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Are there hidden scalars in LHC Higgs results?

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ABSTRACT: The Higgs boson recently discovered at the Large Hadron Collider has shown to have couplings to the remaining particles well within what is predicted by the Standard Model. The search for other new heavy scalar states has so far revealed to be fruitless, imposing constraints on the existence of new scalar particles. However, it is still possible that any existing heavy scalars would preferentially decay to final states involving the light Higgs boson thus evading the current LHC bounds on heavy scalar states. Moreover, decays of the heavy scalars could increase the number of light Higgs bosons being produced. Since the number of light Higgs bosons decaying to Standard Model particles is within the predicted range, this could mean that part of the light Higgs bosons could have their origin in heavy scalar decays. This situation would occur if the light Higgs couplings to Standard Model particles were reduced by a concomitant amount. Using a very simple extension of the SM — the two-Higgs doublet model — we show that in fact we could already be observing the effect of the heavy scalar states even if all results related to the Higgs are in excellent agreement with the Standard Model predictions.

KEYWORDS: Higgs Physics, Beyond Standard Model

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The recent LHC discovery of the Higgs boson [1, 2] completed the particle spectrum predicted by the Standard Model (SM). We are finally able to directly probe the SM’s scalar sector, and eventual discrepancies with SM expectations will likely be signs of new physics or new particles. One of the simplest extensions of the SM is the two-Higgs doublet model (2HDM), proposed by Lee in 1973 [3] as a means to explain matter-antimatter asymmetry. For a recent thorough review of the 2HDM, see [4].

The model has a vast and interesting phenomenology. It boasts not one but *five* scalar states — two CP-even scalars (the lightest h and the heaviest H), a pseudoscalar (A) and a pair of charged scalars ($H^\pm$). The vacuum structure of the model is much richer than the SM’s: for instance, the 2HDM scalar potential can have minima which spontaneously break CP, thus aiding in explaining the abundance of matter over antimatter in the universe. But minima which break electric charge conservation are also possible, as are vacua which preserve electric charge conservation and CP while breaking the electroweak symmetry but are tree-level metastable [5–7]. Analytical conditions to avoid those dangerous vacua have been obtained and are very simple to implement [8–11].

The Yukawa sector of the 2HDM is also quite interesting: *a priori* it exhibits tree-level FCNC, but these can either be eliminated through a discrete Z_2 symmetry [12, 13] or be made “naturally small”, by means of an appropriate global symmetry [14]. Also, the judicious application of the Z_2 symmetry can yield a version of the model — the “inert” 2HDM — which has candidates for dark matter [15–28].

Experimental confirmation of the 2HDM will obviously necessitate the discovery of its extra scalars: out of the five states that the model predicts one has just been discovered, and we take it to be the lightest CP-even scalar. It is unlikely, though not impossible [29, 30], that the LHC-observed scalar is actually the heaviest of the CP-even states, H , and the observation of the Higgs decays into W^+W^- and ZZ excludes the possibility of it being

the pseudoscalar A (though the possibility that the LHC discovery corresponds to a mixed scalar-pseudoscalar particle is not yet ruled out [31]).

Assuming therefore that the scalar h has been observed, what can we already say, with current LHC data, about the remaining 2HDM scalars? What does the non-observation of H , A and $H^\pm$ to date tell us? And how much of parameter space of the 2HDM is curtailed by not having found these other scalars? Similar questions were recently analysed in ref. [32].

In this paper we will perform a thorough examination of these questions and show that, though current LHC results already exclude a sizeable portion of 2HDM parameter space, there is still ample room to allow for the existence of extra scalars with relatively low masses (below 600 GeV). And we will study also an intriguing possibility — that heavier scalars like H may already be indirectly observed at the LHC, not through their decays into gauge bosons or fermions, but rather through their decays into h . In fact, such decays (for instance, $H \rightarrow hh$, $A \rightarrow Zh$ or $H^\pm \rightarrow W^\pm h$) can, for ordinary values of the parameters of the model, be the dominant contribution to the branching ratios of the heavier scalars. If that were the case then, for instance, H would be invisible in decays to gauge bosons or fermions, and its presence could well already be detected through its contribution to h production. The lightest CP-even scalar h could therefore be produced as a result of a chain of production and decays of H , A and/or $H^\pm$, and we call this process *chain Higgs production*. This seemingly exotic scenario can occur without any fine tuning and, as we will see, is in agreement with the existing data.

In section 1 we review basic notation and facts of the 2HDM, describing the constraints, both theoretical and experimental, that the model is subject to. And we explain the scan of parameter space we will be performing, trying to cover as vast a range as possible. In section 1.2 we detail the calculation of cross section values needed for this work — not only for h production but also that of H , A and $H^\pm$, for a wide range of values of their masses and other variables. In section 2 we introduce the variables which we compare with LHC data and show how that data already excludes large chunks of 2HDM parameters due to non-observation of the heavier states. Nonetheless, there is plenty of room left to accommodate the existence of new scalars. In section 3 we treat the possibility of chain Higgs production through decays of the heavy scalar states. We will show that there may be a sizeable contribution to the observed Higgs signals at the LHC coming from these processes, which would mean we already may be, indirectly, observing the remainder of the 2HDM scalar spectrum. We will briefly discuss what could we do to probe this possibility, and present our conclusions in section 4.

