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# Search for extra Higgs bosons (theory)

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We provide an overview of the theory motivations for extra Higgs bosons, focussing on models that address the hierarchy problem (Twin Higgs, the MSSM and the NMSSM), and on the reasons why new Higgses could be the first particles seen in these models. We then discuss a phenomenological framework to describe the phenomenology of extra Higgs doublets and/or singlets, that easily maps on the above and other models, and that allows to set a strategy to perform experimental searches. We finally summarise the LHC8 status of these searches, as well as their prospects at the next runs of the LHC. In particular we describe the interplay of the following measurements: i) SM Higgs couplings to other SM particles, ii) SM Higgs self coupling, iii) direct searches for extra Higgses.

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## 1. Introduction and motivation

Can new Higgs bosons be the first new particles to give signals, direct or indirect, at the LHC? After having observed one in 2012 [1, 2], the quest for other (apparently) fundamental scalar particles is one of the major goals of the high energy frontier. Establishing or ruling out their existence, in the accessible energy domain, is very important also in relation to a possible solution of the hierarchy problem of the Fermi scale. It looks in fact hard to find an anthropic justification for another "light" uncoloured scalar, while such particles are present in several models that keep the Fermi scale almost-natural. Indeed, the presence of extra scalars is a feature of most of the successful proposals to address the hierarchy problem: the Minimal Supersymmetric Standard Model (MSSM, see [3] for a review of its Higgs sector) demands the existence of an extra doublet under the $SU(2)_w$ gauge group, and the Next-to-MSSM (NMSSM, see [4] for a review) adds, on top of it, also an extra singlet. Twin Higgs (TH) models [5] have a built-in extra scalar singlet, and possibly more than a scalar, for example if they are UV completed with supersymmetry. The existence of scalars other than the 125 GeV one is an interesting option of composite Higgs models (CHM) too [6]. Solid reasons exist to justify the existence of extra scalars also independently of the hierarchy problem, for example they are a typical feature of models of electroweak baryogengesis [7, 8, 9].

From an experimental point of view, the 8 TeV LHC run has not found any evidence for the existence of such extra scalars. Also, it has given us a knowledge of the main Higgs properties to a 20% accuracy [10], finding them to be in agreement with the SM expectations. This provides vital information regarding the observables where signals of extra Higgses could show up, which are partly summarised in this contribution, with a focus on the LHC13 and LHC14 runs.

The exposition is organised as follows. In Section 2 we review models motivated by naturalness and their relation with extra Higgses: Twin Higgs, the MSSM and the NMSSM. In Section 3 we discuss a simplified strategy to look for extra Higgses, that easily maps on the parameter spaces of different models, and the impact of Higgs coupling measurements on this picture, independently of the specific model. We then summarise the status and prospects for searches of extra Higgs doublets and singlets in Sections 4 and 5 respectively, making explicit the connection with more complete models. Finally, we provide a compact phenomenological overview in Section 6.

## 2. Models

### 2.1 Twin Higgs

To cancel the large NP contributions to the Higgs mass, Twin Higgs models introduce a copy of the SM, related to it by an approximate $Z_2$ symmetry[1]. In this type of models the Higgs boson emerges as an approximate Goldstone boson associated to the breaking of some global symmetry $\mathscr{G} \to \mathscr{H}$ (*e.g.* $SU(4) \to SU(3)$). In the case where there is only one physical approximate-Goldstone Higgs, the only other additional physical scalar is the "radial mode", *i.e.* the degree of freedom associated with vacuum expectation value $f$, with $f > v = 246$ GeV, that breaks the global

[1] Actually only the doubling of the top sector of the SM is necessary, at least if the only requirement imposed is that of alleviating the little hierarchy problem.

symmetry. If the above description derives from a weakly coupled model at higher energies, then the radial mode could be relatively light, significantly below $4\pi f$. This is for example the case of the Twin Higgs idea with a weakly coupled description [11, 12, 13].

Twin Higgs models solve the little hierarchy problem up to some scale $\Lambda$, where a theory solving the big hierarchy between $\Lambda$ and the Planck (or GUT) scale, like supersymmetry or compositeness, is needed. The TH does not require the presence of coloured degrees of freedom below the scale $\Lambda$, contrary to the usual realisations of SUSY and composite Higgs models, where new coloured bosons or fermions are expected to lie within the LHC reach. In TH models the low energy degrees of freedom that cancel the "quadratic divergences" are total singlets of the SM and hence very difficult to detect at the LHC, while coloured particles are expected to be naturally heavier. As a consequence, even a null result from the LHC will leave the tuning of the weak scale at the level of $(10\%)$ (see *e.g.* [14]), thus the growing interest of the community in this idea.

As emphasised in [15], if the TH has a weakly coupled description, an interesting possibility consists in trying to detect the "radial mode", the twin scalar partner of the Higgs. In fact, differently from other twin particles, it can be singly produced through a mixing with the Higgs. This is complementary to the idea that the only model-independent probe of such scenarios consists of the Higgs signal strengths.

