

## BEYOND THE STANDARD MODEL HIGGS BOSON SELF-COUPPLINGS AT THE LHC

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A study of two-Higgs-doublet models (2HDM) in the decoupling limit reveals the existence of parameter configurations with a large triple-Higgs self-coupling as the only low-energy trace of a departure from a Standard Model (SM) Higgs sector. This observation encourages attempts to search for double Higgs production at the Large Hadron Collider (LHC) and its luminosity upgrade (SLHC) even in mass regions which have been shown to be very hard to probe in the context of SM-like Higgs self-couplings. In a scenario where only an Intermediate Mass Higgs (IMH) boson, with  $120 \text{ GeV} \lesssim m_h \lesssim 140 \text{ GeV}$ , is discovered at the LHC, with measured couplings to fermions and gauge bosons compatible with their SM values, we show that Higgs-pair production (with each Higgs state decaying in two  $b\bar{b}$  pairs) through Weak Boson Fusion (WBF) could open a window on physics beyond the SM in the Higgs sector.

### 1 Introduction

Several detailed studies <sup>1</sup> have established the ability of the ATLAS and CMS experiments to detect a SM Higgs boson over the full range of allowed masses. Many decay channels will be accessible at the LHC, en-

abling the determination of several Higgs boson couplings with accuracies that can be as good as 10% <sup>1</sup>. Possible significant departures from the SM expectations would allow to infer a non-standard Higgs, but there is no guarantee that non-SM Higgs sectors will become manifest via these measurements. Ex-

amples are given by 2HDMs, including Supersymmetric models, where the spectrum of Higgs bosons beyond the lightest one could be very heavy and the couplings of the latter to fermions and gauge bosons reduce to those of the SM. In this contribution, we explore the possibility that, in this *decoupling* scenario (namely only one SM-like Higgs boson  $h$  discovered at LHC in the mass range 120–140 GeV with couplings to fermions and gauge bosons compatible, within the foreseen experimental uncertainty, with the SM), only a large deviation from the SM value  $\lambda_{hhh}^{(0)}$  of the triple-Higgs self-coupling involving the lightest Higgs state (hereafter  $\lambda_{hhh}$ ) is allowed to survive. Such a circumstance would select the production of Higgs boson pairs as the only possible channel for the identification of a non-SM Higgs structure. Recent studies at the LHC (and prospects for the luminosity upgrade SLHC<sup>2</sup>) are reported in<sup>3</sup>, where the case of IMH boson pairs generated via WBF, associate production with  $t\bar{t}$  pairs and with  $W/Z$ , each decaying into  $b\bar{b}$  pairs, is considered in detail. The reason to exploit these non-leading production channels is due to the additional triggers available in each case, with respect to the leading  $gg \rightarrow hh$  mode, which could give an handle to significantly cut the background processes. A critical comparison between a complete (model-dependent) 2HDM calculation and a model-independent prescription, where only the  $\lambda_{hhh}$  parameter is rescaled, shows that non trivial regions of the generic 2HDM parameter space are allowed, giving, as a signal, an excess in the  $X4b$  signatures considered (in particular  $4b + 2$  forward jets). A detailed account on existing studies on Higgs-pair production can be found in<sup>3</sup>.

## 2 The decoupling limit of 2HDMs

A study of the decoupling limit of 2HDMs has recently been presented in<sup>4</sup> (see also<sup>5</sup>), where the general expressions for the spec-

