

# LHC benchmark scenarios for the real Higgs singlet extension of the standard model

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**Abstract** We present benchmark scenarios for searches for an additional Higgs state in the real Higgs singlet extension of the Standard Model in Run 2 of the LHC. The scenarios are selected such that they fulfill all relevant current theoretical and experimental constraints, but can potentially be discovered at the current LHC run. We take into account the results presented in earlier work and update the experimental constraints from relevant LHC Higgs searches and signal rate measurements. The benchmark scenarios are given separately for the low-mass and high-mass region, i.e. the mass range where the additional Higgs state is lighter or heavier than the discovered Higgs state at around 125 GeV. They have also been presented in the framework of the LHC Higgs Cross Section Working Group.

## 1 Introduction

The first run of the LHC at center-of-mass (CM) energies of 7 and 8 TeV has been completed in 2015. Its remarkable success is highlighted by the breakthrough discovery of a scalar boson in July 2012 and the measurements of its coupling properties, which thus far are well compatible with the interpretation in terms of the Higgs boson of the Standard Model (SM) Higgs mechanism [1–5]. The combination of the Higgs mass measurements performed by ATLAS and CMS yields [6]

$$m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV.} \quad (1)$$

If the discovered particle is indeed the Higgs boson of the SM, its mass measurement determines the last unknown ingredient of this model, as all other properties of the electroweak sector then follow directly from theory. In the coming years a thorough investigation of the Higgs boson's properties is

needed in order to identify whether the SM Higgs sector is indeed complete, or instead, the structure of a more involved Higgs sector is realized. This includes detailed and accurate measurements of its coupling strengths and  $\mathcal{CP}$  structure at the LHC and ultimately at future experimental facilities for Higgs boson precision studies. Complementary to this, collider searches for additional Higgs bosons need to be continued over the full accessible mass range. The discovery of another Higgs boson would inevitably prove the existence of a non-minimal Higgs sector.

In this work we consider the simplest extension of the SM Higgs sector, where an additional real scalar field is added, which is neutral under all quantum numbers of the SM gauge groups [7,8] and acquires a vacuum expectation value (VEV). This model has been widely studied in the literature [9–52], also in the context of electroweak higher order corrections [53,54] or offshell and interference effects [33,34,55–59]. Here, we present an update of the exploration of the model parameter space presented in Ref. [38], where we take the latest experimental constraints into account. As before, we consider masses of the second (non-standard) Higgs boson in the whole mass range up to 1 TeV. This minimal setup can be interpreted as a limiting case for more generic BSM scenarios, e.g. models with additional gauge sectors [60] or additional matter content [61,62]. Experimental searches for the model have been presented in [63–70].

As in Ref. [38] we take the following theoretical and experimental constraints into account: bounds from perturbative unitarity and electroweak (EW) precision measurements, in particular focussing on higher order corrections to the  $W$  boson mass [32]; perturbativity, vacuum stability and correct minimization of the model up to a high energy scale using renormalization group (RG) evolved couplings; exclusion limits from Higgs searches at the LEP, Tevatron and LHC experiments via the public tool `HiggsBounds` [71–75], and compatibility of the model

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with the signal strength measurements of the discovered Higgs state using `HiggsSignals` [76] (cf. also Ref. [77]).

We separate the discussion of the parameter space into two different mass regions: (i) the high-mass region,  $m_H \in [130, 1000]$  GeV, where the lighter Higgs boson  $h$  is interpreted as the discovered Higgs state; (ii) the low-mass region,  $m_h \in [1, 120]$  GeV, where the heavier Higgs boson  $H$  is interpreted as the discovered Higgs state.

We find that the most severe constraints in the whole parameter space for the second Higgs mass  $m_H \lesssim 250$  GeV are mostly given by limits from collider searches for a SM Higgs boson as well as by the LHC Higgs boson signal strength measurements. For  $m_H \gtrsim 250$  GeV limits from higher order contributions to the  $W$  boson mass prevail, followed by the requirement of perturbativity of the couplings.

For the remaining viable parameter space we present predictions for signal cross sections of the yet undiscovered second Higgs boson for the LHC at a CM energy of 14 TeV, discussing both the SM Higgs decay signatures and the novel Higgs-to-Higgs decay mode  $H \rightarrow hh$ . For both the high-mass and the low-mass regions we present a variety of *benchmark scenarios*. These are designed to render a maximal direct production rate for the collider signature of interest. Whenever kinematically accessible we give two different benchmark points for each mass, for which the Higgs-to-Higgs decay  $H \rightarrow hh$  is maximal or minimal, respectively.

The paper is organized as follows: In Sect. 2 we briefly review the model and the chosen parametrization. In Sect. 3 we review the constraints that are taken into account and in particular discuss the impact of the new constraints on the parameter space. In Sect. 4 we provide benchmark points and planes discussed above. We summarize and conclude in Sect. 5.

## 2 The model

In the following we briefly review the main features of the real Higgs singlet extension of the SM that are important for the benchmark choices. More details as regards the model can e.g. be found in Refs. [29,32,38,54] and references therein.

### 2.1 Potential and couplings

The real Higgs singlet extension of the SM [7,8,78] contains a complex  $SU(2)_L$  doublet, in the following denoted by  $\Phi$ , and in addition a real scalar  $S$  which is a singlet under the SM gauge group. The most general renormalizable Lagrangian compatible with an additional  $Z_2$  symmetry is then given by

$$\mathcal{L}_s = (D^\mu \Phi)^\dagger D_\mu \Phi + \partial^\mu S \partial_\mu S - V(\Phi, S), \tag{2}$$

with the scalar potential

$$\begin{aligned} V(\Phi, S) &= -m^2 \Phi^\dagger \Phi - \mu^2 S^2 \\ &\quad + (\Phi^\dagger \Phi S^2) \begin{pmatrix} \lambda_1 & \frac{\lambda_3}{2} \\ \frac{\lambda_3}{2} & \lambda_2 \end{pmatrix} \begin{pmatrix} \Phi^\dagger \Phi \\ S^2 \end{pmatrix} \\ &= -m^2 \Phi^\dagger \Phi - \mu^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 \\ &\quad + \lambda_3 \Phi^\dagger \Phi S^2. \end{aligned} \tag{3}$$

The implicitly imposed  $Z_2$  symmetry forbids all linear or cubic terms of the singlet field  $S$  in the potential. We assume that both Higgs fields  $\Phi$  and  $S$  have a non-zero vacuum expectation value (VEV), denoted by  $v$  and  $x$ , respectively. In the unitary gauge, the Higgs fields are given by

$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, \quad S \equiv \frac{h'+x}{\sqrt{2}}. \tag{4}$$

After diagonalization of the mass matrix we obtain the mass eigenstates  $h$  and  $H$  with mass eigenvalues given by

$$m_h^2 = \lambda_1 v^2 + \lambda_2 x^2 - \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \tag{5}$$

$$m_H^2 = \lambda_1 v^2 + \lambda_2 x^2 + \sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}, \tag{6}$$

and  $m_h^2 \leq m_H^2$  by convention. The gauge and mass eigenstates are related via the mixing matrix

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix}, \tag{7}$$

where the mixing angle  $-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$  is given by

$$\sin 2\alpha = \frac{\lambda_3 x v}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}, \tag{8}$$

$$\cos 2\alpha = \frac{\lambda_2 x^2 - \lambda_1 v^2}{\sqrt{(\lambda_1 v^2 - \lambda_2 x^2)^2 + (\lambda_3 x v)^2}}. \tag{9}$$

It follows from Eq. (7) that the light (heavy) Higgs boson couplings to SM particles are suppressed by  $\cos \alpha$  ( $\sin \alpha$ ).

If kinematically allowed, the additional decay channel  $H \rightarrow hh$  is present. Its partial decay width at leading order (LO) is given by [7,78]

$$\Gamma_{H \rightarrow hh} = \frac{|\mu'|^2}{8\pi m_H} \sqrt{1 - \frac{4m_h^2}{m_H^2}}, \tag{10}$$

where the coupling strength  $\mu'$  of the  $H \rightarrow hh$  decay reads

$$\mu' = -\frac{\sin(2\alpha)}{2vx} (\sin \alpha v + \cos \alpha x) \left( m_h^2 + \frac{m_H^2}{2} \right). \tag{11}$$

Next-to-leading order (NLO) corrections to the  $H \rightarrow hh$  decay width for this model have been calculated recently in Ref. [54]. The branching ratios of the heavy Higgs mass eigenstate  $m_H$  are then given by

$$\text{BR}_{H \rightarrow hh} = \frac{\Gamma_{H \rightarrow hh}}{\Gamma_{\text{tot}}}, \tag{12}$$

$$\text{BR}_{H \rightarrow \text{SM}} = \sin^2 \alpha \times \frac{\Gamma_{\text{SM}, H \rightarrow \text{SM}}}{\Gamma_{\text{tot}}}, \tag{13}$$

where  $\Gamma_{SM, H \rightarrow SM}$  is the partial decay width of the SM Higgs boson and  $H \rightarrow SM$  represents any SM Higgs decay mode. The total width is then

$$\Gamma_{\text{tot}} = \sin^2 \alpha \times \Gamma_{SM, \text{tot}} + \Gamma_{H \rightarrow hh}, \tag{14}$$

where  $\Gamma_{SM, \text{tot}}$  denotes the total width of the SM Higgs boson with mass  $m_H$ . The suppression by  $\sin^2 \alpha$  directly follows from the suppression of all SM-like couplings, cf. Eq. (7). For  $\mu' = 0$ , the decay  $H \rightarrow hh$  vanishes and we recover the SM Higgs boson branching ratios.