1 The Two Higgs Doublet Model

The 2HDM has the same fermion and gauge particle content of the SM, and an extra $SU(2) \times U(1)$ doublet Φ_2 , with hypercharge +1 like the first doublet Φ_1 . The most general 2HDM scalar potential has 11 independent parameters. In the most used version of the model one imposes a discrete Z_2 symmetry, $\Phi_1 \rightarrow \Phi_1$ and $\Phi_2 \rightarrow -\Phi_2$, which eliminates four parameters. We will softly break this Z_2 symmetry and thus the scalar potential is

written as

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{1}{2} \lambda_1 |\Phi_1|^4 + \frac{1}{2} \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2} \lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + h.c. \right], \quad (1.1)$$

with all parameters real.¹ When both doublets acquire vacuum expectation values (vevs), $\langle \Phi_1 \rangle = v_1$, $\langle \Phi_2 \rangle = v_2$, electroweak symmetry breaking occurs. Looking at eq. (1.1) we see the potential has 8 independent real parameters. Usually, though, we take as independent parameters the set of scalar masses m_h , m_H , m_A and $m_{H^\pm}$, the sum of the squared vevs, $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$, the angle β defined through the vev ratio, $\tan \beta = v_2/v_1$, the mixing angle α of the CP-even 2×2 mass matrix and the soft breaking parameter m_{12}^2 . Since the lightest Higgs mass has been measured to be $\simeq 125 \text{ GeV}$, the model has therefore 6 unknown parameters.

The coupling of the scalars to the fermions is also affected by the Z_2 symmetry. But the extension of that symmetry to the fermion fields, i.e. how they transform under Z_2 , is not uniquely defined, thus giving rise to different versions of the 2HDM Lagrangian, with different phenomenologies. Model Type I corresponds to all fermion fields swapping sign under Z_2 and thus coupling only to the doublet Φ_2 . In model Type II the fermion transformation laws are such that charged leptons and down-type quarks couple to Φ_1 and up-type quarks couple to Φ_2 .²

In all that follows, when we speak of parameter scans, we have taken $m_h = 125 \text{ GeV}$, $127 \leq m_H \leq 900 \text{ GeV}$, $100 \leq m_A \leq 900 \text{ GeV}$, $100 \leq m_{H^\pm} \leq 900 \text{ GeV}$,³ $1 \leq \tan \beta \leq 30$, $-\pi/2 \leq \alpha \leq \pi/2$ and $|m_{12}^2| \lesssim 4 \times 10^5 \text{ GeV}^2$.

1.1 Constraints on 2HDM parameters

Even before the Higgs discovery, there was plenty one could say about the allowed values for the parameters of the model. For starters, they have to be such that electroweak symmetry breaking occurs. And one must ensure that the potential (1.1) is bounded from below [38], which imposes a set of positivity constraints on the quartic couplings:

$$\begin{aligned} \lambda_1 &> 0, & \lambda_2 &> 0, \\ \lambda_3 &> -\sqrt{\lambda_1 \lambda_2}, & \lambda_3 + \lambda_4 - |\lambda_5| &> -\sqrt{\lambda_1 \lambda_2}. \end{aligned} \quad (1.2)$$

Also, to make sure that unitarity is preserved and the couplings remain perturbative, there is a second set of constraints imposed on the quartic couplings [39, 40]. And if one wishes to be sure that the vacuum of the potential is the global minimum of the model, one ought to impose the following condition [10, 11],

$$m_{12}^2 (\sqrt{\lambda_2} m_{11}^2 - \sqrt{\lambda_1} m_{22}^2) (\sqrt{\lambda_2} \tan \beta - \sqrt{\lambda_1}) > 0. \quad (1.3)$$

¹Another possibility would be to take a complex soft breaking term m_{12}^2 , yielding the *complex 2HDM*. This model has many interesting features [31, 33–35] but will not be studied in the current work.

²There are other versions of the model (X and Y), differing in the specific couplings to leptons [36, 37], but we will not consider them here.

³For model type-II, due to a strong constraint stemming from B-physics (to be discussed shortly), we generate only points with $m_{H^\pm} \geq 360 \text{ GeV}$.

The precision electroweak constraints are also taken into account [41–45].

Regarding the experimental bounds, the most relevant are the ones imposed on the charged Higgs mass and on the $\tan\beta$ parameter coming from B-physics, LEP and from the most recent LHC data. The LEP experiments have set a lower limit on the mass of the charged Higgs boson of 80 GeV at 95% C.L., assuming $BR(H^+ \rightarrow \tau^+\nu) + BR(H^+ \rightarrow c\bar{s}) + BR(H^+ \rightarrow AW^+) = 1$ [46] with the process $e^+e^- \rightarrow H^+H^-$. The bound is increased to 94 GeV if $BR(H^+ \rightarrow \tau^+\nu) = 1$ [46]. Using the constraints [47–54] coming from the measurements of R_b , $B_q\bar{B}_q$ mixing and also from $B \rightarrow X_s\gamma$ [55, 56], we conclude that values of $\tan\beta$ smaller than $O(1)$ together with a charged Higgs with a mass below $O(100\text{ GeV})$ are disallowed for all Yukawa-types. Moreover, for the particular cases of models type II and Y, $B \rightarrow X_s\gamma$ [55, 56] imposes a lower limit on the charged Higgs mass of about 360 GeV.

The LHC, through both the ATLAS [57, 58] and the CMS [59] collaborations, also places bounds on the $(\tan\beta, m_{H^\pm})$ for light charged Higgs with $pp \rightarrow t\bar{t} \rightarrow b\bar{b}W^\mp H^\pm (\rightarrow \tau\nu)$. Finally, we have considered the LEP bounds on the neutral Higgs [60].

We end up with a note about the anomaly observed in the rates $R(D)$ and $R(D^*)$, with $R(D) = (\bar{B} \rightarrow D\tau^-\bar{\nu}_\tau)/(\bar{B} \rightarrow Dl^-\bar{\nu}_l)$ by the BaBar collaboration which deviates by 3.4σ (when D and D^* final states are combined) from the SM prediction [61]. If confirmed by BELLE, it means that the SM is excluded at 3.4σ and also that models type I, II, X and Y will be excluded with a similar significance. It should be noted that 2HDMs that have the SM as its decoupling limit can never be excluded in favour of the SM.

