Bounds for lighter Higgses in extensions of the
Standard Model

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Abstract. Higgs bosons lighter than the 125 GeV one can be present in extensions of the
Standard Model and exclusion or discovery of such a possibility allows to improve our knowledge
of the Higgs sector. I consider Two Higgs Doublet Models, which are the minimal scalar structure
of a large number of models, in order to explore the possibility of constraining a neutral scalar
particle lighter than the 125 GeV Higgs boson. Such a lighter particle is not yet completely
excluded by present data. I show that some new constraints can be obtained at the LHC for
these light particles.

1. Introduction
The Large Hadron Collider (LHC) has confirmed the effective description of the electroweak
sector given by the Standard Model (SM) Lagrangian with the discovery of the 125 GeV Higgs
boson and the analysis of its properties [1, 2]. Many studies, both from the theoretical and
experimental side, have considered extensions of the Standard Model (SM) with an enlarged
scalar sector, but most studies have considered the possibility of new scalars heavier than the
125 GeV Higgs boson which was discovered at the LHC. It is however possible to have a spectrum
in which lighter scalars are present together with an SM-like Higgs boson at 125 GeV. Among
these possibilities there are detailed BSM models as well as effective descriptions including
only the extended scalar sector. Two Higgs Doublet Models (2HDMs) constitute one of
the simplest possibilities, where the SM Lagrangian is extended by the addition of a second
scalar doublet. Previous phenomenological studies describing the lighter Higgs bosons include
[3, 4, 5, 6, 7, 8, 9]. At masses below 125 GeV, the main search channel at the LHC is the
di-photon decay channel [11, 12].

2. Two Higgs Doublet Models
The 2HDMs are extension of the Standard Model including two complex SU(2) doublets, \( \phi_1 \)
and \( \phi_2 \). A \( \mathbb{Z}_2 \) symmetry is introduced to avoid flavour-changing currents, so that all fermions
of a given electric charge couple to at most one Higgs doublet. The convention usually adopted
is given in Table 1.
The 2HDMs potential constrained by the $\mathbb{Z}_2$ symmetry can be written as:

$$
V = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - m_{12}^2 \left( \phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1 \right) + \frac{\lambda_1}{2} \left( \phi_1^\dagger \phi_1 \right)^2 + \frac{\lambda_2}{2} \left( \phi_2^\dagger \phi_2 \right)^2 + \lambda_3 \left( \phi_1^\dagger \phi_1 \right) \left( \phi_2^\dagger \phi_2 \right) + \lambda_4 \left( \phi_1^\dagger \phi_2 \right) \left( \phi_2^\dagger \phi_1 \right) + \frac{\lambda_5}{2} \left[ \left( \phi_1^\dagger \phi_2 \right)^2 + \left( \phi_2^\dagger \phi_1 \right)^2 \right],
$$

where all the parameters are real. The parameter $m_{12}^2$ is a soft breaking term of the $\mathbb{Z}_2$ symmetry. The two scalar doublets get vacuum expectation values (vevs):

$$
\phi_1 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix},
$$

with $v \equiv \sqrt{v_1^2 + v_2^2}$.

After symmetry breaking there are five physical scalars: two neutral $\mathcal{CP}$-even states $h$ and $H$, one neutral $\mathcal{CP}$-odd state $A$ and two charged ones $H^\pm$. The connection of the potential of eq. 1 to mass-eigenstates is given by two angles: $\alpha$ which mixes the $\mathcal{CP}$-even scalar states to give mass-eigenstates and $\beta$, with $\tan \beta = \frac{v_2}{v_1}$, which rotates the two doublets in a basis where only one of them acquires a vev. The relation between the previous parameters and the mass basis is:

$$
\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, m_{11}^2, m_{22}^2, m_{12}^2 \updownarrow
\begin{align*}
m_h, & m_H, m_A, m_{H^\pm}, \tan \beta, \sin(\beta - \alpha), v, m_{12}^2
\end{align*}
$$

where $v$ is the 246 GeV electroweak scale, and one of the masses of the $\mathcal{CP}$-even states is set to be equal to the measured Higgs boson mass. The masses of the two $\mathcal{CP}$-even states are ordered with $m_h < m_H$, where I will call $h$ the light Higgs boson and $H$ the heavy Higgs boson of the model. In the following the heavy Higgs boson $H$ of the model is identified with the Higgs boson discovered at LHC, $m_H = 125$ GeV, while the remaining six parameters are left free.