For the collider phenomenology of the model two features are important:

- the suppression of the *production cross section* of the two Higgs states induced by the mixing, which is given by  $\sin^2 \alpha$  ( $\cos^2 \alpha$ ) for the heavy (light) Higgs, respectively;
- the suppression of the *Higgs decay modes to SM particles*, which is realized if the competing decay mode  $H \rightarrow hh$  is kinematically accessible.

For the high-mass (low-mass) scenario, i.e. the case where the light (heavy) Higgs boson is identified with the discovered Higgs state at  $\sim 125$  GeV,  $|\sin \alpha| = 0$  (1) corresponds to the complete decoupling of the second Higgs boson and therefore the SM-like scenario.

### 2.2 Model parameters

At the Lagrangian level, the model has five free parameters,

$$\lambda_1, \lambda_2, \lambda_3, v, x, \tag{15}$$

while the values of the additional parameters  $\mu^2, m^2$  are fixed by the minimization conditions. A more intuitive basis, where the free model parameters are represented by physical (i.e. observable) quantities, is given by<sup>1</sup>

$$m_h, m_H, \sin \alpha, v, \tan \beta \equiv \frac{v}{x}. \tag{16}$$

The vacuum expectation value of the Higgs doublet  $\Phi$  is given by the SM value  $v \sim 246$  GeV, and one of the Higgs masses is fixed to  $m_{h/H} = 125.09$  GeV, eliminating two of the five parameters. We are thus left with only three independent parameters,

$$\{m \equiv m_{H/h}, \sin \alpha, \tan \beta\}, \tag{17}$$

where the latter enters the collider phenomenology only through the heavy Higgs decay mode into the lighter Higgs,  $H \rightarrow hh$ . Note that from a collider perspective, for cases where the decay mode  $H \rightarrow hh$  is kinematically allowed,

<sup>1</sup> Note that even if the  $Z_2$  symmetry is not imposed, the parameters of the model relevant for the collider phenomenology considered here can always be chosen in terms of the masses, a mixing angle, and an additional parameter determining the  $H \rightarrow hh$  decay channel.

the input parameter  $\tan \beta$  could be replaced by either the total width of the heavier state,  $\Gamma(H)$ , the branching ratio  $\text{BR}(H \rightarrow hh)$ , or the partial decay width of this channel,  $\Gamma(H \rightarrow hh)$ , respectively, rendering the following viable parameter choices besides Eq. (17):

$$\{m \equiv m_{H/h}, \sin \alpha, \Gamma(H)\}, \tag{18}$$

$$\{m \equiv m_{H/h}, \sin \alpha, \text{BR}(H \rightarrow hh)\}, \tag{19}$$

$$\{m \equiv m_{H/h}, \sin \alpha, \Gamma(H \rightarrow hh)\}. \tag{20}$$

If the insertion starts on the Lagrangian level (via e.g. `FeynRules` [79], `SARAH` [80,81] or similar), also the Lagrangian parameters as such can be used as input values, but then care must be taken to correctly translate these into the phenomenologically viable parameter regions.

### 3 Constraints

In this section we list all theoretical and experimental constraints that we take into account, and give an overview over the impact of these constraints on the parameter space. We refer the reader to Ref. [38] for details of the implementation of these constraints. With respect to Ref. [38] we update the experimental limits from LHC Higgs searches, leading to a change in the allowed parameter space especially in the lower mass range,  $m_H \in [130, 250]$  GeV. We also include constraints from the combined ATLAS and CMS Higgs signal strength [82], rendering a significantly stronger limit on the mixing angle. However, this limit is still not as strong as the constraint from the  $W$  boson mass measurement in most of the parameter space.

#### 3.1 Theoretical constraints

We consider the following theoretical constraints in the selection of the benchmark scenarios:

- vacuum stability and minimization of model up to a scale  $\mu_{\text{run}} = 4 \times 10^{10}$  GeV,
- perturbative unitarity of the  $2 \rightarrow 2$   $S$ -matrix for  $(W^+ W^-, ZZ, hh, hH, HH)$  initial and final states,
- perturbativity of the couplings in the potential,  $|\lambda_i| \leq 4\pi$ , up to a high energy scale,  $\mu_{\text{run}} = 4 \times 10^{10}$  GeV, employing one-loop renormalization group equations (RGEs) [83].

#### 3.2 Experimental constraints

The following experimental constraints are taken into account at the 95 % C.L.:

- agreement with electroweak precision observables, employing the oblique parameters  $S, T, U$  [84–87] and using the results from the global fit from the GFitter Group [88],
- agreement with the observed  $W$  boson mass [89–91],  $M_W = 80.385 \pm 0.015$  GeV, employing the NLO calculation presented in Ref. [32],
- agreement with limits from direct Higgs searches at LEP, Tevatron, and the LHC using HiggsBounds (version 4.3.1) [71–75]. With respect to the results presented in Ref. [38], limits from the following searches have been included here:
  - ATLAS search for  $H \rightarrow WW$  [92],
  - ATLAS search for  $H \rightarrow ZZ$  [70],
  - combination of ATLAS searches for  $H \rightarrow hh \rightarrow bb\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, bbbb$  [67],
  - CMS search for  $H \rightarrow VV$  ( $V = W^\pm, Z$ ) [66],
  - CMS search for  $H \rightarrow hh \rightarrow 4\tau$ , where  $H$  is the SM-like Higgs boson at 125 GeV [93].
- agreement with the observed signal strengths of the 125 GeV Higgs boson, using HiggsSignals (version 1.4.0) [76], and using the results from the ATLAS and CMS combination of the LHC Run 1 data,  $\mu = 1.09 \pm 0.11$  [82], leading to

$$|\sin \alpha| \leq 0.36 \tag{21}$$

for the heavy Higgs mass range  $m_H \gtrsim 150$  GeV (high-mass range,  $m_h \sim 125$  GeV), and

$$|\sin \alpha| \geq 0.87 \tag{22}$$

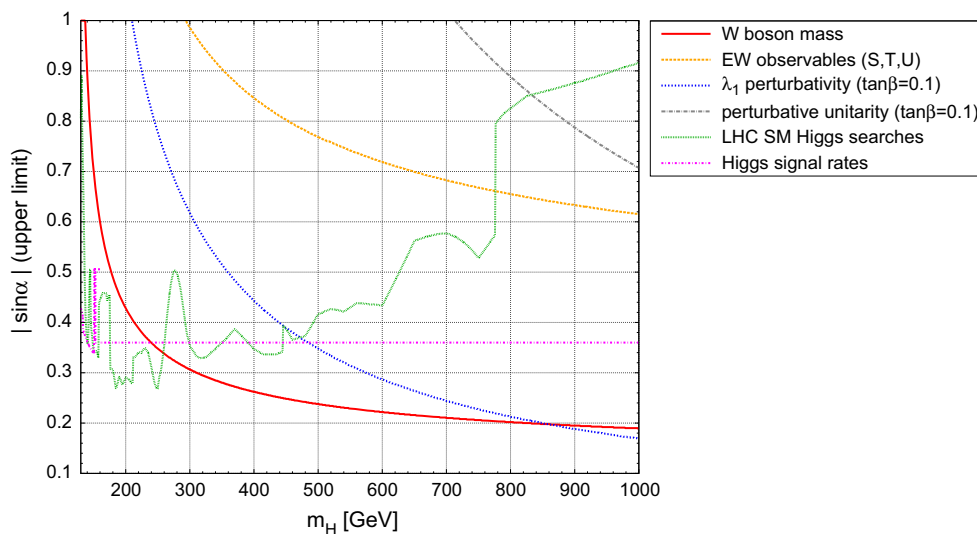
for the light Higgs mass range  $m_h \lesssim 100$  GeV (low-mass range,  $m_H \sim 125$  GeV). In these mass regions potential signal overlap with the SM-like Higgs at 125 GeV can be neglected. For Higgs masses in the range [100, 150] GeV we employ HiggsSignals using observables from the individual Higgs channels, which enables to approximately take into account a potential signal overlap [76], see also Ref. [38] for details.