### 2.2 Supersymmetry: the MSSM and the NMSSM

Weak scale supersymmetry can perhaps be considered as the best candidate to solve the hierarchy between the Fermi and the GUT or Planck scales. In its minimal realisation, the minimal supersymmetric Standard Model (MSSM), the Higgs sector constitutes of two doublets, $H_u$ and $H_d$, with vacuum expectation values (vevs) $v_u$ and $v_d$ respectively. The mass of the SM-like Higgs $h$, observed at the LHC8, is bounded by $m_h^2 < m_Z^2 \cos^2 2\beta + \Delta_t^2$, where $\tan\beta = v_u/v_d \equiv t_\beta$, and $\Delta_t^2$ is a radiative supersymmetry-breaking contribution, mainly coming from the top-stop sector of the model. Given the measured value of $m_h$, $\Delta_t$ has to be larger than about 85 GeV, *i.e.* of the same size of the SUSY-preserving contribution. This value for $\Delta_t$ implies for the mass of the lightest stop

$$m_{\tilde{t}} \gtrsim 1-1.5\ \text{TeV} \qquad (\text{MSSM, Higgs mass constraint}) \tag{2.1}$$

if the mixing between the stops is not maximal, and up to $m_{\tilde{t}} \gtrsim 10$ TeV otherwise, see *e.g.* [16, 17, 18]. This constitutes an issue from the point of view of the tuning of the EW scale $v$, because of its sensitivity to the stop mass $\delta v^2 \propto 1/g^2 \times \text{loop} \times m_{\tilde{t}}^2 \log \Lambda/m_{\tilde{t}}$, where $\Lambda$ is the scale at which SUSY-breaking is mediated. Gluinos also play a major role in the tuning issue, given their large contribution to the stop mass parameter.

The NMSSM alleviates this problem, adding an extra singlet $S$, so that the superpotential $\mathscr{W}$ of the theory reads $\mathscr{W} = \mathscr{W}_{\text{MSSM}} + \lambda H_u H_d S$ up to a polynomial up to order three in $S$, and where $\lambda$ a dimensionless coupling. For a large enough $\lambda$, the different dependence of the weak scale $v$ on the Lagrangian parameters allows, for a fixed amount of tuning, to accommodate stop and gluinos parametrically heavier by a factor of $O(\lambda/g)$ with respect to the MSSM [19, 20]. Also, the upper bound on the Higgs mass becomes $m_h^2 < m_Z^2 \cos^2 2\beta + \frac{\lambda^2 v^2}{2} \sin^2 2\beta + \Delta^2$.

While a very large $\lambda$ is favoured by the first point, it overshoots the measured value of $m_h$, so that a tuning is reintroduced to bring $m_h$ back to 125 GeV [21] [2]. The above parametric considerations have been made precise in the thorough study of [21], which found that, for a tuning of 5% (with a conservative definition of tuning, that multiplies the one in $m_h$ with the one in $v$, thus ignoring their correlation) the lightest new particles are expected to be the scalar Higgses and the lightest neutralino(s) (for other studies of the tuning in the NMSSM see e.g. [22]). The authors of [21] also found that the same amount of tuning is consistent with

$$m_{\tilde{t}} \sim 1.2 \text{ TeV}, \quad m_{\tilde{g}} \sim 2.5 \text{ TeV} \qquad (\text{NMSSM, compatible with } O(5\%) \text{ EW tuning}). \tag{2.2}$$

Summarising, the values of the masses of coloured particles in eqs. (2.1) and (2.2) are likely out of reach at the 13 TeV run of the LHC, and add considerable interest to the search for extra Higgs bosons, as the possible first experimental sign of Supersymmetry.

## 3. A useful parametrization, and Higgs coupling measurements

The models discussed above are characterised by the presence of an extra scalar singlet, doublet, or both. We now provide a description of an Higgs sector containing both an extra doublet and singlet, as a general example useful to set a strategy to look for extra Higgses. This description also turns out to be fairly independent of other details of the specific model to which the Higgses belong, as shown *e.g.* in [23] for the MSSM and NMSSM cases.

We borrow the notation from Supersymmetry, and consider the Higgs doublets to couple as in a type-II Two Higgs doublet model (THDM-II) for definiteness: one $H_u$ to up quarks, and the other $H_d$ to leptons and down quarks. The physical particle content originating from $H_u$, $H_d$ and the singlet field $S$ consists in

- ◇ three CP-even states $h$, $\phi$ and $H$, with $m_h = 125$ GeV,
- ◇ two CP-odds states $A$ and $A_s$,
- ◇ a charged state $H^\pm$.

