

# Two Higgs Bosons at the Tevatron and the LHC?

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## Abstract

The best fit to the Tevatron results in the  $b\bar{b}$  channel and the mild excesses at CMS in the  $\gamma\gamma$  channel at 136 GeV and in the  $\tau\tau$  channel above 132 GeV can be explained by a second Higgs state in this mass range, in addition to the one at 125 GeV recently discovered at the LHC. We show that a scenario with two Higgs bosons at 125 GeV and 136 GeV can be consistent with practically all available signal rates, including a reduced rate in the  $\tau\tau$  channel around 125 GeV as reported by CMS. An example in the parameter space of the general NMSSM is given where, moreover, the signal rates of the 125 GeV Higgs boson in the  $\gamma\gamma$  channels are enhanced relative to the expectation for a SM Higgs boson of this mass.

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# 1 Introduction

In July 2012 the ATLAS and CMS collaborations at the LHC announced the observation of a new particle with the properties of a Higgs boson [1–3], a particle predicted in the Standard Model of particle physics (SM). This observation was supported by evidence for a Higgs boson found by the CDF and D0 collaborations at the Tevatron [4].

The SM makes quite precise predictions for the production cross sections of the Higgs boson  $H$  (via gluon-gluon fusion ( $ggF$ ), vector boson fusion ( $VBF$ ) and associated production with an electroweak gauge boson  $V = W, Z$  ( $VH$ )), and its decay branching fractions into various final states ( $ZZ^{(*)}$ ,  $WW^{(*)}$ ,  $bb$ ,  $\gamma\gamma$  and  $\tau\tau$ ) as a function of its unpredicted mass  $M_H$ . The observation of the Higgs boson at the LHC is based primarily on the  $\gamma\gamma$  [5, 6],  $ZZ^{(*)}$  [7, 8] and  $WW^{(*)}$  [3, 9] decay modes. The Higgs boson mass,  $M_H$ , is quite precisely measured to be in the 125–126 GeV range using the high resolution  $\gamma\gamma$  and  $ZZ^{(*)}$  final states. The evidence for the Higgs boson at the Tevatron is based principally on the  $bb$  decay mode [10], the observed enhancements being consistent with a large range of possible Higgs masses.

Although most of the results originating from the various production and decay channels are consistent with the expected properties of a SM Higgs boson, differences of up to about two standard deviations are observed in some cases:

1. the observed signal rate for  $M_H = 125$  GeV in the  $\gamma\gamma$  decay mode is enhanced relative to the SM expectation in the measurements of both the ATLAS and CMS collaborations [5, 6];
2. in the  $\gamma\gamma$  decay mode, CMS observes an additional excess corresponding to  $M_H \sim 136$  GeV [6];
3. the best fit to the measurement of  $M_H$  at the Tevatron corresponds to  $M_H \sim 135$  GeV with an enhanced signal rate in the  $bb$  decay mode [4, 10];
4. in the  $\tau\tau$  decay mode, CMS observes a deficit for  $M_H \sim 125$  GeV for the  $VBF$ -tag class of events, but an excess for  $M_H \gtrsim 132$  GeV [11].

At present, these deviations are not significant enough to prove that the Higgs sector is non-SM-like. However, in this paper we argue that all of them can be described simultaneously by an extended Higgs sector involving (at least) two states, one near 125 GeV *and* a second near 136 GeV. We show that the desired properties of these two Higgs bosons can be obtained in the Next-to-Minimal Supersymmetric extension of the SM (NMSSM) [12]. In all models with an extended Higgs sector and two light CP-even Higgs bosons, the couplings of these Higgs bosons to electroweak gauge bosons, up-type quarks, down-type quarks and charged leptons, and the radiatively induced couplings to gluons and photons will generally differ from those of a SM Higgs boson; this makes it possible to understand the discrepancies listed above with respect to the SM.

In Section 2 we summarize the necessary properties of two Higgs bosons such that these discrepancies are explained while maintaining consistency with the numerous additional measurements of the various production and decay channels by the ATLAS, CMS, CDF and

D0 collaborations. In Section 3 we briefly review the NMSSM, and discuss the properties of an appropriate point in the NMSSM parameter space. Section 4 is devoted to conclusions.

## 2 Desired properties of and constraints on two Higgs bosons

For each production mode  $\sigma(pp \text{ or } p\bar{p} \rightarrow Y \rightarrow H_i) \equiv \sigma_Y(H_i)$  ( $Y = gg, VV, VH_i$ ) and decay channel  $H_i \rightarrow X$  ( $i = 1, 2$  or  $3$ ) of a non-standard Higgs boson,  $H_i$ , it is useful to define a reduced signal rate  $R_i^X(Y)$  relative to the expected signal rate of a SM Higgs boson  $H_{\text{SM}}$  of the same mass:

$$R_i^X(Y) = \frac{\sigma_Y(H_i)}{\sigma_Y(H_{\text{SM}})} \times \frac{BR(H_i \rightarrow X)}{BR(H_{\text{SM}} \rightarrow X)} \quad (1)$$

For  $Y = gg$  and  $Y = VV$  we use the notations  $ggF$  and  $VBF$ , respectively. The first factor in (1) we term the reduced production cross section, the second factor in (1) the reduced branching fraction.