### 3.3 Allowed parameter regions and sensitivity of the constraints

#### 3.3.1 High-mass region

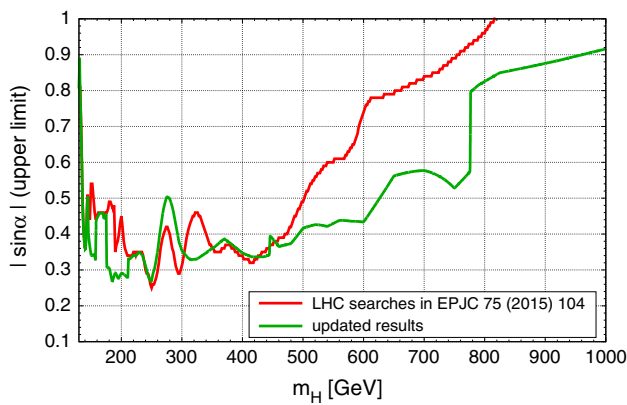
The importance of the different constraints on the mixing angle  $\sin \alpha$  in the high-mass region, where  $m_h \sim 125$  GeV, is summarized in Fig. 1. Recall that this angle is responsible for the *global* suppression of the production cross section with respect to the SM prediction at the same Higgs mass. We see that in the lower mass region,  $m_H \lesssim 250$  GeV, the most important constraints stem from direct Higgs searches [66, 70, 94–96] and the combined Higgs signal strength [82], whereas for higher masses,  $m_H \in [250 \text{ GeV}; 800 \text{ GeV}]$ , the  $W$  boson mass becomes the strongest constraint [32]. Requiring perturbativity of the couplings yields the upper limit on  $|\sin \alpha|$  for very heavy Higgs bosons,  $m_H \geq 800$  GeV.

The updated combined signal strength reduces the maximally allowed mixing angle from previously  $|\sin \alpha| \lesssim 0.50$  [38] to  $|\sin \alpha| \lesssim 0.36$ . The updated limits from LHC Higgs searches in channels with vector boson final states also generally lead to stronger constraints, except in the region  $m_H \in [260, 300]$  GeV, where a statistical upward fluctua-



**Fig. 1** Maximal allowed values for  $|\sin \alpha|$  in the high-mass region,  $m_H \in [130, 1000]$  GeV, from NLO calculations of the  $W$  boson mass (red, solid) [32], electroweak precision observables (EWPOs) tested via the oblique parameters  $S, T$ , and  $U$  (orange, dashed), perturbativity of

the RG-evolved coupling  $\lambda_1$  (blue, dotted), evaluated for an exemplary choice  $\tan \beta = 0.1$ , perturbative unitarity (gray, dash-dotted), direct LHC Higgs searches (green, dashed), and the Higgs signal strength (magenta, dash-dotted)



**Fig. 2** Comparison of the  $|\sin \alpha|$  limit obtained from the LHC Higgs searches with SM final states as presented in Ref. [38] (red) with the updated analysis (green)

**Table 1** List of LHC Higgs search channels that are applied by HiggsBounds in the high-mass region, yielding the upper limit on  $|\sin \alpha|$  shown in Figs. 1 and 2

Range of $m_H$ [GeV]	Search channel	Reference
130–145	$H \rightarrow ZZ \rightarrow 4\ell$	[94] (CMS)
145–158	$H \rightarrow VV$ ( $V=W,Z$ )	[66] (CMS)
158–163	SM comb.	[95] (CMS)
163–170	$H \rightarrow WW$	[96] (CMS)
170–176	SM comb.	[95] (CMS)
176–211	$H \rightarrow VV$ ( $V=W,Z$ )	[66] (CMS)
211–225	$H \rightarrow ZZ \rightarrow 4\ell$	[94] (CMS)
225–445	$H \rightarrow VV$ ( $V=W,Z$ )	[66] (CMS)
445–776	$H \rightarrow ZZ$	[70] (ATLAS)
776–1000	$H \rightarrow VV$ ( $V=W,Z$ )	[66] (CMS)

tion in the CMS  $H \rightarrow ZZ \rightarrow 4\ell$  channel [66] leads to a slightly weaker limit than previously observed. A comparison of previously presented limits from LHC Higgs searches with the current status is displayed in Fig. 2. We see that the updated constraints yield stronger limits in particular for  $m_H \leq 250$  GeV as well as for  $m_H \gtrsim 400$  GeV. We supplement this comparison by giving a detailed list in Table 1 of the LHC Higgs search channels that have been applied by HiggsBounds in the various mass regions.<sup>2</sup>

The relatively strong constraints on the mixing angle lead to a significant suppression of the direct production rates of the heavy Higgs boson at LHC run 2. Figure 3 shows the predicted production cross section at 14 TeV after all con-

<sup>2</sup> HiggsBounds selects the most sensitive channel by comparing the expected exclusion limits first. In a second step, the predicted signal strength is confronted with the observed exclusion limit only of this selected channel. This well-defined statistical procedure allows one to systematically test the model against a plethora of Higgs search limits without diluting the 95 % C.L. of the individual limits.

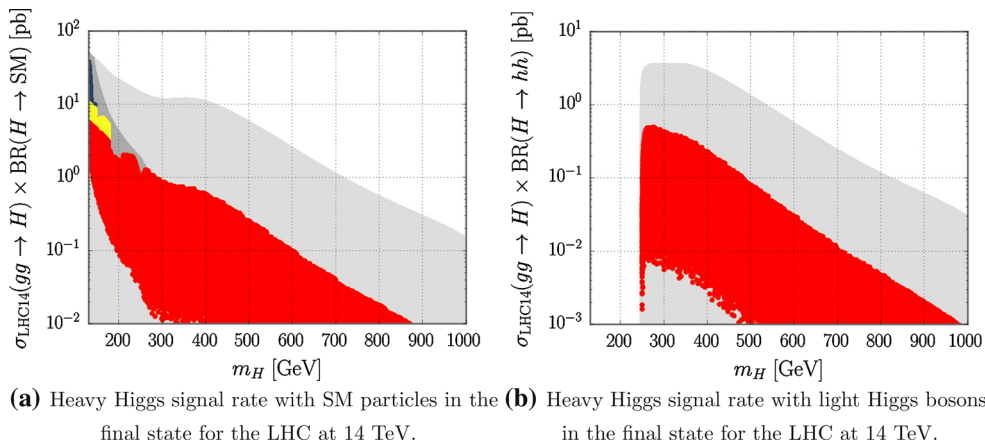
straints have been taken into account. The production cross sections rapidly decrease with higher masses  $m_H$  due to both the stronger constraints on the mixing angle (cf. Fig. 1) and a reduction of the available phase space for higher masses. The cross section for direct production in gluon fusion and successive decay into SM final states ranges from about 10 pb at lower masses to about 10 fb for masses around 800 GeV. Note that in order to obtain the predictions for a particular SM decay mode,  $H \rightarrow XX$ , these numbers need to be multiplied by a factor of  $\text{BR}(H \rightarrow XX)/\text{BR}(H \rightarrow \text{SM})$ , where  $\text{BR}(H \rightarrow \text{SM})$  is the sum over all branching ratios of Higgs decays into SM particles according to Eq. (13). Taking into account the current design strategy for the LHC run (cf. e.g. Ref. [97]) and expecting an integrated luminosity of about 100 and 300  $\text{fb}^{-1}$  before the shutdowns in 2019 and 2023, respectively, this translates into the fact that at least  $\mathcal{O}(10^3)$  heavy Higgs bosons could be produced in that mass range in optimistic scenarios. For the  $hh$  final state, on the other hand, cross sections are about an order of magnitude lower. A comparison of current exclusion limits from LHC  $H \rightarrow hh$  searches with the predictions in the viable parameter space will be given in Sect. 4.

Note that these plots were obtained using a *simple rescaling* of production cross section of a SM Higgs boson of the same mass as given in Ref. [23], i.e. contributions due to interference with the additional scalar are not included. Tools which can handle these have been presented e.g. in Refs. [55, 56, 58, 59]. These studies, however, focus on effects on the line-shape of the heavy scalar boson *after* a possible discovery. Moreover, thus far, their calculations neglect additional higher order corrections, whereas these have been calculated to great precision for the SM Higgs boson and are included in Fig. 3 [23]. For the future, it would be desirable to perform a dedicated study of interference effects including higher order corrections for the benchmark points presented in this work in order to estimate their effects (and the systematic uncertainty introduced here by neglecting them).