Regarding the CP-even scalars, we find it convenient to rotate the gauge eigenstate basis to the one where only one field, $h^0 = \cos\beta\, H_u^0 - \sin\beta\, H_d^0$, takes vacuum expectation value (vev) $v$. Let $H^0$ be its orthogonal field, i.e. the neutral component of the doublet that takes no vev, and let $s^0$ be the CP-even component of the scalar $S$. The mass eigenstates basis $(H,h,\phi)$ is then related with the one $(H^0,h^0,s^0)$ via

$$\begin{pmatrix} H \\ h \\ \phi \end{pmatrix} = R \begin{pmatrix} H^0 \\ h^0 \\ s^0 \end{pmatrix}, \qquad R = R^{13}_\sigma R^{23}_\gamma R^{12}_\delta, \tag{3.1}$$

where $R^{ij}_\theta$ is a rotation of angle $\theta$ in the $ij$ plane. Coming now to the CP-odd scalars, the mass of the doublet-like $A$ (*i.e.* the only CP-odd of the MSSM) is equal to the mass of the charged Higgs

[2] This would not be the case for a quite large $\tan\beta$, however $\tan\beta \gtrsim 5$ is disfavoured by EWPT, for $\lambda \gtrsim 1$ and natural values of the Higgsino masses [21].

$H^{\pm}$, barring corrections of the order of the EW scale. For example in the NMSSM one has

$$m_A^2 = m_{H^\pm}^2 - m_W^2 + \lambda^2 v^2/2, \tag{3.2}$$

to be later diagonalised with $A_s$, while the same expression with $\lambda = 0$ holds for the physical mass in the MSSM. The mass of the extra CP-even doublet $H$ is also very close to $m_A$.

The tree-level couplings of the SM-like Higgs boson to up and down quarks of all generations ($u$ and $d$) and to vector bosons $V$ read

$$\frac{g_{hu\bar{u}}}{g_{hu\bar{u}}^{\rm SM}} = c_\gamma(c_\delta + \frac{s_\delta}{\tan\beta}), \qquad \frac{g_{hd\bar{d}}}{g_{hd\bar{d}}^{\rm SM}} = c_\gamma(c_\delta - s_\delta \tan\beta), \qquad \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = c_\gamma c_\delta\,, \tag{3.3}$$

where we have used the shorthand notation $c_\theta, s_\theta = \cos\theta, \sin\theta$. The mixing of the LHC Higgs with the other doublet, $\delta$, is constrained at the 95% CL by $s_\delta \lesssim 0.15$ for $t_\beta = 1$, down to $s_\delta \lesssim 0.05$ for larger values of $t_\beta$ [23] (the more recent fit of [24] finds slightly more stringent constraints). On the contrary, a large singlet component is still allowed in the LHC Higgs, the 95% CL constraint on the mixing being $s_\gamma < 0.48$. Concerning upcoming experiments, if the LHC14 will not observe deviations in the Higgs couplings, then a quite large singlet component would still be allowed, while the mixing $\delta$ would be constrained down to a few percent level or less. The constraints and projections reported for each angle $\delta$ and $\gamma$ are derived setting the other one to zero, but they do not change much if this assumption is relaxed.

Let us now define two limiting cases, where different degrees of freedom are relevant:

a) $h$ plus $H$. The singlet-like state $\phi$ is decoupled, $m_\phi \gg m_H, m_h$, and $\gamma, \sigma \ll \delta$.

b) $h$ plus $\phi$. The doublet-like states are decoupled , $m_{H,A,H^\pm} \gg m_\phi, m_h$, and $\delta, \sigma \ll \gamma$.

To discuss the phenomenology, since our aim is to give a general search strategy, we stick to the case a) and b) and outline them in Sections 4 and sect. 5 respectively.

## 4. An extra Higgs doublet

In any THDM-II the couplings of the CP-even scalar $H$ to SM particles read

$$\frac{g_{Hu\bar{u}}}{g_{hu\bar{u}}^{\rm SM}} = s_\delta - \frac{c_\delta}{\tan\beta}, \qquad \frac{g_{Hd\bar{d}}}{g_{hd\bar{d}}^{\rm SM}} = \frac{g_{H\ell\bar{\ell}}}{g_{h\ell\bar{\ell}}^{\rm SM}} = s_\delta + c_\delta \tan\beta, \qquad \frac{g_{HVV}}{g_{hVV}^{\rm SM}} = s_\delta, \tag{4.1}$$

while those of $h$ can be read off eq. (3.3) via setting $\gamma = 0$.

The case $m_H < m_h$ receives strong constraints from Higgs coupling measurements, see *e.g.* [25] for both the MSSM and the NMSSM cases. This mass ordering is further disfavoured because a light $H$ implies a light $H^\pm$, and flavour measurements like $\text{BR}_{B\to X_s\gamma}$ impose $m_{H^\pm} \gtrsim 480$ GeV (95%CL) [28]. This bound could perhaps be relaxed by invoking a cancellation with contributions from other light particles. Despite being tuned, for this solution to work one would have to find ways to "hide" those light particles at the LHC.