1.2 Production cross sections

In our analysis, we include all production mechanisms of the lightest scalar h with a mass of 125 GeV. Processes that involve gauge boson couplings to scalars can be obtained by simply rescaling the SM cross section by an appropriate trigonometric factor. Therefore, for VBF and associated Higgs production with either a W , a Z or with $t\bar{t}$ we have used the results of [62]. We have included QCD corrections but not the SM electroweak corrections because they can be quite different for the 2HDMs. Cross sections for $b\bar{b} \rightarrow h$ are included at NNLO [63] and the gluon fusion process $gg \rightarrow h$ was calculated using HIGLU [64]. There are a number of chain processes that lead to final states with at least one light Higgs [65]. From those we have singled out the ones that give the largest contribution to the number of light Higgs in the final state. As a rule, all production processes have at least one of the scalars H , A or $H^\pm$ as an intermediate state that subsequently decays to a final state that includes at least one 125 GeV Higgs boson. For the gluon fusion and $b\bar{b}$ initiated processes in $pp \rightarrow S$, where $S = H, A$ we again use bb@nnlo and HIGLU. Note that the pseudo-scalar production has a much more pronounced peak at the $t\bar{t}$ threshold than the corresponding CP-even production because the $t\bar{t}$ bound state is also CP-odd. Regarding the heavy CP-even scalar associated production we again use [62]. The non-resonant production of $gg(b\bar{b}) \rightarrow hh$ was shown to be negligible for most of 2HDM parameter space when compared to resonant production via a heavy CP-even Higgs [66]. The same is true for $gg(b\bar{b}) \rightarrow hH$. A charged Higgs with a mass below the top threshold is mainly produced in top decays, $t \rightarrow H^+\bar{b}$, originating from $pp \rightarrow t\bar{t}$. However, such a light charged Higgs would not contribute significantly to the chain decays. Therefore we have considered

cross sections for production of charged Higgs with masses above 200 GeV. Moreover, due to the flavour constraints on the charged Higgs mass, the type II charged Higgs mass is taken to be above 360 GeV. For heavy charged Higgs, the main production processes are $pp \rightarrow tH^+$ and $pp \rightarrow t\bar{b}H^+$, and the numerical values for this cross section were obtained from [67]. The remaining single charged Higgs production processes were shown to be less important [68] while both $pp \rightarrow H^+H^-$ and $pp \rightarrow H^\pm W^\mp$ were shown to be small for non-resonant production [68]. In view of the limits on the Higgs couplings in 2HDMs [69, 70] as a consequence of the discovery of a light Higgs boson, it is found that we must have a value of $\sin(\beta - \alpha)$ close to 1. As such, the process $qq' \rightarrow W^+ \rightarrow hH^+$ should be small because it has a coupling proportional to $\cos(\beta - \alpha)$ while $qq' \rightarrow (W^+)^* \rightarrow H(A)H^+$ are phase space suppressed if H or A are allowed to decay to a final state with a light Higgs.

2 Current bounds on heavy states in the 2HDM

Since there are considerable uncertainties in the hadronic cross sections for h production at the LHC, the best observables to compare theory with experimental results are ratios between observed rates of events *versus* what was expected to be observed in the case of a SM Higgs. Namely, if one is interested in the production of a lightest Higgs scalar h being produced and decaying into a given final state f (currently, $f = WW, ZZ, \gamma\gamma, b\bar{b}$ or $\tau\bar{\tau}$) in the context of the 2HDM, the ratio we will be comparing with data is defined as

$$R_f^h = \frac{\sigma^{2\text{HDM}}(pp \rightarrow h) BR^{2\text{HDM}}(h \rightarrow f)}{\sigma^{\text{SM}}(pp \rightarrow h) BR^{\text{SM}}(h \rightarrow f)}, \quad (2.1)$$

where production cross sections σ include all possible *direct* production mechanisms (see section 1.2), both for the SM and 2HDM. Likewise, the branching ratios (BR) of the lightest Higgs boson are computed for both models. Notice the superscript “ h ”, which will become important later.

In a similar manner, one defines ratios pertaining to the searches for the heavy CP-even scalar H and pseudoscalar A . The ratios take as a reference the production of a SM-like scalar with mass identical to that of H or A :

$$R_f^H = \frac{\sigma^{2\text{HDM}}(pp \rightarrow H) BR^{2\text{HDM}}(H \rightarrow f)}{\sigma^{\text{SM}}(pp \rightarrow H) BR^{\text{SM}}(H \rightarrow f)}, \quad R_f^A = \frac{\sigma^{2\text{HDM}}(pp \rightarrow A) BR^{2\text{HDM}}(A \rightarrow f)}{\sigma^{\text{SM}}(pp \rightarrow H) BR^{\text{SM}}(H \rightarrow f)}. \quad (2.2)$$

In figure 1(a) we see the results of our scan of 2HDM parameter space, for model type-I, for the observable R_{ZZ}^H . The black line corresponds to the current experimental bound for this variable [71–73] — all points below this line are still allowed, all points above it are excluded. Green (grey) points shown in this figure include perturbative unitarity, stability, electroweak precision and B-physics cuts.

As we see from figure 1(a), the current experimental bounds on R_{ZZ}^H already exclude a large portion of possible 2HDM points — however, notice that there is still a great amount of 2HDM parameter space allowed, for all the range of masses m_H considered. Analogous results are obtained for R_{ZZ}^H in model type-II.

Figure 1. Comparison between 2HDM predictions and LHC results. (a), the predicted values for R_{ZZ}^H , for model type-I. (b), R_{WW}^H , for model type-II. All points include perturbative unitarity, stability, electroweak precision and B-physics cuts. The black line is the experimental exclusion line from LHC.

In a similar manner, LHC data on R_{WW}^H [71–73] exclude many possible combinations of 2HDM parameters, while still allowing many others. We show this for model type-II (analogous results hold for model type-I) in figure 1(b). Please notice that for type-II the parameter space scan already included the B-physics (and LHC) motivated restriction, $m_{H^\pm} > 360$ GeV [55, 56].