trum and couplings of a generic, non-CP violating, 2HDM are derived. The deviations from the decoupling limit are proportional to  $\epsilon = \hat{\lambda}v^2/m_A^2$  and  $\epsilon^2$  in the case of the couplings to fermions and gauge bosons, whereas the self-coupling is proportional to  $\epsilon\hat{\lambda}/\lambda$ , with  $\lambda$  and  $\hat{\lambda}$  being function of the 2HDM parameters  $\lambda_i$  ( $i = 1, \dots, 7$ ) of Ref.<sup>4</sup>. The possibility that the ratio  $\hat{\lambda}/\lambda$  be large allows for the triple-Higgs self-coupling to remain large even when the other couplings are converging to their SM values. We analyzed this possibility<sup>3</sup> by implementing the exact couplings of a generic 2HDM as discussed in<sup>4</sup> and scanning the parameter space in the range  $1 < \tan\beta < 50$ ,  $-4\pi < \lambda_i < 4\pi$  for all couplings  $\lambda_i$  defined in<sup>4</sup>,  $i = 1, \dots, 7$ . Our general scan was subject to the constraints of tree-level unitarity<sup>4</sup> and to the requirement that the couplings  $g_{hVV}^2$ ,  $g_{htt}^2$  and  $g_{hbb}^2$  differ from the SM values by no more than 30%, 30% and 70%, respectively. These values reflect the measurement accuracies expected after 300 fb<sup>-1</sup> of accumulated LHC luminosity<sup>1a</sup>. The distribution of  $r = \lambda_{hhh}/\lambda_{hhh}^{(0)}$  for the three Higgs mass values of 120, 130 and 140 GeV in the general case ( $\lambda_{6,7} \neq 0$ ) is shown in Fig. 1, where the scan assumed equiprobable input values for all 2HDM inputs. In addition we require no visibility at  $3\sigma$  level of the heavy neutral states  $H$  and  $A$ , resulting in the mass constraints  $m_H \gtrsim 300$  GeV and  $m_A \gtrsim 250$  GeV. Operatively, we define as *decoupling region* of the 2HDM the configurations of 2HDM parameters which survive the above constraints. The scan of all  $\lambda_i$  leads to models with values of  $r$  in the ranges  $-8 \lesssim r \lesssim 36$ ,  $-7 \lesssim r \lesssim 35$  and  $-6 \lesssim r \lesssim 34$  for  $m_h = 120, 130$  and 140 GeV, respectively<sup>b</sup>. We refer to<sup>3</sup> for all the de-

<sup>a</sup>Also a more optimistic scenario of 20%, 20% and 30% of measurement accuracies<sup>6</sup> has been investigated, yielding conclusions similar to the ones outlined below, though over a restricted parameter range (see also next footnote).

<sup>b</sup>In the case of the more optimistic uncertainty scenario we get  $-3.5 \lesssim r \lesssim 18$ ,  $-3 \lesssim r \lesssim 17$  and

$m_h$ (GeV)	120		130		140	
LHC, 95% CL	-1.7	5.2	-2.4	5.5	-3.9	6.9
SLHC, 95% CL	-0.1	3.5	-0.5	3.6	-1.5	4.5
LHC, $3\sigma$	-2.6	6.1	-3.4	6.5	-5.3	8.3
SLHC, $3\sigma$	-0.6	4.0	-1.1	4.2	-2.3	5.2

Table 1. Constraints on the ratio  $\lambda_{hhh}/\lambda_{hhh}^{(0)}$  using the channels  $X4b$ . The results are almost completely driven by WBF. In the top box, the two values in each entry correspond to  $r_{\min}$ ,  $r_{\max}$ , where  $r < r_{\min}$  and  $r > r_{\max}$  define the range which can be excluded at 95% CL (first row) or probed at the  $3\sigma$  level (second row), at both the LHC and SLHC. The number of events corresponding to  $3\sigma$  significance are about 130, 110 and 100 for  $m_h = 120, 130$  and  $140$  GeV respectively at the SLHC.

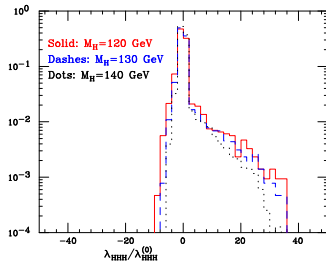


Figure 1. Distribution of the values of  $r = \lambda_{hhh}/\lambda_{hhh}^{(0)}$  in the scans of the 2HDM parameters space, for three values of the lightest Higgs boson mass. Normalization is to unity.

tails on the used selection criteria and on the signal-to-background analysis performed with the ALPGEN event generator <sup>7</sup> as well as a modification of HDECAY <sup>8</sup> and of the program described in <sup>9</sup>. In order to have model-independent predictions, the effects of an anomalous  $\lambda_{hhh}$  coupling have been estimated by simply rescaling the value of  $\lambda_{hhh}^{(0)}$  to a generic  $\lambda_{hhh}$ . Over the range allowed by our scan, cross section enhancements by up to two orders of magnitude can be obtained. Exclusion limits (at 95% CL) and signal evidence (at  $3\sigma$ ) for anomalous triple-Higgs self-couplings by combining all channels are given in Tab. 1. The by far most sensitive mode is WBF, with top-quark( $W/Z$ ) associate production being of some relevance only for small Higgs masses and positive  $\lambda_{hhh}/\lambda_{hhh}^{(0)}$  values(no relevance whatsoever). Notice that the described rescaling is not a gauge invariant operation, because diagrams involving other genuine 2HDM fields (namely,  $H$ ,  $A$  and

<sup>7</sup> $-2 \lesssim r \lesssim 16$  for  $m_h = 120, 130$  and  $140$  GeV, respectively.