We therefore now focus on the case $m_H > m_h$. In the MSSM, where the measured value of $m_h$ fixes its radiative correction $\Delta_t$, the phenomenology of the Higgs sector depends on only two free parameters, $\tan\beta$ and $m_H$ [27, 23]. The fit of the Higgs couplings does not allow for values

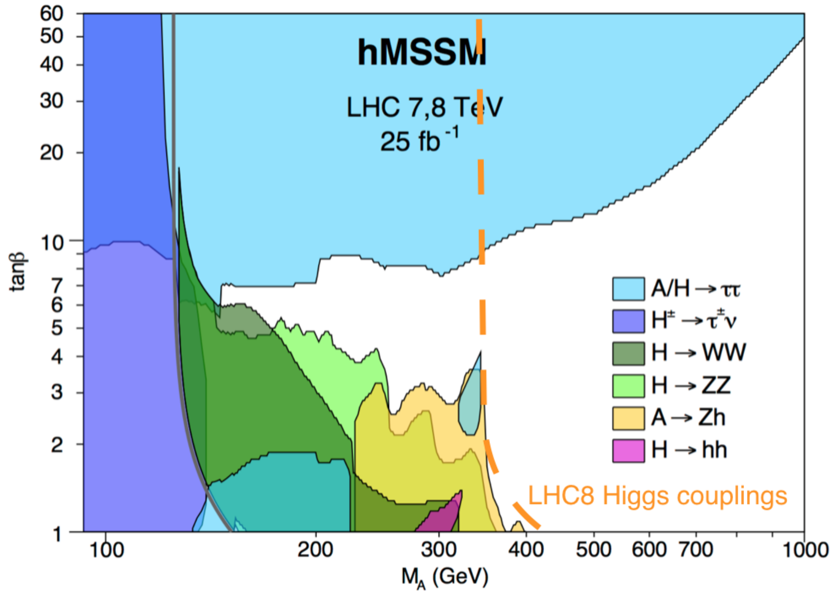


**Figure 1:** Current phenomenological status of the MSSM Higgs parameter space. Indirect reach of [23] overlaid on direct searches of [29].

of $m_{H,H^\pm}$ smaller than about 350 GeV, as shown with the dashed orange line in fig. 1. There we also show the current reach of various direct searches, one can see that the only one probing regions unaccessible to Higgs couplings is $A,H \to \tau^+\tau^-$, and only for large $\tan\beta$. The LHC14 is expected to roughly double the reach in $m_{A,H,H^\pm}$ with Higgs coupling measurements. For larger values of $m_{A,H,H^\pm}$, the region of large $\tan\beta$ will be best probed via searches of $H,A \to \tau^+\tau^-$, see *e.g.* [29]. The region of small to moderate $\tan\beta$ could be probed, at a first thought, by searches of $A,H \to \bar{t}t$. However, the typical peak-dip structure of the signal with the background is expected to be completely washed out once detector mass resolution effects are taken into account, likely preventing any significant detection even at the HL-LHC [24]. Then, as emphasised in [24, 30], the most promising channels to probe that $\tan\beta$ regions are those that involve the charged Higgs, like for example $pp \to \bar{t}bH^+ \to \bar{t}b\bar{b}t$ (see also the recent review [31]). The LHC has already started this exploration, see *e.g.* [32].

In the MSSM it is apparently[3] not possible to achieve "alignment without decoupling", *i.e.* to have $\delta = 0$ even for low values of $m_{H,A}$. One can instead realise this in a more general 2HDM-II, like *e.g.* the NMSSM with $\phi$ decoupled, as understandable from fig. 2 (the line $\delta = 0$ can be inferred from the allowed regions). Contrary to the case of a light singlet-like state (see next section), the "alignement" limit $\delta \to 0$ does not imply that also the couplings of $H$ (and $A$ and $H^\pm$) to SM states go to zero, see eq. (4.1)[4]. Actually, in this limit, the couplings to SM fermions of $H$ and $A$ coincide. This adds to the motivation to perform direct searches of extra Higgses, both charged and neutral, into fermions. They might be our only window on the $\delta = 0$ limit of these models, which is not less motivated than other regions of the parameter space.

[3]Our discussion of the MSSM phenomenology holds for $\mu A_t/m_{\tilde{t}}^2 \lesssim 1$, as motivated by naturalness. By relaxing this requirement one could have alignment without decoupling also in the MSSM (see [33] for a recent study).

[4]On the contrary, $\delta = 0$ implies $\mathrm{BR}_{H\to VV} = \mathrm{BR}_{H\to hh} = \mathrm{BR}_{A\to Zh} = \mathrm{BR}_{H^\pm\to W^\pm h} = 0$.