What these plots are telling us is quite simple: the heaviest CP-even scalar H , if it exists, should not couple too strongly to gauge bosons. This is hardly surprising, given that the LHC data indicates that the lightest CP-even state, h , seems to couple to gauge bosons with practically its SM-expected strength. Now, gauge symmetry implies the following sum rule for the couplings of h and H to the gauge bosons:

$$g_{hVV}^2 + g_{HVV}^2 = 1. \quad (2.3)$$

If h is almost SM-like then $g_{hVV} \simeq 1$, which means $g_{HVV} \simeq 0$ — thus it is to be expected that H couples weakly to gauge bosons, making it more difficult to observe that scalar state in this channel.

Some care must be taken while comparing the ZZ and WW calculated rates at such high values of m_H . In fact, there is the possibility that, if the scalar’s width is too large, the interference of the process $pp \rightarrow h \rightarrow ZZ/WW$ with the ZZ/WW background becoming relevant. Previous studies [74–76] analysed this possibility, which was shown to, at most, provoke a reduction of 10% on the observed signal. To be conservative, then, we will “add” 10% to the experimental exclusion line of figures 1, left and right. This way we accept all 2HDM points which lie below that line or which, at most, live above 10% of its value for a given choice of m_H .

In figure 2(a) we show the results of our parameter space scan for the product $\sigma(pp \rightarrow H) \times BR(H \rightarrow \tau\bar{\tau})$ for model type-I, and compare it to the current bound from LHC⁴ [77].

⁴Unlike all other channels, for the $\tau\bar{\tau}$ results at high masses the LHC collaborations have published results for $\sigma \times BR$.

Figure 2. Comparison between 2HDM predictions and LHC results: (a), the predicted values for $\sigma(pp \rightarrow H) \times BR(H \rightarrow \tau\tau)$, for model type-I. (b), $\sigma(pp \rightarrow A) \times BR(A \rightarrow \tau\tau)$, for model type-II. All points include perturbative unitarity, stability, electroweak precision and B-physics cuts. The black line is the experimental exclusion line from LHC.

As we see, there is still no exclusion coming from the $\tau\bar{\tau}$ channel (which is understandable, considering that even for the h scalar the knowledge of this channel is still in its infancy). For model type-II, however, we would find a sizeable portion of parameter space *above* the LHC exclusion line, so the $\tau\bar{\tau}$ data is already helping us putting constraints on the 2HDM. The reason why one obtains a more pronounced exclusion in model type-II is the fact that the Higgs coupling to the bottom quarks, and to the tau leptons, increases significantly with $\tan\beta$ (something which does not occur in model type-I). Thus both the production and decays of h are enhanced for large values of $\tan\beta$.

Likewise, the $\tau\bar{\tau}$ exclusion is already extremely useful in constraining the existence of the pseudoscalar A . As we see from figure 2(b), the same bound we used in the production and decay of H already excludes a sizeable region of parameter space due to the decays of A to $\tau\bar{\tau}$ in model type-II. The exclusion is less pronounced for model type-I. The reason for the added importance of the $\tau\bar{\tau}$ channel in the pseudoscalar's decays is simple to understand: for A masses below ~ 350 GeV (the threshold for $A \rightarrow t\bar{t}$ decays), the decays of A into $b\bar{b}$ and $\tau\bar{\tau}$ are dominant over all others.⁵ This dominance clearly does not occur for the CP-even state H , which decays predominantly to WW or ZZ in the same mass range. As such, the expected $\sigma \times BR$ for τ 's are larger for A than for H , explaining the difference in behaviour in figures 2(a) and 2(b). The excluded region has mostly high values of $\tan\beta$ since they enhance immensely the production cross section in model type-II [78], due to the coupling of the pseudoscalar to the bottom quarks being proportional to $\tan\beta$.⁶

Finally, the $\gamma\gamma$ data can also be used to search for a second peak which might reveal the presence of the H and/or A . The LHC collaborations provides us with an exclusion curve for $R_{\gamma\gamma}$ for several masses [79, 80], but the published results go only up to masses

⁵Certainly dominant over loop decays such as $A \rightarrow \gamma\gamma$ and $A \rightarrow Z\gamma$, and favoured over the decay $A \rightarrow Zh$ (which is proportional to $\cos(\beta - \alpha)$), even above its threshold of ~ 216 GeV, for many choices of parameters in the model.

⁶For those high values of $\tan\beta$ the pseudoscalar coupling to the top quark is suppressed, which explains why we do not see a decrease on $\sigma(pp \rightarrow A) \times BR(A \rightarrow \tau\tau)$ in figure 2(b) around $2m_t$.

Figure 3. Comparison between 2HDM predictions and LHC results. (a), the predicted values for $R_{\gamma\gamma}^A$, for model type-I. (b), $R_{\gamma\gamma}^A$, for model type-II. All points include perturbative unitarity, stability, electroweak precision and B-physics cuts. The black line is the experimental exclusion line from LHC.

Figure 4. Predictions, within the 2HDM, for R_{ZZ}^h vs $R_{\gamma\gamma}^h$, for model type-I (a) and type II (b). Green (grey) points include perturbative unitarity, stability, electroweak precision and B-physics cuts. Blue (black) points include, on top of that, the exclusion of 2HDM parameters from the non-observation of H and A .

of the pseudoscalar of 150 GeV. In figure 3 we see the results of our scans for models I and II, for the pseudoscalar rate $R_{\gamma\gamma}^A$ (similar results hold for $R_{\gamma\gamma}^H$ in both models). Like for the $\tau\bar{\tau}$ channel, not much of the parameter space is excluded. However, it is worth pointing out that it is possible to obtain, in the 2HDM, extremely large enhancements of the diphoton signal. The sharp decrease we observe around masses of 350 GeV is clearly due to the opening of the decay channel $A \rightarrow t\bar{t}$, but before that we can have enhancements of a factor of 1000 or more over the expected SM value. Now, the diphoton channel is very difficult to analyse, but we would expect that such large enhancements in the signal coming from A can easily be excluded by existing data. It would be interesting to obtain experimental exclusion curves in the high mass region for the diphoton channel as well, since it is clear that a great deal of 2HDM parameter space may well be ruled out by that analysis.