### 3.3.2 Low-mass region

In the low-mass region, where the heavier Higgs state takes the role of the discovered Higgs boson,  $m_H \sim 125$  GeV, the parameter space is extremely constrained by the Higgs signal strength and exclusion limits from LEP Higgs searches [89]. The updated experimental results do not change the limits presented in Ref. [38]. We review these limits in Table 2. Note that in the low-mass region the couplings of the heavy Higgs boson at 125 GeV become SM-like for  $|\sin \alpha| = 1$ .

Table 3 gives the direct production cross section in gluon fusion for the undiscovered light Higgs state at a 8 and 14 TeV LHC, respectively. Again, the production cross section stems from a simple rescaling of the corresponding cross section for a SM Higgs boson of that mass [23, 98].



**Fig. 3** LHC signal rates of the heavy Higgs boson  $H$  decaying into SM particles (a) or into two light Higgs bosons,  $H \rightarrow hh$ , (b), in dependence of the heavy Higgs mass,  $m_H$ , for a center-of-mass (CM) energy of 14 TeV. Shown are regions which are still allowed after all constraints are taken into account: *Red and yellow regions* correspond to agreement with the Higgs signal strength measurements at the  $1\sigma$

and  $2\sigma$  level, respectively, *blue points* comply with direct experimental searches but do not agree with the Higgs signal strength within  $2\sigma$ . *Light gray points* denote scan points that are excluded by either perturbative unitarity, perturbativity of the couplings, RGE running or the  $W$  boson mass, while *dark gray points* denote regions in parameter space that obey these constraints but are excluded by direct searches

**Table 2** Limits on  $\sin \alpha$  and  $\tan \beta$  in the low-mass scenario for various light Higgs masses  $m_h$  and  $\tan \beta = 1$ . In the second column we give the lower limit on  $\sin \alpha$  stemming from exclusion limits from LEP or LHC Higgs searches (evaluated with `HiggsBounds`). If the lower limit on  $\sin \alpha$  obtained from the Higgs signal rates (evaluated with `HiggsSignals`) results in stricter limits, they are displayed in the third column. The fourth column displays the upper limit on  $\tan \beta$  that stems from perturbative unitarity in the complete decoupling case ( $|\sin \alpha| = 1$ ). In the fifth column we give the  $\tan \beta$  value for which  $\Gamma_{H \rightarrow hh} = 0$  is obtained given the maximal mixing angle allowed by the Higgs exclusion limits (second column). At this  $\tan \beta$  value, the  $|\sin \alpha|$  limit obtained from the Higgs signal rates (third column) is abrogated. The table is taken from Ref. [38]

$m_h$ [GeV]	$ \sin \alpha _{\min, \text{HB}}$	$ \sin \alpha _{\min, \text{HS}}$	$(\tan \beta)_{\max}$	$(\tan \beta)_{\text{no } H \rightarrow hh}$
120	0.410	0.918	8.4	–
110	0.819	0.932	9.3	–
100	0.852	0.891	10.1	–
90	0.901	–	11.2	–
80	0.974	–	12.6	–
70	0.985	–	14.4	–
60	0.978	0.996	16.8	0.21
50	0.981	0.998	20.2	0.20
40	0.984	0.998	25.2	0.18
30	0.988	0.998	33.6	0.16
20	0.993	0.998	50.4	0.12
10	0.997	0.998	100.8	0.08

### 3.3.3 Intermediate mass region

The intermediate mass region, where both Higgs bosons have masses between 120 and 130 GeV, was originally discussed in Ref. [38]. In this mass region the observed Higgs signal at

**Table 3** Maximally allowed cross section for light Higgs production in gluon fusion,  $\sigma_{gg} = (\cos^2 \alpha)_{\max} \times \sigma_{gg, \text{SM}}$ , at the LHC at CM energies of 8 and 14 TeV after all current constraints have been taken into account, corresponding to the mixing angles from Table 2. This is an updated version of Tab. V in Ref. [38]

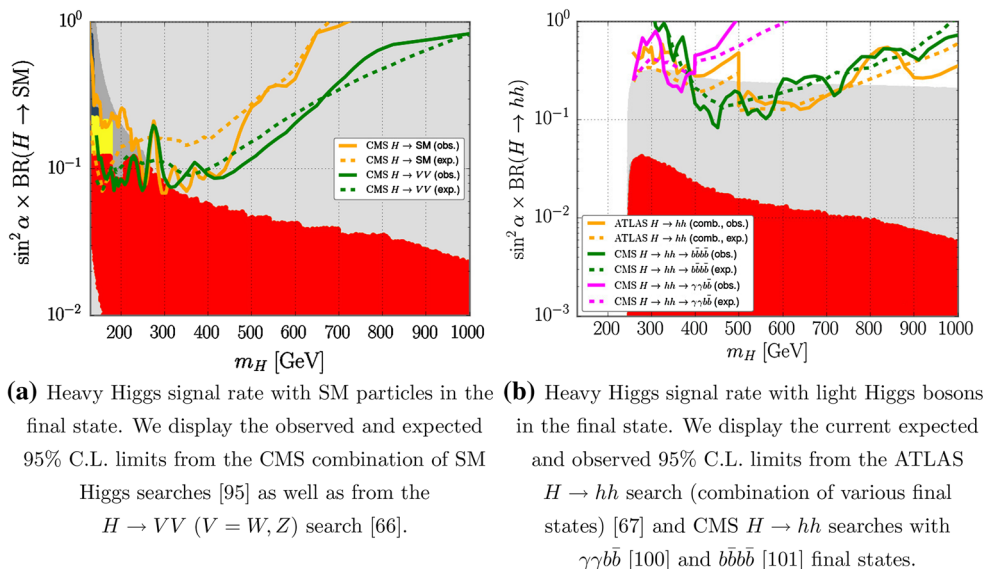
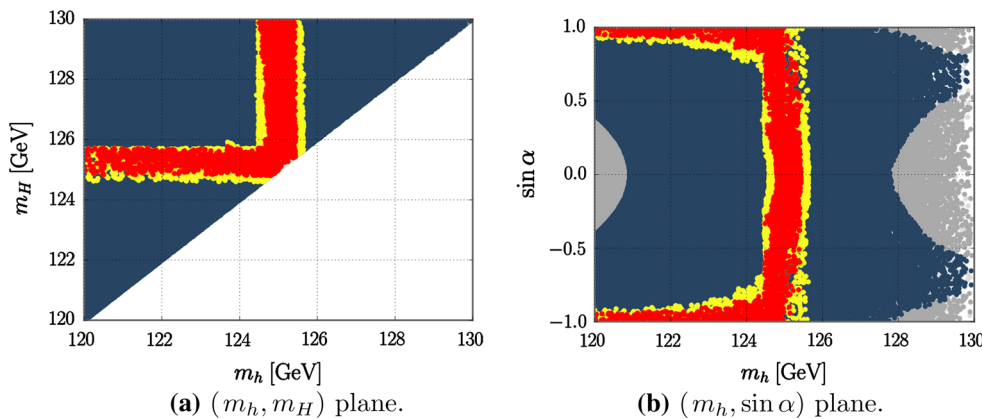
$m_h$ [GeV]	$\sigma_{gg}^{8\text{TeV}}$ [pb]	$\sigma_{gg}^{14\text{TeV}}$ [pb]	$m_h$ [GeV]	$\sigma_{gg}^{8\text{TeV}}$ [pb]	$\sigma_{gg}^{14\text{TeV}}$ [pb]
120	3.28	8.41	60	0.63	1.38
110	3.24	8.17	50	0.45	0.96
100	6.12	15.10	40	0.76	1.59
90	6.82	16.47	30	1.60	3.09
80	2.33	5.41	20	5.04	8.97
70	1.72	3.91	10	18.44	29.74

125 GeV may be due to a signal overlap of both Higgs bosons, depending on the mass separation and the mass resolution of the experimental analysis. We show the allowed parameter space in the  $(m_h, m_H)$  and  $(m_h, \sin \alpha)$  plane from the updated fit in Fig. 4. The updated signal strength observables in `HiggsSignals-1.4.0` yield only marginal improvements in the constrained parameter space, while the updated limits from direct Higgs searches are irrelevant in this mass region.