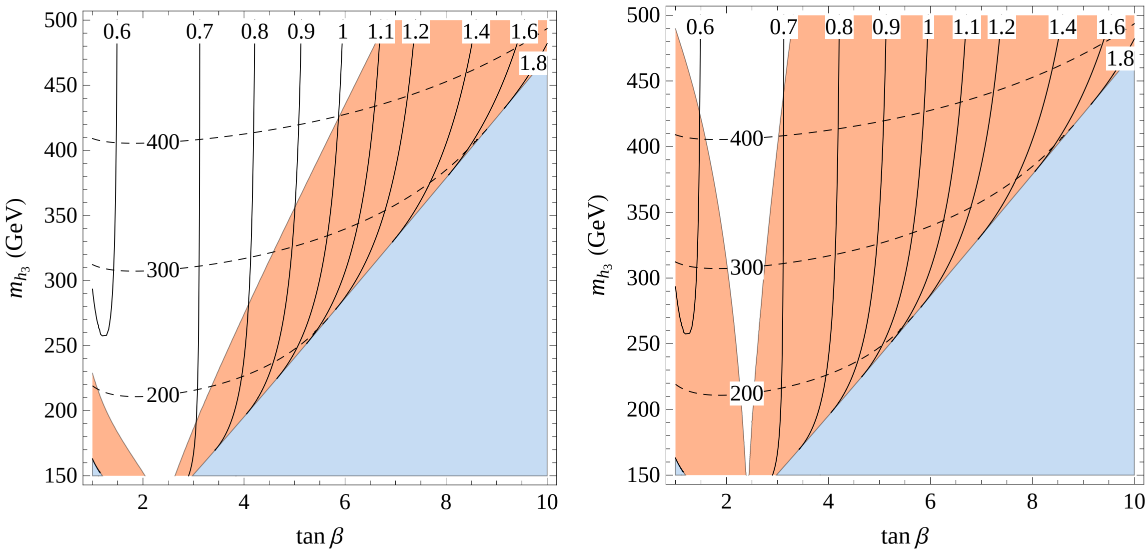


**Figure 2:** Shaded pink: 95% CL exclusions from Higgs coupling measurements at the LHC8 (left), and expected reaches at the LHC14 with 300 fb$^{-1}$ (right). Lines: values of $\lambda$ (continuous), and of $m_{H^\pm}$ (dashed). Light blue: unphysical regions. Taken from [25], where the notation $H \to h_3$ was used.

## 5. An extra Higgs singlet

When the SM is extended with an extra singlet scalar, the Higgs couplings are modified as in eq. (3.3) with $\delta = 0$, while those of the extra CP even singlet $\phi$ are analogous upon the substitution $c_\delta \to s_\delta$. Therefore the signal strengths $\mu_{A\to B} = \sigma_{pp\to A} \times \mathrm{BR}_{A\to B}$ are[5]

$$\Delta\mu/\mu_{\rm SM} \equiv \frac{\mu_{h\to\rm SM} - \mu_{\rm SM}(m_h)}{\mu_{\rm SM}(m_h)} = s_\gamma^2, \tag{5.1}$$

$$\frac{\mu_{\phi\to VV,ff}}{\mu_{\rm SM}(m_\phi)} = s_\gamma^2 \times (1 - \mathrm{BR}_{\phi\to hh}), \qquad \frac{\mu_{\phi\to hh}}{\sigma_{\rm SM}(m_\phi)} = s_\gamma^2 \times \mathrm{BR}_{\phi\to hh}, \tag{5.2}$$

where $\sigma_{\rm SM}(m)$ is the total cross section of a SM Higgs boson of mass $m$, $\mu_{\rm SM}(m)$ is its signal strength into the channel of interest, and $\mathrm{BR}_{\phi\to hh}$ is the branching ratio of $\phi$ into $hh$. The mixing angle $\gamma$, that governs almost all the phenomenology, takes the very simple form

$$s_\gamma^2 = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}, \qquad (M_{hh}^2)_{\rm NMSSM} = c_{2\beta}^2 m_Z^2 + s_{2\beta}^2 \frac{\lambda^2 v^2}{2} + \Delta^2, \quad (M_{hh}^2)_{\rm TH} = (m_h^2 + m_\phi^2)\frac{v^2}{f^2}, \tag{5.3}$$

where $M_{hh}$ is a parameter of the order of the EW scale, for which we have given the explicit expression in the NMSSM with $H$ decoupled, and in TH. Higgs coupling measurements put constraints on the plane $M_{hh} - m_\phi$, and they are shown in pink in fig. 3. They can then be mapped on the parameters of a particular model upon use of its specific $M_{hh}$ expression, see [15].

The study of direct searches of the extra singlet require the knowledge of $\mathrm{BR}_{\phi\to hh}$, which in turns depend on the many unknown parameters of the scalar potential (from which the use of scatter plots and/or of benchmark points diffused in the literature). However, one [15] can show that, for

[5] We assume that no other channels are open, like $\phi \to A_s A_s$, or the SUSY $\phi \to$LSP LSP.