In short, the current LHC results allow us to exclude portions of 2HDM parameter space, from the non-observation of a second peak corresponding to $H \rightarrow WW$ or $H \rightarrow ZZ$ for masses $125 \lesssim m_H \lesssim 600$ GeV. The $\tau\bar{\tau}$ data provide us with nice restrictions due to the non-observation of a pseudoscalar A and, in model type-II, also from signals coming from H . The $\gamma\gamma$ channels also give some mild exclusion, again mostly due to the pseudoscalar A . But if we combine all of these exclusions, we conclude there is still a great deal of 2HDM parameter space allowed, with extra scalar masses in ranges from 125 to 600 GeV (or even larger) completely allowed. Neither does the excluded region have any dramatic consequences for the lightest h observables. As we see from figures 4(a) and (b), the non-observation of H and A does give some differences in the allowed predictions for $R_{\gamma\gamma}^h$ and R_{ZZ}^h . But since the current best values for these observables are, respectively, $1.55^{+0.33}_{-0.26}$ and 1.5 ± 0.4 (ATLAS) or $0.78^{+0.28}_{-0.26}$ and 0.91 ± 0.30 (CMS), we conclude that there is nothing dramatic one can thus far conclude from the non-observation of neutral heavy states at the LHC. However, future improvements on the $\tau\bar{\tau}$ exclusion bounds for high masses, and the extension of the $\gamma\gamma$ exclusion to the high mass regime, hold the potential for severe restrictions on the 2HDM parameter space.

3 Higgs chain production

If the heaviest CP-even state H is heavy enough, it can decay to the lighter h via several possibilities — for instance, the decay channel $H \rightarrow hh$. Since the production cross sections for H , for certain 2HDM parameter choices, can actually be quite large, we see that there is another possibility of lightest Higgs production at the LHC: the heavy state H is produced and then decays to h . We call this process Higgs chain production, and H is not the single contributor to it: the pseudoscalar A and the charged Higgs $H^\pm$ can also have decays in which h is present, and as such may contribute to the number of lightest Higgs produced at the LHC.

In fact, chain production raises an interesting possibility: the decays of the heavier states to the lightest h may correspond to the *dominant* branching ratio of those particles. For instance, when the decay channel $H \rightarrow hh$ is open, for a wide range of values of 2HDM parameters this decay is dominant over all others. It is easy to understand why: since the Higgs scalars couple proportionally to the mass, for an H mass of, say, 300 GeV, decaying to two h 's is favoured over decaying to two W 's or two Z 's, or any fermions - unless the triple coupling Hhh is accidentally small, which is possible with some parameter fine-tuning. As such, for those (ample) regions of parameter space H could not be detected via its decays to fermions or gauge bosons, and only the study of h production could infer the presence of the heavier CP-even state. Similar circumstances, involving other channels, can also occur for the pseudoscalar A or the charged scalar $H^\pm$. Chain Higgs production is thus an alternate source of LHC lightest Higgs scalars, and we wish to verify whether it can have any impact on current observables. As we see from figure 5, the branching ratios for the decays $H \rightarrow hh$ and $A \rightarrow Zh$ can indeed be quite large and close to one, these becoming the dominant decays for a wide region of parameter space. Likewise for the decay $H^\pm \rightarrow W^\pm h$.

Figure 5. Branching ratios for the decays $H \rightarrow hh$ and $A \rightarrow Zh$ in terms of m_H and m_A for model type-II. All non-LHC (B-physics, perturbative unitarity, stability and electroweak precision) constraints have been imposed. Analogous results hold for model type-I.

3.1 New contributions to observable rates

The rates shown in eq. (2.1) are *partial* ones, since they do not take into account h indirect production through the decays of the heavier scalars. As such, the observed/expected *total* ratios for the lightest scalar h will have two contributions:

$$R_f^{T,h} = R_f^h + R_f^C \quad (3.1)$$

where we see the contribution of eq. (2.1) which describes direct h production; and a new contribution from chain h production, *a priori* including contributions from all the other scalar states (when suitably heavy):

$$R_f^C = R_f^{C,H} + R_f^{C,A} + R_f^{C,H^\pm}. \quad (3.2)$$

These contributions are given by, for H ,

$$R_f^{C,H} = \frac{\sigma^{2\text{HDM}}(pp \rightarrow H)}{\sigma^{\text{SM}}(pp \rightarrow h)} N_{H,h} \frac{BR^{2\text{HDM}}(h \rightarrow f)}{BR^{\text{SM}}(h \rightarrow f)}, \quad (3.3)$$

where $N_{H,h}$ is the expectation value of the number of lightest Higgs scalars h produced in the decays of H , i.e.

$$N_{H,h} = 2 \times P_{H,2h} + 1 \times P_{H,1h} \quad (3.4)$$

where $P_{H,2h}$ is the probability of finding two h scalars in decays of H , and $P_{H,1h}$ the probability of obtaining a single h . Taking into account all possible decays, we will have⁷

$$\begin{aligned} P_{H,2h} = & BR(H \rightarrow hh) \\ & + BR(H \rightarrow H^+ H^-) [BR(H^+ \rightarrow W^+ h)^2 + BR(H^+ \rightarrow W^+ A)^2 BR(A \rightarrow Zh)^2 \\ & \quad + 2BR(H^+ \rightarrow W^+ h) BR(H^+ \rightarrow W^+ A) BR(A \rightarrow Zh)] \\ & + BR(H \rightarrow AA) [BR(A \rightarrow Zh)^2 + 4BR(A \rightarrow W^- H^+)^2 BR(H^+ \rightarrow W^+ h)^2 \\ & \quad + 4BR(A \rightarrow Zh) BR(A \rightarrow W^- H^+) BR(H^+ \rightarrow W^+ h)] \end{aligned} \quad (3.5)$$

⁷We thank J. Yun for useful discussions concerning these formulae.