## 4 Benchmark scenarios for LHC Run 2

The benchmark scenarios that are presented in this section are chosen such that they feature the *maximally* allowed production cross section at the LHC. We first present the benchmark scenarios for the high-mass region, where the light Higgs plays the role of the discovered SM-like Higgs at 125 GeV,

**Fig. 4** Parameter space for the intermediate mass region after taking all constraints into account. The color coding follows Fig. 3



**Fig. 5** Collider signal rates of the heavy Higgs boson  $H$  decaying into SM particles (a) or into two light Higgs bosons,  $H \rightarrow hh$ , (b), in dependence of the heavy Higgs mass,  $m_H$ . The color coding is the same as in

**Fig. 3**. The rates are normalized to the inclusive SM Higgs production cross section at the corresponding mass value [23, 102, 103]

and then turn to the low-mass range, where the heavy Higgs state is the SM-like Higgs boson.<sup>3</sup>

### 4.1 High-mass region

We distinguish between two different search channels:

- **Higgs decays into SM particles:** Maximizing the production cross section corresponds to maximizing the parameter [29]

$$\kappa \equiv \frac{\sigma}{\sigma_{SM}} \times BR(H \rightarrow SM) = \sin^4 \alpha \frac{\Gamma_{SM,tot}}{\Gamma_{tot}}$$

<sup>3</sup> See also Ref. [99] for recent benchmark point suggestions within the complex singlet model.

- **Higgs decays into two light Higgs bosons,  $H \rightarrow hh$ :** Here, the parameter

$$\kappa' \equiv \frac{\sigma}{\sigma_{SM}} \times BR(H \rightarrow hh) = \sin^2 \alpha \frac{\Gamma_{H \rightarrow hh}}{\Gamma_{tot}}$$

is maximized to obtain the largest possible signal yield.

Figure 5 shows the allowed range of these two quantities, after all constraints have been taken into account. For the

**Table 4** Benchmark points for mass ranges where the on-shell decay  $H \rightarrow hh$  is kinematically forbidden. Maximal values of  $\tan \beta$  were calculated at the maximal mixing angle, and should be applied for consistency reasons

$m_H$ [GeV]	$ \sin \alpha _{\max}$	$\tan \beta_{\max}$	$m_H$ [GeV]	$ \sin \alpha _{\max}$	$\tan \beta_{\max}$
130	0.42	1.79	195	0.28	1.22
135	0.38	1.73	200	0.29	1.19
140	0.36	1.69	210	0.28	1.14
145	0.35	1.62	215	0.33	1.12
150	0.34	1.57	220	0.34	1.10
160	0.36	1.49	230	0.35	1.05
180	0.30	1.32	235	0.34	1.03
185	0.27	1.28	240	0.31	1.00
190	0.29	1.26	245	0.28	0.98

**Table 5** Maximal and minimal allowed branching ratios of the decay  $H \rightarrow hh$ , taken at the maximally allowed value of  $|\sin \alpha|$ . Note that minimal values for the  $\text{BR}(H \rightarrow hh)$  stem from  $\sin \alpha \leq 0$

$m_H$ [GeV]	$ \sin \alpha _{\max}$	$BR_{\min}^{H \rightarrow hh}$	$BR_{\max}^{H \rightarrow hh}$	$m_H$ [GeV]	$ \sin \alpha _{\max}$	$BR_{\min}^{H \rightarrow hh}$	$BR_{\max}^{H \rightarrow hh}$
255	0.31	0.09	0.27	430	0.25	0.19	0.30
260	0.34	0.11	0.33	470	0.24	0.19	0.28
265	0.33	0.13	0.36	520	0.23	0.19	0.26
280	0.32	0.17	0.40	590	0.22	0.19	0.25
290	0.31	0.18	0.40	665	0.21	0.19	0.24
305	0.30	0.20	0.40	770	0.20	0.19	0.23
325	0.29	0.21	0.40	875	0.19	0.19	0.22
345	0.28	0.22	0.39	920	0.18	0.19	0.22
365	0.27	0.21	0.36	975	0.17	0.19	0.21
395	0.26	0.20	0.32	1000	0.17	0.19	0.21

Higgs decay channel into SM particles, we see that searches from CMS pose important constraints for  $m_H \lesssim 400$  GeV. For the Higgs-to-Higgs decay channel  $H \rightarrow hh$ , on the other hand, both ATLAS [67] and CMS [100, 101] searches are not yet sensitive enough to exclude points that are not already in conflict with other constraints.

We quantify the benchmark scenarios for both signal channels in this regime by considering the *maximally* allowed mixing angle together with the *maximal* and *minimal* branching ratio for the decay  $H \rightarrow hh$ , respectively. While these maximal and minimal points define *benchmark points*, all  $\text{BR}(H \rightarrow hh)$  values in between are in principle allowed. Therefore, an interpolation between the minimal and maximal values defines a higher-dimensional benchmark scenario (*benchmark slope* or *plane*), where the additional third parameter (cf. Eqs. (17)–(20)) is floating.

We furthermore distinguish scenarios for which the  $H \rightarrow hh$  on-shell decay mode is kinematically allowed or forbidden. As we neglect all other triple and quartic Higgs self-couplings apart from  $\mu'$ , and work in the on-shell approximation,  $\tan \beta$  only influences the collider phenomenology for regions in parameter space where the decay  $H \rightarrow hh$  is kinematically allowed, i.e. for heavy Higgs masses  $m_H \geq 2m_h \approx 250$  GeV. For lower masses  $\tan \beta$  is irrelevant for the

phenomenology considered here. However, to be consistent, we recommend to still keep the values within the respective parameter regions allowed by perturbativity and perturbative unitarity.

Benchmark scenarios for both cases are given in Tables 4 and 5, respectively. Parameter ranges which are not explicitly listed can to a first approximation be linearly interpolated.

In addition, we also list exemplary *benchmark points* for this mass region in Tables 6 and 7, where we additionally give the predictions for other relevant decay modes. Whenever kinematically accessible, we provide two benchmark points for every heavy Higgs mass, representing the maximal and minimal branching ratio for the  $H \rightarrow hh$  decay, respectively.<sup>4</sup> The mixing angle is always chosen such that the production rate of the additional scalar is maximized.

#### 4.2 Low-mass region

For the case that the heavier Higgs boson is taken to be the discovered SM-like Higgs boson with  $m_H \sim 125$  GeV,  $|\sin \alpha| = 1$  corresponds to the SM limit, and deviations

<sup>4</sup> Electroweak corrections to the decay  $H \rightarrow hh$  have been presented for some of these benchmark points in Ref. [54].



**Table 6** Benchmark scenarios for the high-mass region for fixed masses and  $|\sin \alpha|$ , floating  $\tan \beta$  (between scenarios  $a$  and  $b$ ). Reference production cross sections have been taken from the upcoming CERN Yellow Report 4 by the LHC Higgs Cross Section Working Group [104]

Benchmark scenarios for the real singlet	
Main features	Real singlet extension, with two vevs and no hidden sector interaction with heavy Higgs $H$ and light Higgs $h$
Fixed parameters	$M_h = 125.1$ GeV or $M_H = 125.1$ GeV
Irrelevant parameters	$\tan \beta$ whenever channel $H \rightarrow hh$ kinematically not accessible
Additional comments	Predictions at LO, factorized production and decay; $a, b$ signify maximal and minimal $\text{BR}(H \rightarrow hh)$ ; for $b$ , $\sin \alpha < 0$ ; any values for $\tan \beta$ between scenario $a$ and $b$ are allowed
<i>Production cross sections at 14 TeV [pb] and branching fractions</i>	
BHM300 $a, b$	
Spectrum	$M_H = 300$ GeV, $ \sin \alpha  = 0.31, \tan \beta (a) = 0.79, \tan \beta (b) = 0.79$
$\sigma(gg \rightarrow h)$	44.91
$\sigma(gg \rightarrow H)$	1.09
$\text{BR}(H \rightarrow hh)$	0.41 ( $a$ ), 0.17 ( $b$ )
$\text{BR}(H \rightarrow WW)$	0.41 ( $a$ ), 0.57 ( $b$ )
$\text{BR}(H \rightarrow ZZ)$	0.18 ( $a$ ), 0.25 ( $b$ )
BHM400 $a, b$	
Spectrum	$M_H = 400$ GeV, $ \sin \alpha  = 0.26, \tan \beta (a) = 0.58, \tan \beta (b) = 0.59$
$\sigma(gg \rightarrow h)$	46.32
$\sigma(gg \rightarrow H)$	0.76
$\text{BR}(H \rightarrow hh)$	0.32 ( $a$ ), 0.20 ( $b$ )
$\text{BR}(H \rightarrow WW)$	0.40 ( $a$ ), 0.47 ( $b$ )
$\text{BR}(H \rightarrow ZZ)$	0.18 ( $a$ ), 0.22 ( $b$ )
$\text{BR}(H \rightarrow t\bar{t})$	0.10 ( $a$ ), 0.12 ( $b$ )
BHM500 $a, b$	
Spectrum	$M_H = 500$ GeV, $ \sin \alpha  = 0.24, \tan \beta (a) = 0.44, \tan \beta (b) = 0.46$
$\sigma(gg \rightarrow h)$	46.82
$\sigma(gg \rightarrow H)$	0.31
$\text{BR}(H \rightarrow hh)$	0.26 ( $a$ ), 0.19 ( $b$ )
$\text{BR}(H \rightarrow WW)$	0.41 ( $a$ ), 0.44 ( $b$ )
$\text{BR}(H \rightarrow ZZ)$	0.19 ( $a$ ), 0.21 ( $b$ )
$\text{BR}(H \rightarrow t\bar{t})$	0.14 ( $a$ ), 0.16 ( $b$ )

from this value parametrize the new physics contributions. As in the high-mass region, the following channels are interesting:

- *Direct production* of the lighter Higgs state  $h$  and successive decay into SM particles,
- *Decay* of the SM-like Higgs boson  $H$  into the lighter Higgs states,  $H \rightarrow hh$ .