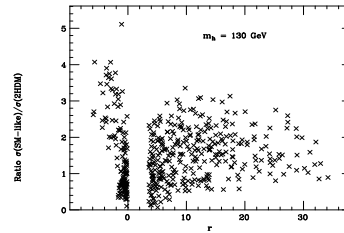


Figure 2. Ratio between the SM cross section with rescaled value of  $\lambda_{hhh}^{(0)}$  and the full 2HDM prediction, as described in the text. Only the region of  $r$  accessible at the SLHC (Tab. 1) is shown.

$H^\pm$ ) in the Lagrangian, as well the rescaling of the Higgs-to-SM-particle couplings to the 2HDM values, are neglected. Therefore, one might suspect that the cross sections are anomalously enhanced by unitarity violation effects even in decoupling regime. To investigate this possibility we have re-computed the WBF cross section, including the full set of 2HDM diagrams, for 436 points uniformly distributed over the 2HDM parameter space, fulfilling the decoupling conditions described previously, and with  $r$  in the ranges accessible at the SLHC. As a results of this exercise, we did find points, for any value of  $r$ , where the 2HDM cross section agrees almost exactly with the model-independent approximation (see Fig. 2). As a further check, we also verified, using the same points, that the correct decoupling limit is recovered for large values of the mass of the heavy Higgs states (see Fig. 3). Since the calculation is now gauge invariant, the existence of points with ratio  $\sigma(\text{SM} - \text{like})/\sigma(2\text{HDM}) \approx 1$  demonstrates that the approximation of neglecting

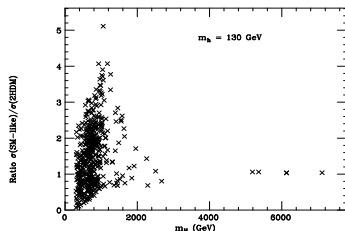


Figure 3. As the previous figure, as a function of  $m_H$ .

additional graphs and coupling modifications does not lead to an artificial enhancement of the sensitivity to  $\lambda_{hhh}$ . Furthermore, for  $\approx 70\%$  of the points in Fig. 2 the cross section is reproduced by the above described approximation within a factor two. Finally, for a small, but sizable, portion of points the cross section is substantially underestimated while for even fewer points is grossly overestimated. We also tried to understand the origin of such discrepancies. Firstly, the most noticeable ones are due to the  $\text{BR}(h \rightarrow b\bar{b})$ , as our definition of decoupling region allows for rather sizable deviations of the latter from the SM value and, since we are looking for two Higgs bosons decaying into  $b\bar{b}$ , this BR enters quadratically into our predictions. Secondly, also the diagrams proportional to  $g_{hVV}$  ( $V = W, Z$ ) can give an important contribution: although the decoupling limit strongly constraints deviations of  $g_{hVV}$  from the SM value, the consequences of the latter can be enhanced by large destructive interferences. Once these two effects are accounted for, the overall agreement is fairly good: the contribution of the SM diagrams to the total cross section is correct within a 20% accuracy, except for a small fraction of points where the production rate is strongly underestimated. We have finally verified that the latter effect is due to neglecting diagrams where a light 2HDM Higgs pair is produced via the decay of the heavy 2HDM Higgs boson,  $H \rightarrow hh$ . Notice that the effect of this additional contribution reinforces our conclusion that the signal is detectable, actually suggesting that a search is possible even in

regions where  $\lambda_{hhh}$  exhibits deviations from the SM value smaller than those in Tab. 1.

### 3 Summary

The main conclusion of our analysis is that in a large portion of the explored 2HDM region the production of an IMH pair will be detectable at the (S)LHC through the study of the reactions of the type  $pp \rightarrow Xhh \rightarrow X4b$ . We emphasize that, due to the decoupling constraints, this anomalous enhancement of the  $b\bar{b}b\bar{b}$  signal will be, in the decoupling scenario, the only accessible signature of departure from the SM at the LHC. In closing, we note that our results are not confined to the 2HDM in the decoupling limit but are model independent, thereby being applicable to other Higgs sectors displaying a similar decoupling behavior between the lightest CP-even Higgs state and the heavier ones.

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