as well as

$$\begin{aligned}
 P_{H,1h} = & BR(H \rightarrow ZA) BR(A \rightarrow Zh) + 2BR(H \rightarrow W^- H^+) BR(H^+ \rightarrow W^+ h) \\
 & + 2BR(H \rightarrow AA) [BR(A \rightarrow Zh) \\
 & \quad + 2BR(A \rightarrow W^- H^+) BR(H^+ \rightarrow W^+ h)] p(A \not\rightarrow h) \\
 & + 2BR(H \rightarrow H^+ H^-) [BR(H^+ \rightarrow W^+ h) \\
 & \quad + BR(H^+ \rightarrow W^+ A) BR(A \rightarrow Zh)] p(H^+ \not\rightarrow h). \quad (3.6)
 \end{aligned}$$

Finally, we have to define the probabilities that A or $H^\pm$ do *not* decay into h , given by

$$\begin{aligned}
 p(A \not\rightarrow h) &= 1 - BR(A \rightarrow Zh) - 2BR(A \rightarrow W^- H^+) BR(H^+ \rightarrow W^+ h), \\
 p(H^+ \not\rightarrow h) &= 1 - BR(H^+ \rightarrow W^+ h) - BR(H^+ \rightarrow W^+ A) BR(A \rightarrow Zh). \quad (3.7)
 \end{aligned}$$

Please notice that many of the decays present in these formulae may well be kinematically forbidden for many choices of 2HDM parameters, in which case the corresponding branching ratios will automatically be zero.⁸ So, for instance, the decay $H \rightarrow hh$ will only be relevant if $m_H > 2m_h \simeq 250$ GeV, the decay $A \rightarrow Zh$ requires $m_A > m_Z + m_h \simeq 216$ GeV, and so on.

Likewise, we will have, for h chain production via pseudoscalar A production, the following contribution to the rate ratios:

$$R_f^{C,A} = \frac{\sigma^{2\text{HDM}}(pp \rightarrow A)}{\sigma^{\text{SM}}(pp \rightarrow h)} N_{A,h} \frac{BR^{2\text{HDM}}(h \rightarrow f)}{BR^{\text{SM}}(h \rightarrow f)}, \quad (3.8)$$

where the expectation value of the numbers of h scalars produced through decays of A is given by

$$N_{A,h} = 2 \times P_{A,2h} + 1 \times P_{A,1h} \quad (3.9)$$

where the decay probabilities are

$$\begin{aligned}
 P_{A,2h} &= BR(A \rightarrow ZH) [BR(H \rightarrow hh) + BR(H \rightarrow H^- H^+) BR(H^+ \rightarrow W^+ h)^2] \\
 &\quad + 2BR(A \rightarrow W^- H^+) BR(H^+ \rightarrow W^+ H) BR(H \rightarrow hh), \\
 P_{A,1h} &= BR(A \rightarrow Zh) + 2BR(A \rightarrow W^- H^+) BR(H^+ \rightarrow W^+ h) \\
 &\quad + 2BR(A \rightarrow ZH) \{BR(H \rightarrow H^- H^+) BR(H^+ \rightarrow W^+ h) [1 - BR(H^+ \rightarrow W^+ h)] \\
 &\quad + BR(H \rightarrow W^- H^+) BR(H^+ \rightarrow W^+ h)\}. \quad (3.10)
 \end{aligned}$$

Finally, for the $H^\pm$ contribution, we have

$$R_f^{C,H^\pm} = \frac{\sigma^{2\text{HDM}}(pp \rightarrow H^\pm)}{\sigma^{\text{SM}}(pp \rightarrow h)} N_{H^\pm,h} \frac{BR^{2\text{HDM}}(h \rightarrow f)}{BR^{\text{SM}}(h \rightarrow f)}, \quad (3.11)$$

with

$$N_{H^\pm,h} = 2 \times P_{H^\pm,2h} + 1 \times P_{H^\pm,1h} \quad (3.12)$$

⁸Notice, however, that like for the WW and ZZ channels, we also utilized off-shell formulae for the decays of heavier scalars into h [81].

Figure 6. Ratio of number of h scalars coming from chain production to the total number produced (direct production and chain production) for models I and II. Green (grey) points include perturbative unitarity, stability, electroweak precision and B-physics cuts. In blue (black) we further imposed cuts coming from non-observation of the heavy scalars H and A and we also required that the total rates $R_f^{T,h}$ be within 20% of their SM values, for all final states f .

where the decay probabilities are

$$\begin{aligned}
 P_{H^\pm, 2h} &= BR(H^+ \rightarrow W^+ H) [BR(H \rightarrow hh) + BR(H \rightarrow AA) BR(A \rightarrow Zh)^2] , \\
 P_{H^\pm, 1h} &= BR(H^+ \rightarrow W^+ h) + BR(H^+ \rightarrow W^+ A) BR(A \rightarrow Zh) \\
 &\quad + BR(H^+ \rightarrow W^+ H) BR(H \rightarrow ZA) BR(A \rightarrow Zh) .
 \end{aligned} \tag{3.13}$$

3.2 Chain Higgs production at the LHC

With these expressions established, we can begin by looking at the extra number of lightest scalars h which come from Higgs chain production. In figure 6 we plot the ratio of the number of h 's produced at the LHC via chain production (N_h^C) to the *total* number of h 's produced (via chain production and direct production, $N_h^C + N_h$), for both models type I and II. If one only requires that non-LHC constraints are satisfied, we see that chain production can even be the dominant process for production of the lightest scalar h . However, if we further require that the h 's being produced have rates to ZZ , WW , $\gamma\gamma$, etc, all within 20% of their expected SM values,⁹ we see that the contributions from chain production are substantially reduced. We have also included the cuts stemming from the non-observation of H and A at the LHC so far, as detailed in section 2. Those cuts do not have a major impact on chain Higgs production, as was to be expected: the regions of parameter space where chain Higgs production is expected to be significant correspond to large branching ratios for the decays $H \rightarrow hh$ and/or $A \rightarrow Zh$. Correspondingly, for such choices of parameters the decays of H into WW , ZZ or fermions would be highly suppressed, thus it being natural that H would not have been yet observed in those channels.