For the direct production of the light Higgs state smaller  $|\sin \alpha|$  values are of interest, as the cross section scales with  $\cos^2 \alpha$ . We provide the minimally allowed values for  $|\sin \alpha|$  in Table 2. Table 3 lists the respective direct production cross sections at 8 and 14 TeV. These values can directly be used

as benchmark scenarios for collider searches for direct light Higgs production.

For the second channel—the decay of the SM-like Higgs into two lighter Higgs states—we list maximal branching ratios for the decay  $H \rightarrow hh$  in Table 8. As long as the decay  $H \rightarrow hh$  is kinematically accessible, the maximal value of its branching ratio,  $\text{BR}(H \rightarrow hh) \simeq 0.259$ , is not dependent on the light Higgs mass. The lighter Higgs bosons then decay further according to the branching ratios of a SM Higgs of the respective mass. A first experimental search of this signature with the light Higgs boson decaying into  $\tau$  lepton pairs in the mass range  $m_h \in [5, 15]$  GeV has already been performed by the CMS experiment [93].

**Table 7** Benchmark scenarios for the high-mass region for fixed masses and  $|\sin \alpha|$ , floating  $\tan \beta$  (between scenarios  $a$  and  $b$ ). Reference production cross sections have been taken from the upcoming CERN Yellow Report 4 by the LHC Higgs Cross Section Working Group [104]

Production cross sections at 14 TeV [pb] and branching fractions (*continued*)

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<b>BHM600 <math>a, b</math></b>	
Spectrum	$M_H = 600 \text{ GeV},$ $ \sin \alpha  = 0.22, \tan \beta (a) = 0.37, \tan \beta (b) = 0.38$
$\sigma(gg \rightarrow h)$	47.28
$\sigma(gg \rightarrow H)$	0.12
$\text{BR}(H \rightarrow hh)$	0.25 ( $a$ ), 0.19 ( $b$ )
$\text{BR}(H \rightarrow WW)$	0.41 ( $a$ ), 0.45 ( $b$ )
$\text{BR}(H \rightarrow ZZ)$	0.21 ( $a$ ), 0.22 ( $b$ )
$\text{BR}(H \rightarrow t\bar{t})$	0.13 ( $a$ ), 0.14 ( $b$ )
<b>BHM700 <math>a, b</math></b>	
Spectrum	$M_H = 700 \text{ GeV},$ $ \sin \alpha  = 0.21, \tan \beta (a) = 0.31, \tan \beta (b) = 0.32$
$\sigma(gg \rightarrow h)$	47.49
$\sigma(gg \rightarrow H)$	0.050
$\text{BR}(H \rightarrow hh)$	0.24 ( $a$ ), 0.19 ( $b$ )
$\text{BR}(H \rightarrow WW)$	0.44 ( $a$ ), 0.47 ( $b$ )
$\text{BR}(H \rightarrow ZZ)$	0.22 ( $a$ ), 0.23 ( $b$ )
$\text{BR}(H \rightarrow t\bar{t})$	0.10 ( $a$ ), 0.11 ( $b$ )
<b>BHM800 <math>a, b</math></b>	
Spectrum	$M_H = 800 \text{ GeV},  \sin \alpha  = 0.2, \tan \beta (a) = 0.25, \tan \beta (b) = 0.27$
$\sigma(gg \rightarrow h)$	47.69
$\sigma(gg \rightarrow H)$	0.022
$\text{BR}(H \rightarrow hh)$	0.23 ( $a$ ), 0.19 ( $b$ )
$\text{BR}(H \rightarrow WW)$	0.46 ( $a$ ), 0.48 ( $b$ )
$\text{BR}(H \rightarrow ZZ)$	0.23 ( $a$ ), 0.24 ( $b$ )
$\text{BR}(H \rightarrow t\bar{t})$	0.08 ( $a$ ), 0.09 ( $b$ )
<b>BHM200</b>	
Spectrum	$M_H = 200 \text{ GeV},$ $ \sin \alpha  = 0.29, \tan \beta = 1.19$
$\sigma(gg \rightarrow h)$	45.50
$\sigma(gg \rightarrow H)$	1.74
$\text{BR}(H \rightarrow \text{SM})$	As for a SM Higgs boson with mass of 200 GeV

**Table 8** Maximal branching ratios for  $H \rightarrow hh$ . This BR can always be zero for the choice  $\tan \beta = -\cot \alpha$

$m_h [\text{GeV}]$	$\sin \alpha$	$\text{BR}_{\text{max}}^{H \rightarrow hh}$
60	0.9996	0.259
50	0.9999	0.259
40	0.9999	0.259
30	0.9999	0.259
20	0.9998	0.259
10	0.9999	0.259

**Table 9** Low-mass benchmark scenarios for the Higgs-to-Higgs decay signature for fixed masses and  $|\sin \alpha|$ , floating  $\tan \beta$  (between scenarios  $a$  and  $b$ ). In scenario  $b$  we have  $\tan \beta = -\cot \alpha$ . The  $|\sin \alpha|$  values have been optimized for scenario  $a$ , which in turn leads to a suppression of direct production for the lighter state. For direct production of the lighter scalar, the parameters in Tables 2 and 3 should be used. For BHM50 - BHM10, the production cross section for the SM like Higgs is  $\sigma(gg \rightarrow H) = 49.66 \text{ pb}$ . Reference production cross sections have been taken from the upcoming CERN Yellow Report 4 by the LHC Higgs Cross Section Working Group [104]

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<b>BHM60 <math>a, b</math></b>	
Spectrum	$M_h = 60 \text{ GeV},  \sin \alpha  = 0.9997, \tan \beta (a) = 3.48, \tan \beta (b) = 0.025$
$\sigma(gg \rightarrow h)$	0.10
$\sigma(gg \rightarrow H)$	49.65
$\text{BR}(H \rightarrow hh)$	0.26 ( $a$ ), 0 ( $b$ )
$\text{BR}(H \rightarrow \text{SM})$	Rescaled by 0.74 ( $a$ ), as in SM ( $b$ )
<b>BHM50 <math>a, b</math></b>	
Spectrum	$M_h = 50 \text{ GeV},  \sin \alpha  = 0.9998, \tan \beta (a) = 3.25, \tan \beta (b) = 0.020$
$\sigma(gg \rightarrow h)$	0.098
$\text{BR}(H \rightarrow hh)$	0.26 ( $a$ ), 0 ( $b$ )
$\text{BR}(H \rightarrow \text{SM})$	Rescaled by 0.74 ( $a$ ), as in SM ( $b$ )
<b>BHM40 <math>a, b</math></b>	
Spectrum	$M_h = 40 \text{ GeV},  \sin \alpha  = 0.9998, \tan \beta (a) = 3.13, \tan \beta (b) = 0.020$
$\sigma(gg \rightarrow h)$	0.16
$\text{BR}(H \rightarrow hh)$	0.26 ( $a$ ), 0 ( $b$ )
$\text{BR}(H \rightarrow \text{SM})$	Rescaled by 0.74 ( $a$ ), as in SM ( $b$ )
<b>BHM30 <math>a, b</math></b>	
Spectrum	$M_h = 30 \text{ GeV},  \sin \alpha  = 0.9998, \tan \beta (a) = 3.16, \tan \beta (b) = 0.020$
$\sigma(gg \rightarrow h)$	0.31
$\text{BR}(H \rightarrow hh)$	0.26 ( $a$ ), 0 ( $b$ )
$\text{BR}(H \rightarrow \text{SM})$	Rescaled by 0.74 ( $a$ ), as in SM ( $b$ )
<b>BHM20 <math>a, b</math></b>	
Spectrum	$M_h = 20 \text{ GeV},  \sin \alpha  = 0.9998, \tan \beta (a) = 3.23, \tan \beta (b) = 0.020$
$\sigma(gg \rightarrow h)$	0.90
$\text{BR}(H \rightarrow hh)$	0.26 ( $a$ ), 0 ( $b$ )
$\text{BR}(H \rightarrow \text{SM})$	Rescaled by 0.74 ( $a$ ), as in SM ( $b$ )
<b>BHM10 <math>a, b</math></b>	
Spectrum	$M_h = 10 \text{ GeV},  \sin \alpha  = 0.9998, \tan \beta (a) = 3.29, \tan \beta (b) = 0.020$
$\sigma(gg \rightarrow h)$	2.98
$\text{BR}(H \rightarrow hh)$	0.26 ( $a$ ), 0 ( $b$ )
$\text{BR}(H \rightarrow \text{SM})$	Rescaled by 0.74 ( $a$ ), as in SM ( $b$ )