In addition, it is useful to define “reduced couplings” (relative to the couplings of the SM Higgs boson) of the non-standard Higgs bosons  $H_i$  to electroweak gauge bosons ( $c_{V_i}$ ), to up-type quarks ( $c_{U_i}$ ), to down-type quarks ( $c_{D_i}$ ), to gluons ( $c_{g_i}$ ) and to photons ( $c_{\gamma_i}$ ). We will make the assumption that the reduced couplings to charged leptons such as the  $\tau$ -lepton are also given by  $c_{D_i}$ , as is the case in supersymmetric extensions of the SM (up to radiative corrections relevant for very large  $\tan\beta$ ). If only SU(2) doublet and singlet Higgs bosons exist, the  $c_{V_i}$  can never exceed 1, and are identical for  $V = W$  and  $V = Z$ . The radiatively induced coupling to gluons originates mostly from top quark loops; correspondingly one has  $c_{g_i} \sim c_{U_i}$  if there are no additional SM-like or non-SM-like loop contributions. The radiatively induced coupling to photons originates mostly from the  $W$  loop which leads to  $c_{\gamma_i} \approx c_{V_i}$  neglecting the much smaller top loop contribution and loops involving non-SM particles. (Note that one must not confuse  $c_{\gamma_i}$  with the reduced branching fraction into  $\gamma\gamma$ , see below.)

In the case of the observed Higgs boson with a mass of 125–126 GeV, the experimental collaborations have published best fits to reduced signal rates for various decay modes. Sometimes these are combinations of different production modes, in particular  $ggF$  and  $VBF$ , which have to be disentangled. For all other Higgs masses, the experimental collaborations have published bounds on (or p-values for) reduced signal rates; again these correspond often to combinations of different production modes. Using the available information, we will estimate the production-mode specific signal rates (1) for both a Higgs boson  $H_1$  with a mass of 125–126 GeV and a Higgs boson  $H_2$  with a mass of 135–136 GeV. From the production-mode specific signal rates we can deduce the desired ranges of reduced couplings of both Higgs states. We now sketch the corresponding steps.

The dependence of the reduced production cross sections of non-standard Higgs bosons  $H_i$  on the reduced couplings is given by (including most radiative corrections)

$$\frac{\sigma_i(ggF)}{\sigma_{H_{\text{SM}}}(ggF)} = (c_{g_i})^2, \quad \frac{\sigma_i(VBF)}{\sigma_{H_{\text{SM}}}(VBF)} = \frac{\sigma_i(VH)}{\sigma_{H_{\text{SM}}}(VH)} = (c_{V_i})^2. \quad (2)$$

However, the dependence of the reduced decay branching fractions of a non-standard Higgs boson  $H_i$  on the reduced couplings is more involved. First, the partial widths  $\Gamma(H_i \rightarrow X)$  have to be rescaled correspondingly:

$$\begin{aligned}\Gamma(H_i \rightarrow bb) &= (c_{D_i})^2 \times \Gamma(H_{\text{SM}} \rightarrow bb), \\ \Gamma(H_i \rightarrow WW^{(*)}) &= (c_{V_i})^2 \times \Gamma(H_{\text{SM}} \rightarrow WW^{(*)}), \\ \Gamma(H_i \rightarrow \gamma\gamma) &= (c_{\gamma_i})^2 \times \Gamma(H_{\text{SM}} \rightarrow \gamma\gamma), \quad \text{etc.}\end{aligned}\tag{3}$$

Hence the total width is

$$\Gamma_{\text{Tot}}(H_i) = (c_{D_i})^2 \times \Gamma(H_{\text{SM}} \rightarrow bb) + (c_{V_i})^2 \times \Gamma(H_{\text{SM}} \rightarrow WW^{(*)}) + \dots\tag{4}$$

where we have shown only the dominant contributions. Finally the reduced branching fractions are

$$\frac{BR(H_i \rightarrow X)}{BR(H_{\text{SM}} \rightarrow X)} = \frac{\Gamma(H_i \rightarrow X)}{\Gamma(H_{\text{SM}} \rightarrow X)} \times \frac{\Gamma_{\text{Tot}}(H_{\text{SM}})}{\Gamma_{\text{Tot}}(H_i)}.\tag{5}$$

The reduced signal rates of Eq. (1) can then be computed in terms of the reduced couplings, Eqs. (2) and (5).

If two Higgs bosons with masses of about 125 GeV and 136 GeV exist, one must distinguish Higgs search channels with high mass resolution for which it is possible to measure the masses and reduced signal rates separately (the  $\gamma\gamma$  and  $ZZ$  modes) from Higgs search channels with low mass resolution to which the contributions from the two states can overlap (the  $WW$ ,  $bb$  and  $\tau\tau$  modes). Let us begin with the present situation in the high mass resolution channels.