Still, one sees that chain production can still account for as much as $\sim 25\%$ of the number of h scalars produced at the LHC — more frequently, chain production can give

⁹By this we mean that the total rates $R_f^{T,h}$ of eq. (3.1) are all between 0.8 and 1.2, regardless of the final state f .

Figure 7. Ratio of number of h scalars coming from chain production to the total number produced (direct production and chain production) for model type-II. In red (dark grey) we show the contribution to chain production from the pseudoscalar A ; in green (light grey) the contribution from the CP-even heaviest scalar, H ; and in blue (black) the contribution from the charged scalar $H^\pm$.

an extra 10 to 20% number of h 's at the LHC. Thus, current LHC trends in the observable rates of h do not allow us to dismiss chain Higgs production as an irrelevant curiosity — it may well have an impact on what we are already measuring. For completeness, in figure 7 we show the individual contributions to the number of lightest Higgs coming from chain production from each of the extra scalars,¹⁰ in model type-II. Like before, we demanded that the h rates be within 20% of its SM values, as well as all non-LHC cuts. We see that the charged Higgs $H^\pm$ contribution to chain production is quite small. The largest contribution stems from the pseudoscalar, via (mostly) the decay $A \rightarrow Zh$. Slightly smaller, but comparable in size, is the contribution from the heaviest CP-even scalar H , via (mostly) the decay $H \rightarrow hh$. Also, from figure 7, we ascertain that the largest contributions to chain production occur for relatively smaller values of $\tan\beta$ (i.e., smaller than about 5). Finally, the off-shell contributions from decays such as $A \rightarrow Zh$ or $H \rightarrow hh$ are much smaller than the on-shell ones, and have a negligible effect on the final results.

It is interesting to profile the pseudo-scalars that can give the largest contribution to chain decays. Their mass should be above the hZ threshold and not too large. The values of $\tan\beta$ should close to 1 in both models. Moreover, we have checked that the preferred values of $\sin(\beta - \alpha)$ are those close to 1. Because $\Gamma(A \rightarrow hZ) \propto \cos(\beta - \alpha)$, and $\cos(\beta - \alpha) \sim 0$, this width is small. Hence, to obtain a significant $BR(A \rightarrow hZ)$, the total width has to be small as well (below 1 GeV, at least). Further, the low values of $\tan\beta$ enhance the production cross sections of the pseudoscalar, via gluon-gluon fusion.

3.3 Chain Higgs production contributions to observable h rates

Having established that chain Higgs production may have a sizeable contribution to the number of h scalars seen at the LHC, we need then to ask how one might detect this

¹⁰Meaning, from the direct production of one of the extra scalars and subsequent decays to h .

Figure 8. Contributions from chain Higgs production to the rates of h to ZZ and $\gamma\gamma$. All cuts (B-physics, non observation of heavy scalars, ...) considered. In blue (black) we show the rates *excluding* chain Higgs production. In green (grey) the rates which *include* chain Higgs production.

phenomenon. Let us first consider the rates of production and decay of h to two photons and two Z bosons — meaning, the *total* rates, as defined and explained in eqs. (3.1)–(3.13). As one can observe from figure 8, the contributions from chain Higgs production do have an impact on the observables $R_{\gamma\gamma}^h$ and R_{ZZ}^h , by increasing them. This is of course to be expected, since the chain Higgs process increases the number of h scalars being produced. In particular, we see that for model type-I chain Higgs production allows one to obtain values of R_{ZZ}^h above unity, something that would otherwise not be possible for this model. In fact, if one excludes chain Higgs production, the Higgs production cross section at the LHC is dominated by gluon-gluon fusion which, for model type-I, is approximately given by

$$\sigma^{2\text{HDM}}(gg \rightarrow h) \simeq \frac{\cos^2 \alpha}{\sin^2 \beta} \sigma^{\text{SM}}(gg \rightarrow h). \quad (3.14)$$

On the other hand, the total h width is dominated by the decay $h \rightarrow b\bar{b}$, so that

$$BR^{2\text{HDM}}(h \rightarrow ZZ) \simeq \frac{\Gamma^{2\text{HDM}}(h \rightarrow ZZ)}{\Gamma^{2\text{HDM}}(h \rightarrow b\bar{b})} = \frac{\sin^2 \beta}{\cos^2 \alpha} \sin^2(\beta - \alpha) \frac{\Gamma^{\text{SM}}(h \rightarrow ZZ)}{\Gamma^{\text{SM}}(h \rightarrow b\bar{b})}, \quad (3.15)$$

and thus

$$BR^{2\text{HDM}}(h \rightarrow ZZ) \simeq \frac{\sin^2 \beta}{\cos^2 \alpha} \sin^2(\beta - \alpha) BR^{\text{SM}}(h \rightarrow ZZ). \quad (3.16)$$

Therefore, under these approximations, the ZZ rate excluding chain Higgs production is

$$R_{ZZ}^{2\text{HDM}} \simeq \frac{\sigma^{2\text{HDM}}(gg \rightarrow h) BR^{2\text{HDM}}(h \rightarrow ZZ)}{\sigma^{\text{SM}}(gg \rightarrow h) BR^{\text{SM}}(h \rightarrow ZZ)} = \sin^2(\beta - \alpha) \lesssim 1. \quad (3.17)$$

Model type-I therefore predicts values of R_{ZZ} always smaller than about 1. Confirmation of the higher values measured for this variable by ATLAS could then, in the context of model type-I, be interpreted as a sign of observation of chain Higgs production. For comparison, it has been shown [82] that one-loop corrections to the hZZ coupling in the 2HDM are of the order of less than 5% for $\cos(\beta - \alpha) \simeq 0$, while for $\cos(\beta - \alpha) \simeq 0.2$ the correction

Figure 9. Contributions from chain Higgs production to the rates of h to $\tau\bar{\tau}$ and $\gamma\gamma$. All constraints (B-physics, non observation of heavy scalars, etc) considered. In blue (black) we show the rates *excluding* chain Higgs production. In green (grey) the rates which *include* chain Higgs production.

could be as large as 15%, but *negative*. An observed enhancement on R_{ZZ}^h would therefore be difficult to attribute to loop corrections. For completeness, in figure 9 we plot the h rates to $\tau\bar{\tau}$ and $\gamma\gamma$ with and without the chain Higgs contributions. Again we see that chain Higgs production tends to increase the values of these rates, but the effects are not as pronounced as in the previous plots.