We present benchmark points for fixed masses in Table 9. Here,  $|\sin \alpha|$  values closer to unity are needed in order to obtain maximal branching ratios for this channel, which in turn leads to the reduction of direct production for the lighter state by almost an order of magnitude with respect to the val-

ues presented in Table 3. Again, we recommend to scan over  $\tan \beta$  between the values of scenario  $a$  and  $b$  (thus defining a higher-dimensional benchmark scenario) in order to obtain a range of possible branching ratios.

## 5 Conclusions

In this paper we have revisited and updated the constraints on the parameter space of the real scalar singlet extension of the SM. In comparison with the previous results presented in Ref. [38], the most important improvements have been made in the constraints from new results in LHC searches for a heavy Higgs boson decaying into vector boson final states, as well as from the ATLAS and CMS combination of the signal strength of the discovered Higgs state. We found that these modify our previous findings in the mass range  $130 \text{ GeV} \leq m_H \leq 250 \text{ GeV}$ , where now the direct Higgs searches as well as the ATLAS and CMS signal strength combination render the strongest constraints on the parameter space.

Based on these updated results, we have provided benchmark scenarios for both the high-mass and the low-mass regions for upcoming LHC searches. Hereby, we pursued the philosophy of selecting those points which feature a maximal discovery potential in a dedicated collider search of the corresponding signature. We provided predictions of production cross sections for the LHC at 14 TeV, and supplemented these with information as regards the branching fractions of the relevant decay modes. We encourage the experimental collaborations to make use of these benchmark scenarios in the current and upcoming LHC runs.

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## References

1. P.W. Higgs, Phys. Lett. **12**, 132 (1964)
2. P.W. Higgs, Phys. Rev. Lett. **13**, 508 (1964)
3. F. Englert, R. Brout, Phys. Rev. Lett. **13**, 321 (1964)
4. G. Guralnik, C. Hagen, T. Kibble, Phys. Rev. Lett. **13**, 585 (1964)
5. T. Kibble, Phys. Rev. **155**, 1554 (1967)
6. G. Aad et al. (ATLAS, CMS), Phys. Rev. Lett. **114**, 191803 (2015). [arXiv:1503.07589](https://arxiv.org/abs/1503.07589)
7. R. Schabinger, J.D. Wells, Phys. Rev. D **72**, 093007 (2005). [arXiv:hep-ph/0509209](https://arxiv.org/abs/hep-ph/0509209)
8. B. Patt, F. Wilczek (2006). [arXiv:hep-ph/0605188](https://arxiv.org/abs/hep-ph/0605188)
9. V. Barger, P. Langacker, M. McCaskey, M.J. Ramsey-Musolf, G. Shaughnessy, Phys. Rev. D **77**, 035005 (2008). [arXiv:0706.4311](https://arxiv.org/abs/0706.4311)
10. G. Bhattacharyya, G.C. Branco, S. Nandi, Phys. Rev. D **77**, 117701 (2008). [arXiv:0712.2693](https://arxiv.org/abs/0712.2693)
11. S. Dawson, W. Yan, Phys. Rev. D **79**, 095002 (2009). [arXiv:0904.2005](https://arxiv.org/abs/0904.2005)
12. S. Bock, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas et al., Phys. Lett. B **694**, 44 (2010). [arXiv:1007.2645](https://arxiv.org/abs/1007.2645)
13. P.J. Fox, D. Tucker-Smith, N. Weiner, JHEP **1106**, 127 (2011). [arXiv:1104.5450](https://arxiv.org/abs/1104.5450)
14. C. Englert, T. Plehn, D. Zerwas, P.M. Zerwas, Phys. Lett. B **703**, 298 (2011). [arXiv:1106.3097](https://arxiv.org/abs/1106.3097)
15. C. Englert, J. Jaeckel, E. Re, M. Spannowsky, Phys. Rev. D **85**, 035008 (2012). [arXiv:1111.1719](https://arxiv.org/abs/1111.1719)
16. B. Batell, S. Gori, L.-T. Wang, JHEP **1206**, 172 (2012). [arXiv:1112.5180](https://arxiv.org/abs/1112.5180)
17. C. Englert, T. Plehn, M. Rauch, D. Zerwas, P.M. Zerwas, Phys. Lett. B **707**, 512 (2012). [arXiv:1112.3007](https://arxiv.org/abs/1112.3007)
18. R.S. Gupta, J.D. Wells, Phys. Lett. B **710**, 154 (2012). [arXiv:1110.0824](https://arxiv.org/abs/1110.0824)
19. M.J. Dolan, C. Englert, M. Spannowsky, Phys. Rev. D **87**, 055002 (2013). [arXiv:1210.8166](https://arxiv.org/abs/1210.8166)
20. D. Bertolini, M. McCullough, JHEP **1212**, 118 (2012). [arXiv:1207.4209](https://arxiv.org/abs/1207.4209)
21. B. Batell, D. McKeen, M. Pospelov, JHEP **1210**, 104 (2012). [arXiv:1207.6252](https://arxiv.org/abs/1207.6252)
22. D. Lopez-Val, T. Plehn, M. Rauch, JHEP **1310**, 134 (2013). [arXiv:1308.1979](https://arxiv.org/abs/1308.1979)
23. S. Heinemeyer et al. (The LHC Higgs Cross Section Working Group) (2013). [arXiv:1307.1347](https://arxiv.org/abs/1307.1347)
24. R.S. Chivukula, A. Farzinnia, J. Ren, E.H. Simmons, Phys. Rev. D **88**, 075020 (2013). [arXiv:1307.1064](https://arxiv.org/abs/1307.1064)
25. C. Englert, M. McCullough, JHEP **1307**, 168 (2013). [arXiv:1303.1526](https://arxiv.org/abs/1303.1526)
26. B. Cooper, N. Konstantinidis, L. Lambourne, D. Wardrope, Phys. Rev. D **88**, 114005 (2013). [arXiv:1307.0407](https://arxiv.org/abs/1307.0407)
27. C. Caillol, B. Clerbaux, J.-M. Frere, S. Mollet, Eur. Phys. J. Plus **129**, 93 (2014). [arXiv:1304.0386](https://arxiv.org/abs/1304.0386)
28. R. Coimbra, M.O. Sampaio, R. Santos, Eur. Phys. J. C **73**, 2428 (2013). [arXiv:1301.2599](https://arxiv.org/abs/1301.2599)
29. G.M. Pruna, T. Robens, Phys. Rev. D **88**, 115012 (2013). [arXiv:1303.1150](https://arxiv.org/abs/1303.1150)
30. S. Dawson, A. Gritsan, H. Logan, J. Qian, C. Tully et al. (2013). [arXiv:1310.8361](https://arxiv.org/abs/1310.8361)
31. L. Basso, O. Fischer, J.J. van Der Bij, Phys. Lett. B **730**, 326 (2014). [arXiv:1309.6086](https://arxiv.org/abs/1309.6086)
32. D. Lopez-Val, T. Robens, Phys. Rev. D **90**, 114018 (2014). [arXiv:1406.1043](https://arxiv.org/abs/1406.1043)
33. C. Englert, M. Spannowsky, Phys. Rev. D **90**, 053003 (2014). [arXiv:1405.0285](https://arxiv.org/abs/1405.0285)
34. C. Englert, Y. Soreq, M. Spannowsky, JHEP **05**, 145 (2015). [arXiv:1410.5440](https://arxiv.org/abs/1410.5440)
35. C.-Y. Chen, S. Dawson, I.M. Lewis, Phys. Rev. D **91**, 035015 (2015). [arXiv:1410.5488](https://arxiv.org/abs/1410.5488)
36. D. Karabacak, S. Nandi, S.K. Rai, Phys. Lett. B **737**, 341 (2014). [arXiv:1405.0476](https://arxiv.org/abs/1405.0476)
37. S. Profumo, M.J. Ramsey-Musolf, C.L. Wainwright, P. Winslow, Phys. Rev. D **91**, 035018 (2015). [arXiv:1407.5342](https://arxiv.org/abs/1407.5342)
38. T. Robens, T. Stefaniak, Eur. Phys. J. C **75**, 104 (2015). [arXiv:1501.02234](https://arxiv.org/abs/1501.02234)