3. Bounds on 2HDMs

The spectrum of neutral and charged scalars of the 2HDMs is a minimal extension of the scalar sector with one additional doublet and gives rise to five physical scalars: two charged $H^\pm$ and three neutral $h$, $H$ and $A$ states. If the Higgs boson discovered at the LHC is associated with the heavier $H$, the two other neutral states can be candidates for a lighter Higgs boson. I briefly discuss the different constraints used to impose bounds on the model: indirect constraints, LEP constraints and LHC constraints.
A summary of the results is available in Table 3.

3.1. Indirect constraints
The indirect constraints include limits on the precision electroweak parameters \( S, T \) and \( U \), flavour constraints and theoretical requirements to ensure stability of the potential, unitarity and perturbativity. The electroweak parameters are computed using the program 2HDMC \([14]\) and compared to the experimental limits \([15]\) at 2\( \sigma \) (see Table 2 for the experimental values with 1\( \sigma \) uncertainties and the correlations between them).

The stability of the potential requires:

\[
\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \lambda_3 \geq -\sqrt{\lambda_1 \lambda_2},
\]

\[
\lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1 \lambda_2}
\]

In addition we require to have tree-level perturbative unitarity for the scattering of Higgs bosons and the longitudinal parts of electroweak gauge bosons \([16]\).

In order to trust perturbative calculations, a condition is added on the quartic Higgs bosons couplings \( C_{h_i h_j h_k h_l} \):

\[
|C_{h_i h_j h_k h_l}| \leq 4\pi
\]

These three conditions are also computed via the 2HDMC program.

The parameter space of the model is further tested against flavour bounds looking at the branching ratios \( BR(B \rightarrow X_s \gamma) \) and \( BR(B_s \rightarrow \mu^+ \mu^-) \), which obtain contributions from the charged Higgs bosons and the neutral ones respectively and at the isospin asymmetry \( \Delta \theta(B \rightarrow K^* \gamma) \) and the \( \Delta M_d \) frequency oscillation which are sensitive to the presence of charged Higgs bosons. The value of each process is computed in the 2HDMs via the program SuperIso \([17, 18]\) and then compared to the experimental limits \([15]\) at 2\( \sigma \). In order to take into account the theoretical uncertainties and the correlations between them, the program SuperIso \([17, 18]\) is able to test a model against experimental data and perturbativity. The electroweak parameters are computed using the program 2HDMC \([14]\) and then compared to the experimental limits \([19]\) at 2\( \sigma \). In our analysis we use SuperIso version 4.2.1 with the LEP experiment constraints only, in order to impose LHC constraints separately.

| Process | Experimental values | Theoretical computation | Combined error at 1\( \sigma \) |
|---------|---------------------|-------------------------|-------------------------------|
| \( BR(B \rightarrow X_s \gamma) \) | \( (3.43 \pm 0.22) \times 10^{-4} \) \([19]\) | \( (3.40 \pm 0.19) \times 10^{-4} \) \([20]\) | 0.29 \times 10^{-4} |
| \( BR(B_s \rightarrow \mu^+ \mu^-) \) | \( (2.9 \pm 0.7) \times 10^{-9} \) \([21, 22]\) | \( (3.54 \pm 0.27) \times 10^{-9} \) \([20]\) | 0.8 \times 10^{-9} |
| \( \Delta \theta(B \rightarrow K^* \gamma) \) | \( (5.2 \pm 2.6) \times 10^{-2} \) \([23]\) | \( (5.1 \pm 1.5) \times 10^{-2} \) \([20]\) | 3.0 \times 10^{-2} |
| \( \Delta M_d \) | \( 0.510 \pm 0.003 \text{ ps}^{-1} \) \([19]\) | \( 0.543 \pm 0.091 \text{ ps}^{-1} \) \([24]\) | 0.091 \text{ ps}^{-1} |

Table 3. Values of the experimental and theoretical flavour constraints.