However, care must be taken when analysing these extra contributions to the rates R . The current LHC results are the product of a careful and complex dedicated experimental analysis, which assumes direct Higgs production. Now, our analysis above did not take into account the kinematic distributions of any particles in the final states, or intermediate ones. But one obvious place where there will be a difference in direct or chain Higgs production will be in the transverse momentum (p_T) distributions of the h scalars.¹¹ *Naïvely*, we can expect that the h scalars are produced almost at rest in direct Higgs production, and having a p_T distribution favouring smaller values. However, the chain Higgs contributions stemming from the decay $H \rightarrow hh$ would generate h 's which could have high p_T , which might in turn change considerably the kinematic distributions of their decay products. Also, chain Higgs production associated with the decays $A \rightarrow Zh$ or $H^\pm \rightarrow W^\pm h$ would certainly affect the associated production of a scalar h and a gauge boson.

We are therefore confronted with some very important questions which, to the best of our knowledge, are thus far unanswered, and require (a) heavy input from our experimentalist colleagues from LHC and (b) thorough Monte Carlo simulations. In short:

1. For many choices of parameters, the main contribution to chain Higgs production comes from the decay $H \rightarrow hh$. Clearly, confirmation of this would come from the identification of two scalars of masses ~ 125 GeV in the LHC data. However, as explained, it is possible that these h scalars were not produced at rest and have a p_T

¹¹We thank S. Dawson, J. Gunion and S. Kraml for discussions on this subject, after a presentation of an early version of this work in the Scalars 2013 conference.

distribution quite different from that which is expected from direct Higgs production. Is it possible to go back to the data already collected and verify this possibility? One possibility would be to check the presence of two very energetic jets and two photons, both pairs with invariant masses close to 125 GeV. These requirements should reduce considerably the QCD backgrounds.

2. Somewhat related to the previous question, does the current experimental analysis performed by the LHC collaborations even allow for the testing of chain Higgs production? If not, then this is the perfect time to re-evaluate those choices, since the LHC is undergoing maintenance and will not begin taking data for another two years.
3. Is it possible that, despite originating in chain Higgs production, the extra h scalars and/or their decay products might be indistinguishable from those originating in direct Higgs production? This would seem to certainly be the case for h 's being chain-produced via the decays $A \rightarrow Zh$ and $H^\pm \rightarrow W^\pm h$.

We are confronted with two possibilities, both quite exciting: on the one hand, it is possible that what is being observed at the LHC already includes signs of a heavy scalar H , for instance, but we simply have not yet performed the correct analyses to detect those new states; on the other hand, it is also possible that the experimental analyses performed make it at all impossible to test the chain Higgs production hypothesis.

4 Conclusions

The LHC has provided us with a wealth of data, which confirmed the existence of the Higgs boson. Within the next years, we should be able to verify whether this new particle conforms perfectly to its expected SM behaviour or, on the contrary, exhibits properties which indicate the existence of new physics. One of the simplest extensions of the SM is the 2HDM, which predicts three other scalars. We have analysed what the current LHC results can tell us about these new scalars. In the mass scan on the WW , ZZ , $\tau\bar{\tau}$ and $\gamma\gamma$ channels, non-observation of any excesses above the expected backgrounds allow us to constrain the 2HDM parameter space. However, there is still plenty of parameter space available within the model to comply with those restrictions and it is simple, and in fact expected, for the 2HDM neutral scalars A and H to elude such bounds: A , being a pseudoscalar, does not couple (at tree-level) to W 's or Z 's, and H is expected to couple very weakly to gauge bosons, since the CP-even lighter scalar h seems to couple to them with SM-like strength (as would occur in the decoupling limit). The $\tau\bar{\tau}$ data also excludes a large chunk of parameter space — mostly for large values of $\tan\beta$, due to the enhanced pseudoscalar production in that region. The $\gamma\gamma$ signal is also promising if one can obtain exclusion bounds from LHC for large values of A and H masses.

Another possibility which arises in the 2HDM is that the heavier scalars might be undetectable in the “usual” channels, because they decay mostly to the lighter scalar h . In fact, it is easy to find vast regions of 2HDM parameter space where the decays $H \rightarrow hh$, or $A \rightarrow Zh$, or $H^\pm \rightarrow W^\pm h$, are the dominant ones, occurring with branching ratios close to

1. Under such circumstances, the only way to detect the heavier scalars would be through h itself. These chain decays of the heavier scalars would contribute to the lightest Higgs production at the LHC, and we have shown that they might enhance its rates to ZZ , WW , $\gamma\gamma$ or $\tau\tau$. Chain Higgs production could therefore be already in effect at the LHC, and we are seeing signs of the presence of the heavy 2HDM scalars without knowing it.

The unequivocal sign of chain Higgs production would be the identification of two h scalars being produced at the same time, compatible with being the result of the decay of an H scalar. This tantalizing possibility can either be indistinguishable from direct Higgs production with the current experimental analyses, or, even more excitingly, may already be possible to detect using the current data, requiring that a completely new analysis be performed. In either case, Monte Carlo simulation, beyond the scope of the current work, is necessary to verify these possibilities. Also, the experimental search for double Higgs production (within the SM) is not yet conclusive; when more data is available it may put constraints on some of the channels we have looked into.

Finally, the issue of chain Higgs production is not exclusive to the 2HDM. That possibility could also be present in SUSY models, and in fact in any multi-Higgs doublet models. Any thorough analysis of what the current LHC data can tell us about chain Higgs production is therefore also relevant for studies of those other models.

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