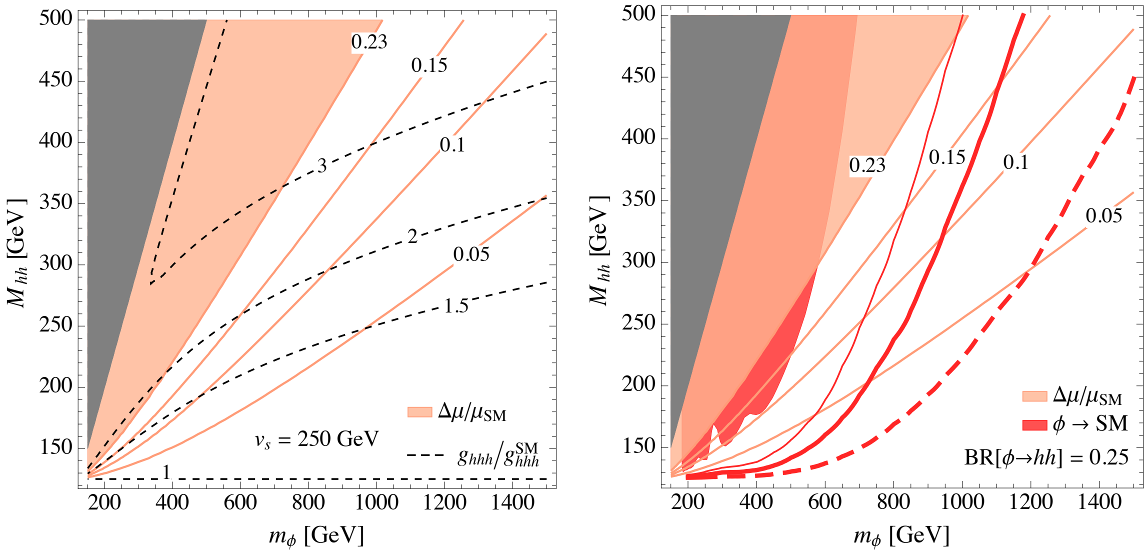


**Figure 3:** Shaded: excluded by LHC8 measurements of the Higgs couplings (pink), excluded by LHC8 $\phi \to$ SM SM searches (red), unphysical (grey). Lines: contours of deviations in the Higgs signal strengths (pink), in the Higgs trilinear coupling (black dashed), and expected reaches of the LHC13 with 100 fb$^{-1}$ (thin red), the LHC14 with 300 fb$^{-1}$ (red), the HL-LHC (dashed red). Taken from [15].

a most general potential and to leading order in $v/m_\phi$, it is the singlet vev $v_s$ that controls $\mathrm{BR}_{\phi\to hh}$ (and the trilinear Higgs coupling $g_{hhh}$ as well):

$$\mathrm{BR}_{\phi\to hh} = \frac{1}{4} - \frac{3}{4}\frac{v}{v_s}\frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi} + \left(\frac{v^2}{m_\phi^2}\right), \tag{5.4}$$

$$\frac{g_{hhh}}{g_{hhh}^{\mathrm{SM}}} = 1 + \frac{2}{3}\frac{v}{v_s}\frac{\sqrt{M_{hh}^2 - m_h^2}}{m_\phi}\left(\frac{M_{hh}^2}{m_h^2} - 1\right) + \left(\frac{v^2}{m_\phi^2}\right). \tag{5.5}$$

Notice that, for $m_\phi \gg v$, $\mathrm{BR}_{\phi\to hh}$ correctly tends to the fixed value of $1/4 = \mathrm{BR}_{\phi\to ZZ} = \mathrm{BR}_{\phi\to WW}/2$, because of the Goldstone nature of the vector bosons. Therefore, by observing a heavier scalar in diboson, and measuring either $g_{hhh}$ or its BR to $hh$, one could in principle tell its vev, if a singlet. To make the previous statement more precise, we show in fig. 3 the expected deviations in $g_{hhh}$ (for $v_s = 250$ GeV) on the left, and the expected direct reach (for $\mathrm{BR}_{\phi\to hh} = 1/4$, a value for which searches in vector bosons dominate over those in $hh$) on the right. The expected direct reaches are computed assuming a parton luminosity scaling of the backgrounds, see [15] for details.

Notice that the large deviations of $g_{hhh}$ from one, shown in fig. 3 for a generic singlet case, are possible in the NMSSM, but are not realisable in TH, given the peculiar structures of the two models. Finally, an extra-singlet-like Higgs could be hiding also below 125 GeV, also because it does not suffer of the flavour problems of the previous case. We refer the reader to [25, 34, 35] for the discussion of this mass domain.

## 6. Summary and outlook

The quest for other Higgs bosons is one of the primary goals of the exploration of the high

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energy frontier, in particular (but not only) in models that address the hierarchy problem of the Fermi scale, like Twin Higgs, and the supersymmetric MSSM and NMSSM. They all feature an extra doublet, or an extra singlet, or both. The status and prospects of searches for these particles at the LHC can be summarised as follows[6]:

- ◇ Extra doublet-like state $H$, predicted both in the MSSM and the NMSSM. Measurements of the Higgs couplings at LHC are expected to probe a significant part of the model parameter space, particularly in the MSSM. Direct searches are more effective than Higgs coupling measurements, in probing the MSSM the parameter space, only at large $\tan\beta$ with $pp \to A,H \to \tau\tau$, see fig. 1. Contrary to the MSSM, in more general 2HDM-II like the NMSSM, a region of "alignment without decoupling" ($\delta \simeq 0$ and $m_{H,A,H\pm}$ "light") survives, see fig. 2. The only chance to probe this region appears to be to look for direct signs of the extra Higgses. The resonant $A,H \to t\bar{t}$ channel, that dominates the $A$ and $H$ branching ratios for low to moderate $\tan\beta$, suffers from detector effects that, unless overcome (a motivated experimental task for the second LHC run!), will likely prevent any significant detection. The quest for the charged Higgs $H^{\pm}$, that in the allowed regions is predicted to lie close in mass to $A$ and $H$ (at most tens of GeV apart), looks then as the best way to probe the low to moderate $\tan\beta$ regions of type-II 2HDMs.

- ◇ Extra singlet-like Higgs $\phi$, predicted in both TH and the NMSSM. Quite generically, Higgs coupling measurements are and will be more constraining for larger values of $m_\phi$, while direct searches will dominate below roughly a TeV, see fig.3 right (and see [15] for the specific NMSSM and TH cases). The most relevant channels to directly look for $\phi$ are in $ZZ$ and $WW$. The $hh$ channel can play a role for certain values of the singlet vev $v_s$ and for a not too large $m_\phi$, otherwise $VV$ searches are more effective. Contrary to the extra-doublet case, a sizeable deviation of the trilinear Higgs coupling from its SM value could be observable at the future LHC stages, potentially even before deviations in the Higgs signal strengths, see fig. 3 left.

The above summary provides a theoretically and phenomenologically motivated orientation in the quest for extra Higgs bosons, identifying regions that should be more explored at the LHC. However, we conclude by encouraging the experimentalists to keep looking for resonances in other spots (*e.g.* for Higgses lighter than 125 GeV) and in channels not explicitly mentioned here ($\gamma\gamma$, $bb$,...), since we ultimately do not know where Nature could first manifest itself in the higher energy domain, that we are just start exploring.

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[6] More details can be found *e.g.* in the short review [36].

## References

[1] G. Aad *et al.* [ATLAS Collaboration], *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1 [arXiv:1207.7214 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012) 30 [arXiv:1207.7235 [hep-ex]].

[3] A. Djouadi, *The Anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model*, Phys. Rept. **459** (2008) 1 [hep-ph/0503173].

[4] U. Ellwanger, C. Hugonie and A. M. Teixeira, *The Next-to-Minimal Supersymmetric Standard Model*, Phys. Rept. **496** (2010) 1 [arXiv:0910.1785 [hep-ph]].

[5] Z. Chacko, H. S. Goh and R. Harnik, *The Twin Higgs: Natural electroweak breaking from mirror symmetry*, Phys. Rev. Lett. **96** (2006) 231802 [hep-ph/0506256].

[6] B. Gripaios, A. Pomarol, F. Riva and J. Serra, *Beyond the Minimal Composite Higgs Model*, JHEP **0904** (2009) 070 [arXiv:0902.1483 [hep-ph]].

[7] S. Profumo, M. J. Ramsey-Musolf and G. Shaughnessy, *Singlet Higgs phenomenology and the electroweak phase transition*, JHEP **0708** (2007) 010 [arXiv:0705.2425 [hep-ph]].

[8] D. Curtin, P. Meade and C. T. Yu, *Testing Electroweak Baryogenesis with Future Colliders*, JHEP **1411** (2014) 127 [arXiv:1409.0005 [hep-ph]].

[9] N. Craig, H. K. Lou, M. McCullough and A. Thalapillil, *The Higgs Portal Above Threshold*, JHEP **1602** (2016) 127 [arXiv:1412.0258 [hep-ph]].

[10] G. Aad *et al.* [ATLAS and CMS Collaborations], *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV*, arXiv:1606.02266 [hep-ex].

[11] A. Falkowski, S. Pokorski and M. Schmaltz, *Twin SUSY*, Phys. Rev. D **74** (2006) 035003 [hep-ph/0604066].

[12] S. Chang, L. J. Hall and N. Weiner, *A Supersymmetric twin Higgs*, Phys. Rev. D **75** (2007) 035009 [hep-ph/0604076].

[13] N. Craig and K. Howe, *Doubling down on naturalness with a supersymmetric twin Higgs*, JHEP **1403** (2014) 140 [arXiv:1312.1341 [hep-ph]].

[14] N. Craig, A. Katz, M. Strassler and R. Sundrum, *Naturalness in the Dark at the LHC*, JHEP **1507** (2015) 105 [arXiv:1501.05310 [hep-ph]].

[15] D. Buttazzo, F. Sala and A. Tesi, *Singlet-like Higgs bosons at present and future colliders*, JHEP **1511** (2015) 158 [arXiv:1505.05488 [hep-ph]].

[16] J. Pardo Vega and G. Villadoro, *SusyHD: Higgs mass Determination in Supersymmetry*, JHEP **1507** (2015) 159 [arXiv:1504.05200 [hep-ph]].