3.2. LEP and LHC constraints
The HiggsBounds program \([25, 26, 27, 28]\) is able to test a model against experimental data coming from LEP, Tevatron and the LHC. In our analysis we use HiggsBounds version 4.2.1 with the LEP experiment constraints only, in order to impose LHC constraints separately.
The LHC constraints are coming from the experimental results on the 125 GeV Higgs boson at Run 1, i.e. the 2HDM heavy Higgs boson $H$, in our case. We use the exclusion contours in the plane of the signal strength for each individual production mode $\mu_{VBF/VH}$ vs $\mu_{ggh/tth}$ given by the combined ATLAS and CMS experiments [29]. Assuming a Gaussian profile for the likelihood $L$ at 68% C.L., we fit the ellipses for each decay channel $Y = \{WW, ZZ, \gamma\gamma, \tau\tau, bb\}$ and hence obtain the parametrisation for each of them (see [30] for details). Combining the log-likelihood ratios:

$$\Delta \chi^2(p_j) = \sum_Y \chi^2_Y(p_j) - \sum_Y \chi^2_Y(\hat{p}_j),$$

with $p_j$ the set of free parameters on which the function depends and $\hat{p}_j$ their value minimising the $\chi^2$ function. In our case, we have six degrees of freedom ($\kappa^2_Y, \kappa^2_Y, BR_{H\rightarrow WW}, BR_{H\rightarrow ZZ}$, $BR_{H\rightarrow b\bar{b}}$, $BR_{H\rightarrow \gamma\gamma}$, as $BR_{H\rightarrow H\rightarrow ZZ}$ is linked to $BR_{H\rightarrow H\rightarrow WW}$). This choice in the free parameters implies that we assume no correlation between the kappas and the branching ratios, which is correct as long as the deviation of the branching ratios is not too large with respect to the Standard Model values. A point in the 2HDM parameter space passing the LHC constraints, therefore, has a $\Delta \chi^2$ value lower than 12.85, which is the value at 95% C.L. for 6 degrees-of-freedom.

4. Searches for a lighter scalar Higgs

A light resonance decaying into two photons was searched for by CMS [11] in the range of mass between 80 and 110 GeV. To compare with the experimental sensitivity, we need to compute the expected production cross sections in the different production modes and branching ratios into the observed final states.

4.1. Cross sections and branching ratios

The program 2HDMC [14] version 1.7.0 is used to compute the branching ratios of the different Higgs bosons of the theory. The cross sections are calculated using an approximation that we denote in the following as the “kappa trick”. Defining the generic parameter $\kappa_Y$ as $\kappa_Y^2 = \frac{\Gamma^2_{SM,Y}}{\Gamma^2_{2HDM,Y}}$ for a specific decay channel $Y$, the cross sections can be approximated as:

$$\sigma_{ggh}^{2HDM} \simeq \kappa_Y^2 \times \sigma_{ggh}^{SM}, \quad \sigma_{VBF/VH}^{2HDM} \simeq \kappa_Y^2 \times \sigma_{VBF/VH}^{SM} = \sin^2(\beta - \alpha) \times \sigma_{VBF/VH}^{SM}. \quad (7)$$

