinematic feature has not been applied for the H^0/A and $H^\pm$ searches at the LHC.

To fully utilize the kinematic features of the signal events, a Boosted Decision Tree method may be used to search for heavy Higgses decaying to semileptonic tops or taus.[51] The 5σ discovery reaches and 95% C.L. exclusion limits yielded by these channels are presented in Fig. 3, with various luminosities (3 ab^{-1}, and 30 ab^{-1}) and an ATLAS-type detector assumed. The exclusion limits for both the neutral and charged Higgs bosons are pushed from the $\mathcal{O}(1)$ TeV scale at the LHC to the $\mathcal{O}(10)$ TeV scale at a 100 TeV pp collider for almost the whole range of $\tan\beta$ (except the low $\tan\beta$ region for the neutral Higgs, which potentially can be covered by the channel $pp \to ttH^0/A \to tttt$ [46]). In particular, the wedge region for the neutral Higgs searches ($\tan\beta \sim 7$) and the low $\tan\beta$ region for the charged Higgs searches are fully covered by the channels $pp \to bbH^0/A \to bbtt$ and $pp \to tbH^\pm \to tbtb$, respectively.

6. Exotic Search Channels

Other than decays into conventional searches channels as mentioned in Sec. 5, exotic Higgs decays to final states with two light Higgses or one Higgs plus one SM gauge boson provide complementary search channels. Here, we list such exotic Higgs decays and consider potential search strategies.

- $\boldsymbol{H^0 \to AA}$

With one final state Higgs decay via bb, and the other decay via $\gamma\gamma$, the $bb\gamma\gamma$ channel has been shown to be sensitive to the di-Higgs final states,[52] in particular, with resonance enhancement of the production cross section. Final states involve taus might also be useful in probing this decay. Associated production with bb can enhance the reach further at large $\tan\beta$.

- $\boldsymbol{H^0 \to AZ}$ ***or*** $\boldsymbol{A \to H^0 Z}$

With $Z \to \ell\ell$ and $H^0/A \to bb, \tau\tau$, the final states of $bb\ell\ell$, $\tau\tau\ell\ell$ can be obtained with gluon fusion production, or in the bb associated production with two additional b jets.[21–23] Recent searches from ATLAS and CMS have shown certain sensitivity in this channel.[33–36] In parameter regions where $\mathrm{Br}(A \to H^0 Z) \times \mathrm{Br}(H^0 \to ZZ)$ is not completely suppressed, ZZZ final states with two Z decaying leptonically and one Z decaying hadronically can also be useful.[22] Other channels with top final states could be explored as well.

- $\boldsymbol{H^0 \to H^+H^-}$

With both $H^\pm$ decaying via $\tau\nu$ final states, the signal of $\tau\tau\nu\nu$ can be separated from the SM W^+W^- background since the charged tau decay product in the signal typically has a hard spectrum compared to that of the background.[26] Utilizing the top identification strategy as mentioned in Sec. 5, $ttbb$ or $tb\tau\nu$ final states could also be useful.

- $\boldsymbol{H^0/A \to H^\pm W^\mp}$

Similar to the H^+H^- case, $H^\pm \to \tau\nu, tb$ and $W \to \ell\nu$ with $\ell\tau\nu\bar{\nu}$ or $tb\ell\nu$ could be used to search for $H^0/A \to H^\pm W^\mp$. Note that for the CP-even Higgs H^0, the branching fraction of $H^0 \to H^\pm W^\mp$ is mostly suppressed comparing to $H^0 \to H^+H^-$ as long as the latter process is kinematically open and not accidentally suppressed (see Fig. 2).[26] However, for the CP-odd Higgs A, this is the only decay channel with a charged Higgs in the decay products.

- $\boldsymbol{H^\pm \to H^0W, AW}$

This is the only exotic decay channel for the charged Higgs in the 2HDM. Given the associated production of $tbH^\pm$, and the decay of H^0, A into the bb or $\tau\tau$ channel, $\tau\tau bbWW$ or $bbbbWW$ can be used to probe this channel.[24] $H^0/A \to t\bar{t}$ could also be used given the boosted top in the high energy environment.

7. Conclusion

Discovery of the non-SM Higgs bosons in an extended Higgs sector would provide clear evidence for new physics beyond the SM. At the 14 TeV LHC, the conventional search channels for neutral and charged Higgses leave a wedge region open around intermediate $\tan\beta \sim 7$ and $m_A \gtrsim 300$ GeV in which only the SM Higgs is detected. Exotic decays of heavy Higgses into two light Higgses or one light Higgs and one SM gauge boson provide complementary search channels once they are kinematically open.

A 100 TeV pp collider offers great discovery potential for non-SM heavy Higgses. In this write-up, we summarized the reach at the 100 TeV pp collider for conventional search modes, in particular, via the $H^0/A \to t\bar{t}$ and $H^\pm \to tb$ channels. Potentially, the whole range of $\tan\beta$ can be probed for masses up to about 10 TeV when various channels are combined. We also outline the possible search channels for exotic decays when the branching fractions for conventional channels are suppressed. Combinations of those channels can greatly extend the reach of the non-SM Higgs at a 100 TeV pp collider.

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