[17] E. Bagnaschi, G. F. Giudice, P. Slavich and A. Strumia, *Higgs Mass and Unnatural Supersymmetry*, JHEP **1409** (2014) 092 [arXiv:1407.4081 [hep-ph]].

[18] T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, *High-Precision Predictions for the Light CP -Even Higgs Boson Mass of the Minimal Supersymmetric Standard Model*, Phys. Rev. Lett. **112** (2014) no.14, 141801 [arXiv:1312.4937 [hep-ph]].

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[19] R. Barbieri, L. J. Hall, Y. Nomura and V. S. Rychkov, *Supersymmetry without a Light Higgs Boson*, Phys. Rev. D **75** (2007) 035007 [hep-ph/0607332].

[20] L. J. Hall, D. Pinner and J. T. Ruderman, *A Natural SUSY Higgs Near 126 GeV*, JHEP **1204** (2012) 131 [arXiv:1112.2703 [hep-ph]].

[21] T. Gherghetta, B. von Harling, A. D. Medina and M. A. Schmidt, *The Scale-Invariant NMSSM and the 126 GeV Higgs Boson*, JHEP **1302** (2013) 032 [arXiv:1212.5243 [hep-ph]].

[22] J. Cao, D. Li, L. Shang, P. Wu and Y. Zhang, *Exploring the Higgs Sector of a Most Natural NMSSM and its Prediction on Higgs Pair Production at the LHC*, JHEP **1412** (2014) 026 [arXiv:1409.8431 [hep-ph]].

[23] R. Barbieri, D. Buttazzo, K. Kannike, F. Sala and A. Tesi, *Exploring the Higgs sector of a most natural NMSSM*, Phys. Rev. D **87** (2013) no.11, 115018 [arXiv:1304.3670 [hep-ph]].

[24] N. Craig, F. D'Eramo, P. Draper, S. Thomas and H. Zhang, *The Hunt for the Rest of the Higgs Bosons*, JHEP **1506** (2015) 137 [arXiv:1504.04630 [hep-ph]].

[25] R. Barbieri, D. Buttazzo, K. Kannike, F. Sala and A. Tesi, *One or more Higgs bosons?*, Phys. Rev. D **88** (2013) 055011 [arXiv:1307.4937 [hep-ph]].

[26] A. Andreazza *et al.*, *What Next: White Paper of the INFN-CSN1*, Frascati Phys. Ser. **60** (2015) 1.

[27] L. Maiani, A. D. Polosa and V. Riquer, *Probing Minimal Supersymmetry at the LHC with the Higgs Boson Masses*, New J. Phys. **14** (2012) 073029 [arXiv:1202.5998 [hep-ph]].

[28] M. Misiak *et al.*, *Updated NNLO QCD predictions for the weak radiative B-meson decays*, Phys. Rev. Lett. **114** (2015) no.22, 221801 [arXiv:1503.01789 [hep-ph]].

[29] A. Djouadi, L. Maiani, A. Polosa, J. Quevillon and V. Riquer, *Fully covering the MSSM Higgs sector at the LHC*, JHEP **1506** (2015) 168 [arXiv:1502.05653 [hep-ph]].

[30] J. Hajer, Y. Y. Li, T. Liu and J. F. H. Shiu, *Heavy Higgs Bosons at 14 TeV and 100 TeV*, JHEP **1511** (2015) 124 [arXiv:1504.07617 [hep-ph]].

[31] A. G. Akeroyd *et al.*, *Prospects for charged Higgs searches at the LHC*, arXiv:1607.01320 [hep-ph].

[32] M. Aaboud *et al.* [ATLAS Collaboration], *Search for charged Higgs bosons produced in association with a top quark and decaying via $H^{\pm} \to \tau\nu$ using pp collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector*, Phys. Lett. B **759** (2016) 555 [arXiv:1603.09203 [hep-ex]].

[33] M. Carena, H. E. Haber, I. Low, N. R. Shah and C. E. M. Wagner, *Complementarity between Nonstandard Higgs Boson Searches and Precision Higgs Boson Measurements in the MSSM*, Phys. Rev. D **91** (2015) no.3, 035003 [arXiv:1410.4969 [hep-ph]].

[34] M. Badziak, M. Olechowski and S. Pokorski, *New Regions in the NMSSM with a 125 GeV Higgs*, JHEP **1306** (2013) 043 [arXiv:1304.5437 [hep-ph]].

[35] S. F. King, M. Mühlleitner, R. Nevzorov and K. Walz, *Discovery Prospects for NMSSM Higgs Bosons at the High-Energy Large Hadron Collider*, Phys. Rev. D **90** (2014) 9, 095014 [arXiv:1408.1120 [hep-ph]].

[36] F. Sala, *Higgs and flavour as doors to new physics*, Eur. Phys. J. Plus **131** (2016) no.4, 79 [arXiv:1509.08655 [hep-ph]].