As the couplings of the light scalar Higgs boson to the W and Z bosons are rescaled in the same way compared to the SM couplings, we have that $\kappa_Z = \kappa_W = \kappa_V = \sin(\beta - \alpha)$. The SM cross section is taken from the LHC Higgs Cross-Section Working Group [31]. The kappas are computed using 2HDMC. A comment on the validity of this approximation is in order. The cross section production in VBF and VH mode does not cause any problem as the leading effect arises at tree level, however for the gluon fusion mode a loop induced coupling is present and thus it is important to check the validity of the “kappa trick” for this production mode. Note indeed that for loop induced vertices the use of an effective kappa factor is not always appropriate and more general parameterisations exist (see for example [32, 33]). In order to explore this issue, we performed a comparison between the cross sections in gluon fusion obtained via the program SusHi and the ones obtained with the “kappa trick”. This comparison shows that the deviation is less than 3% for the whole mass range and stable upon modification of the values of the input parameters. As it stays within the range allowed by the uncertainties (theoretical, PDF and $\alpha_s$) calculated by the LHC Higgs Cross-Section Working Group [31], we can safely use our method for the light Higgs boson.
4.2. Constraining the 2HDMs parameter space

In this section we study the influence of the three sets of constraints defined in Section 3 (indirect, LEP and LHC constraints) on the free parameters of the model. For this purpose we generate a set of one million points for each of the four different types of model defined in Table 1 with random values for each of the free parameters. The available ranges we use in the simulation are given in Table 4. The range of variation for $m_h$ corresponds to the mass range in the CMS di-photon analysis. The lower bound of 80 GeV for $m_{H^\pm}$ comes from the bound obtained at the LEP experiment [34]. The ranges for $m_A$ and $m_{12}^2$, although not totally general, are the result of previous quick scans which eliminate areas with a very low density of points passing the three sets of constraints (indirect, LEP and LHC constraints).

| $m_h$ (GeV) | $m_{H^\pm}$ (GeV) | $m_A$ (GeV) | $m_{H^\pm}$ (GeV) | $\sin(\beta - \alpha)$ | $\tan \beta$ | $m_{12}^2$ (GeV)$^2$ |
|-------------|-------------------|-------------|-------------------|--------------------------|------------|----------------|
| [80;110]    | 125               | [60;1000]   | [80;1000]         | [-1;1]                   | [1/50;50]  | [-(300)$^2$;+(200)$^2$] |

**Table 4.** Range of variation for the free parameters used in the analysis.

![Figure 1](image-url)

**Figure 1.** Constraints on the parameter space in the plane $m_A$ vs $m_{H^\pm}$. Top left: Type I. Top right: Type II. Bottom left: Flipped. Bottom right: Lepton Specific. In green the points passing indirect constraints only. In blue the points passing indirect and LEP constraints. In red the points passing indirect, LEP and LHC constraints.