39. V. Martfn Lozano, J.M. Moreno, C.B. Park, JHEP 08, 004 (2015). [arXiv:1501.03799](#)
40. A. Falkowski, C. Gross, O. Lebedev, JHEP 05, 057 (2015). [arXiv:1502.01361](#)
41. G. Ballesteros, C. Tamarit, JHEP 09, 210 (2015). [arXiv:1505.07476](#)
42. D. Buttazzo, F. Sala, A. Tesi, JHEP 11, 158 (2015). [arXiv:1505.05488](#)
43. S. Banerjee, M. Mitra, M. Spannowsky, Phys. Rev. D 92, 055013 (2015). [arXiv:1506.06415](#)
44. T. Corbett, O.J.P. Eboli, M.C. Gonzalez-Garcia, Phys. Rev. D 93, 015005 (2016). [arXiv:1509.01585](#)
45. A. Tofghi, O.N. Ghodsi, M. Saeedhoseini, Phys. Lett. B 748, 208 (2015). [arXiv:1510.00791](#)
46. C.-Y. Chen, Q.-S. Yan, X. Zhao, Y.-M. Zhong, Z. Zhao, Phys. Rev. D 93, 013007 (2016). [arXiv:1510.04013](#)
47. S.I. Godunov, A.N. Rozanov, M.I. Vysotsky, E.V. Zhemchugov, Eur. Phys. J. C 76, 1 (2016). [arXiv:1503.01618](#)
48. M. Duch, B. Grzadkowski, M. McGarrie, JHEP 09, 162 (2015). [arXiv:1506.08805](#)
49. Z.-W. Wang, T.G. Steele, T. Hanif, R.B. Mann (2015). [arXiv:1510.04321](#)
50. N. Bernal, X. Chu, JCAP 1601, 006 (2016). [arXiv:1510.08527](#)
51. S. Ghosh, A. Kundu, S. Ray (2015). [arXiv:1512.05786](#)
52. M.J. Dolan, J.L. Hewett, M. KrSmer, T.G. Rizzo (2016). [arXiv:1601.07208](#)
53. S. Kanemura, M. Kikuchi, K. Yagyu, Nucl. Phys. B 907, 286 (2016). [arXiv:1511.06211](#)
54. F. Bojarski, G. Chalons, D. Lopez-Val, T. Robens, JHEP 02, 147 (2016). [arXiv:1511.08120](#)
55. E. Maina, JHEP 06, 004 (2015). [arXiv:1501.02139](#)
56. N. Kauer, C. O'Brien, Eur. Phys. J. C 75, 374 (2015). [arXiv:1502.04113](#)
57. C. Englert, I. Low, M. Spannowsky, Phys. Rev. D 91, 074029 (2015). [arXiv:1502.04678](#)
58. A. Ballestrero, E. Maina, JHEP 01, 045 (2016). [arXiv:1506.02257](#)
59. S. Dawson, I.M. Lewis, Phys. Rev. D 92, 094023 (2015). [arXiv:1508.05397](#)
60. L. Basso, S. Moretti, G.M. Pruna, Phys. Rev. D 82, 055018 (2010). [arXiv:1004.3039](#)
61. M.J. Strassler, K.M. Zurek, Phys. Lett. B 651, 374 (2007). [arXiv:hep-ph/0604261](#)
62. M.J. Strassler, K.M. Zurek, Phys. Lett. B 661, 263 (2008). [arXiv:hep-ph/0605193](#)
63. ATLAS Collaboration (2014). ATLAS-CONF-2014-005
64. ATLAS Collaboration (2014). ATLAS-CONF-2014-010
65. G. Aad et al., ATLAS Collaboration. Phys. Rev. Lett. 113, 171801 (2014). [arXiv:1407.6583](#)
66. V. Khachatryan et al. (CMS), JHEP 10, 144 (2015). [arXiv:1504.00936](#)
67. G. Aad et al. (ATLAS), Phys. Rev. D 92, 092004 (2015). [arXiv:1509.04670](#)
68. G. Aad et al. (ATLAS), JHEP 11, 206 (2015). [arXiv:1509.00672](#)
69. ATLAS Collaboration (2015). ATLAS-CONF-2015-081
70. G. Aad et al. (ATLAS), Eur. Phys. J. C 76, 45 (2016). [arXiv:1507.05930](#)
71. P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K.E. Williams, Comput. Phys. Commun. 181, 138 (2010). [arXiv:0811.4169](#)
72. P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K.E. Williams, Comput. Phys. Commun. 182, 2605 (2011). [arXiv:1102.1898](#)
73. P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak et al., PoS CHARGED2012, 024 (2012). [arXiv:1301.2345](#)
74. P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak et al., Eur. Phys. J. C 74, 2693 (2013). [arXiv:1311.0055](#)
75. P. Bechtle, S. Heinemeyer, O. Stal, T. Stefaniak, G. Weiglein, Eur. Phys. J. C 75, 421 (2015). [arXiv:1507.06706](#)
76. P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, Eur. Phys. J. C 74, 2711 (2014). [arXiv:1305.1933](#)
77. P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, JHEP 1411, 039 (2014). [arXiv:1403.1582](#)
78. M. Bowen, Y. Cui, J.D. Wells, JHEP 0703, 036 (2007). [arXiv:hep-ph/0701035](#)
79. N.D. Christensen, C. Duhr, Comput. Phys. Commun. 180, 1614 (2009). [arXiv:0806.4194](#)
80. F. Staub (2008). [arXiv:0806.0538](#)
81. F. Staub, Comput. Phys. Commun. 185, 1773 (2014). [arXiv:1309.7223](#)
82. ATLAS and CMS Collaborations (2015). ATLAS-CONF-2015-044
83. R.N. Lerner, J. McDonald, Phys. Rev. D 80, 123507 (2009). [arXiv:0909.0520](#)
84. G. Altarelli, R. Barbieri, Phys. Lett. B 253, 161 (1991)
85. M.E. Peskin, T. Takeuchi, Phys. Rev. Lett. 65, 964 (1990)
86. M.E. Peskin, T. Takeuchi, Phys. Rev. D 46, 381 (1992)
87. I. Maksymyk, C. Burgess, D. London, Phys. Rev. D 50, 529 (1994). [arXiv:hep-ph/9306267](#)
88. M. Baak et al., Gfitter Group. Eur. Phys. J. C 74, 3046 (2014). [arXiv:1407.3792](#)
89. J. Alcaraz et al. (ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, LEP Electroweak Working Group) (2006). [arXiv:hep-ex/0612034](#)
90. T. Aaltonen et al., CDF Collaboration. Phys. Rev. Lett. 108, 151803 (2012). [arXiv:1203.0275](#)
91. V.M. Abazov et al., D0 Collaboration. Phys. Rev. D 89, 012005 (2014). [arXiv:1310.8628](#)
92. G. Aad et al. (ATLAS), JHEP 01, 032 (2016). [arXiv:1509.00389](#)
93. CMS Collaboration (2015). CMS-PAS-HIG-14-022
94. S. Chatrchyan et al., CMS Collaboration. Phys. Rev. D 89, 092007 (2014). [arXiv:1312.5353](#)
95. CMS Collaboration (2012). CMS-PAS-HIG-12-045
96. CMS Collaboration (2013). CMS-PAS-HIG-13-003
97. P. Lebrun, Accelerators at the high-energy frontier: Cern plans, projects and future studies. Talk given at XLIII International Meeting on Fundamental Physics Centro de Ciencias de Benasque Pedro Pascual 12–21, March 2015
98. M. Grazzini, Private communication
99. R. Costa, M. Muehleitner, M.O.P. Sampaio, R. Santos (2015). [arXiv:1512.05355](#)
100. V. Khachatryan et al. (CMS) (2016). [arXiv:1603.06896](#)
101. V. Khachatryan et al. (CMS), Phys. Lett. B 749, 560 (2015). [arXiv:1503.04114](#)
102. S. Dittmaier et al. (LHC Higgs Cross Section Working Group) (2011). [arXiv:1101.0593](#)
103. S. Dittmaier, S. Dittmaier, C. Mariotti, G. Passarino, R. Tanaka et al. (2012). [arXiv:1201.3084](#)
104. The LHC Higgs Cross Section Working Group (2016), to appear