In Figure 1, the generated points are plotted in the plane $m_A$ vs $m_{H^\pm}$. The upper left panel corresponds to Type I, the upper right to Type II, the lower left to the Flipped model and the lower right to Lepton Specific model. The points passing only the indirect constraints are plotted in green, those passing indirect and LEP constraints are in blue and those passing indirect, LEP and LHC constraints are in red. I will use these same conventions in the following.
Note that the $m_A$ and $m_{H^\pm}$ masses are correlated: when $m_A$ and $m_{H^\pm}$ grow, the indirect constraints force them to be near the black line corresponding to $m_A = m_{H^\pm}$. This is due to the T parameter which is very sensitive to these two masses and enforces them to be close to each other. In Type I, we find that most of the red points lie in the ranges $m_A \in [60 \text{ GeV}; 650 \text{ GeV}]$ and $m_{H^\pm} \in [80 \text{ GeV}; 630 \text{ GeV}]$. In Type II and Flipped, the two masses are much more constrained $m_A \in [400 \text{ GeV}; 650 \text{ GeV}]$ and $m_{H^\pm} \in [430 \text{ GeV}; 630 \text{ GeV}]$: this is due to the fact that the down-type quarks couple now to the $\phi_1$ doublet instead of the $\phi_2$ doublet as in Type I, thus the $\mathcal{B}(B \rightarrow X_s \gamma)$ flavour limit imposes a very strong constraint on the mass of the charged Higgs bosons. Note that the most recent BELLE data [35] further constrain Type II and Flipped models (see for details [36]). These recent constraints are not included in the previous plots, but for Type I (on which I will focus in the following) the limit only affect the very low $\tan \beta < 2$ values. When the bounds are combined with the T parameter constraint, they impose also limits on the pseudo-scalar mass. The Lepton Specific case is very similar to Type I, as the couplings of the down-type quark are the same. We find $m_A \in [80 \text{ GeV}; 630 \text{ GeV}]$ and $m_{H^\pm} \in [80 \text{ GeV}; 630 \text{ GeV}]$ to be the preferred regions. For $\sin(\beta - \alpha)$, the allowed range is close to zero, which is consistent with the choice of $m_H = 125 \text{ GeV}$: as $\sin(\beta - \alpha) \simeq 0$, we have $\cos(\beta - \alpha) \simeq 1$ so that the couplings of the heavy Higgs boson $H$ to gauge bosons are similar to the SM ones (this is the alignment limit described in [8]). We find that the preferred ranges are $\sin(\beta - \alpha) \in [-0.4; 0.3]$ for Type I, $\sin(\beta - \alpha) \in [-0.5; 0.05]$ for Type II and Flipped model and $\sin(\beta - \alpha) \in [-0.3; 0.2]$ for Lepton Specific model.

**Figure 2.** Constraints on the free parameters in the plane $m_{12}$ vs $\sin(\beta - \alpha)$. Top left: Type I. Top right: Type II. Bottom left: Flipped. Bottom right: Lepton Specific. Same colour code as in Figure 1.

Inspecting the plane $m_{12}$ vs $\sin(\beta - \alpha)$ we can see the constrains on $m_{12}^2$ (see Figure 2): $m_{12}^2 < (100 \text{ GeV})^2$ in all the four types.
The parameter space can be limited in order to increase the statistics of the allowed points using the domains indicated by the previous plots. In addition to this, as we are interested in checking the sensitivity to a lighter Higgs boson at LHC Run 1 in the di-photon decay channel, we can further restrict to the areas of relatively high values of cross section times branching ratio into two photons. The minimum value of the CMS observed upper limit [11] is 0.032 pb in the gluon fusion channel, obtained for \( m_h = 103 \text{ GeV} \) and 0.019 pb in the VBF/VH channel, obtained for \( m_h = 100.5 \text{ GeV} \). We checked that with the results for the gluon fusion production mode, CMS is not sensitive to a lighter Higgs boson in this particular channel at LHC Run 1. On the contrary for the VBF channel there is some sensitivity for model type I at the LHC, as shown in figure 3. One can deduce from these results that in the Type II, Flipped and Lepton

**Figure 3.** 2HDM generated points in the plane \( \sigma \times BR_{h\rightarrow \gamma\gamma} \) vs \( \sin(\beta - \alpha) \) in the VBF/VH production mode. Top left: Type I. Top right: Type II. Bottom left: Flipped. Bottom right: Lepton Specific. Same colour code as in Figure 1. The dashed line corresponds to the minimum value of the CMS observed upper limit in the VBF/VH production mode.

Specific models, CMS had no sensitivity to a lighter Higgs boson at LHC Run 1 in the \( h \rightarrow \gamma\gamma \) decay channel, neither in the gluon fusion nor in the VBF/VH production mode. For Type I, there is no sensitivity in the gluon fusion channel, but only in the VBF/VH channel, where we find red points above the dashed line. As the value of the CMS observed upper limit depends on the mass of the light Higgs boson considered, the dashed line represented on the plots is not an absolute bound. Some of the red points above it can be in practice below the CMS observed limit, but it is a good indication of the potential capability of the VBF/VH channel for some exclusion.

We use Figure 3 even further by choosing to consider only areas where the points have relatively high values of cross section times branching ratio. We choose a lower bound at 0.01 pb to select the points, which corresponds to \( \sin(\beta - \alpha) \in [-0.3; 0.05] \). We can similarly work
Figure 4. Value of the cross section times branching ratio in the VBF/VH production mode as a function of $\tan \beta$ (left) and $sgn(m_{12}) \times \sqrt{|m_{12}^2|}$ (right) in Type I. Same colour code as in Figure 1.

with tighter ranges for the parameters $\tan \beta$ and $m_{12}^2$ (see Figure 4). We choose $\tan \beta \in [2;12]$ and $m_{12}^2 \in [-100 \text{ GeV}^2;+100 \text{ GeV}^2]$.

4.3. Comparison with the CMS low mass di-photon analysis

We now perform a second “focused” scan and make a detailed comparison with the sensitivity of the CMS search at 8 TeV with one million points, this time for Type I only, using the restricted parameter ranges we found in the previous section (see Table 5).

| $m_h$ (GeV) | $m_H$ (GeV) | $m_A$ (GeV) | $m_{H^+}$ (GeV) | $\sin(\beta - \alpha)$ | $\tan \beta$ | $m_{12}^2$ |
|-------------|-------------|-------------|-----------------|------------------------|-------------|------------|
| [80;110]    | 125         | 60;650      | 80;630          | [-0.3,-0.05]           | [2;12]      | -(100)$^2$;+(100)$^2$ |

Table 5. Allowed range of variation for the free parameters.

The resulting points of this second scan are plotted in Figure 5 in the plane $\sigma \times BR_{h\rightarrow \gamma \gamma}$ in the gluon fusion production mode (left panel) and the VBF/VH production mode (right panel) vs $m_h$, superimposed on the public exclusion limits of CMS collaboration. For convenience only the red points, i.e. the points passing all of the indirect, LEP and LHC constraints, are plotted here. These results confirm the expectation that there is no sensitivity in the gluon fusion production mode but many points are above the CMS observed limit in the VBF/VH production mode for a light Higgs boson with mass below 105 GeV. As the points above the observed CMS upper limit are excluded at 95% C.L., we can expect to exclude some new region in the parameter space thanks to this analysis.

5. Conclusions

The search for an extended Higgs sector represents one of the most important avenues for probing the possible structure of physics beyond the Standard Model. In the simplified setting of Two Higgs Doublet Models, we have explored current constraints from flavour, precision electroweak tests and direct collider searches. We have studied the reach of the CMS experiment at the LHC Run 1 for a second Higgs particle lighter than the 125 GeV Higgs boson. We have explored the different production modes (gluon fusion, vector boson fusion, associated production with a gauge boson) and the decay of the Higgs boson to two photons for the light boson. There is indeed some sensitivity in these last two production modes as shown recasting an existing Run
Figure 5. Points generated in the 2HDM Type I passing indirect, LEP and LHC constraints, superimposed on the results of the CMS 8 TeV low-mass di-photon analysis [11] in the gluon fusion production mode (left panel) and the combined VBF and VH production mode (right panel). The dashed line corresponds to the expected upper limit on $\sigma \times BR_{h \rightarrow \gamma\gamma}$ at 95% C.L., with 1 and 2 sigma errors in green and yellow respectively. The solid line is the observed upper limit at 95% C.L.

1 CMS analysis. A lighter neutral scalar particle is not completely excluded by present bounds and searches. Out of the four types of 2HDMs, in the low-mass region for a neutral scalar, only Type I has in its parameter space points with large enough cross section times branching ratio to allow detection or exclusion in the two photon decay channel. It is for sure interesting to perform a similar low mass search (even for lower masses than those considered at Run 1) at 13 TeV for the LHC in Run 2 as the increased sensitivity to lower cross section values allow to further explore and constrain or possibly discover new scalar neutral particles and in any case will allow a better understanding of an extended Higgs sector.

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