### 1) A Higgs boson $H_1$ at 125–126 GeV

The dominant production process allowing for the observation of a Higgs boson in the  $\gamma\gamma$  mode at the LHC is  $ggF$ . The best fits to  $R_1^{\gamma\gamma}(ggF)$  from the ATLAS and CMS collaborations are both significantly larger than 1:  $R_1^{\gamma\gamma}(ggF) \simeq 1.8 \pm 0.5$  (ATLAS [5]),  $R_1^{\gamma\gamma}(ggF) \simeq 1.5 \pm 0.5$  (CMS [6]). Combining, we estimate

$$R_1^{\gamma\gamma}(ggF) \simeq 1.66 \pm 0.36.\tag{6}$$

In addition, both collaborations have studied events with two additional forward jets to which the contribution from  $VBF$  is dominant. At CMS, combining the 7 TeV dijet tag and 8 TeV dijet tight results, yields  $R_1^{\gamma\gamma}(VBF) \sim 2.6 \pm 1.3$  [6]; note that here the  $VBF$  category contains roughly 25%  $ggF$  production. For ATLAS, we obtain  $R_1^{\gamma\gamma}(VBF) \sim 2.7 \pm 1.5$  [5] (with unspecified  $ggF$  contamination). Subsequently we merely assume  $R_1^{\gamma\gamma}(VBF) > 1$ .

The  $ggF$  process also dominates the Higgs signal in the  $ZZ$  channel. The best fits to  $R_1^{ZZ^{(*)}}(ggF)$  from the ATLAS and CMS collaborations are both consistent with 1:  $R_1^{ZZ^{(*)}}(ggF) \simeq 1.4 \pm 0.6$  (ATLAS [5]),  $R_1^{ZZ^{(*)}}(ggF) \simeq 0.75 \pm 0.5$  (CMS [6]). Combining, we estimate

$$R_1^{ZZ^{(*)}}(ggF) \simeq 1.02 \pm 0.38.\tag{7}$$

### 2) A Higgs boson $H_2$ at 135–136 GeV

In the  $\gamma\gamma$  mode, CMS has observed an excess of events of about two standard deviations around 136 GeV [2, 6], the excess being a bit larger for the 7 TeV data than for the 8 TeV

data. Combining the two data sets, the corresponding reduced signal rate can be estimated as  $R_2^{\gamma\gamma}(ggF) \simeq 0.9 \pm 0.4$  (CMS). However, no excess of events at this mass was observed by ATLAS [7]. We estimate  $R_2^{\gamma\gamma}(ggF) \simeq 0.0 + 0.4$  (ATLAS). Taken together, one obtains

$$R_2^{\gamma\gamma}(ggF) \simeq 0.45 \pm 0.3. \quad (8)$$

The above is a crude estimate, which could be improved by more detailed analyses and/or more data; here we consider it as a first hint for the existence of a second state near 136 GeV in the Higgs sector.

In the  $ZZ^{(*)}$  mode, no excess has been observed by the ATLAS and CMS collaborations for  $M_H \sim 136$  GeV [7, 8]. Combining both upper bounds on the reduced signal rate, we estimate

$$R_2^{ZZ^{(*)}}(ggF) \lesssim 0.2 \quad (9)$$

at the level of one standard deviation.

Next we turn to the low mass resolution channels. In the  $\tau\tau$  channel and tagging two jets (sensitive mostly to the  $VBF$  production mode), CMS observes a deficit with respect to the background-only hypothesis assuming  $M_H \sim 125$  GeV [2, 11]. Hence  $R_1^{\tau\tau}(VBF)$  should be as small as possible.<sup>1</sup> Assuming  $M_H \gtrsim 132$  GeV, CMS observes an excess of events [11] of about half a standard deviation; the upper limit on  $R_2^{\tau\tau}(VBF)$  (for  $M_{H_2} \sim 135$  GeV) is given as

$$R_2^{\tau\tau}(VBF) < 1.81. \quad (10)$$

In the presence of two Higgs states these values have to be reinterpreted. In principle, a state at  $M_{H_2} \sim 135$  GeV can contribute to the signal rate obtained assuming  $M_{H_{SM}} \sim 125$  GeV. However, the production cross section for  $M_H \sim 135$  GeV is about 30% lower than for  $M_H \sim 125$  GeV and, moreover, the mass resolution is not very well known (estimated as 15–20% in [11]). Subsequently we assume that the contribution to the signal rate obtained assuming  $M_{H_{SM}} \sim 125$  GeV from a state at  $M_{H_2} \sim 135$  GeV is not very large, without being able to quantify it more precisely. Conversely, the contribution to the signal rate obtained assuming  $M_{H_{SM}} \sim 135$  GeV from a state at  $M_{H_1} \sim 125$  GeV will not be large if  $R_1^{\tau\tau}(VBF)$  is small; in any case such a contribution can be tolerated given the weak bound (10).

In the  $bb$  channel, the CDF and D0 collaborations at the Tevatron (where the dominant production mode is  $VH$ ) have observed large values of  $R^{bb}(VH)$ :  $R_{125}^{bb}(VH) \simeq 1.97 + 0.74 - 0.68$  assuming  $M_{H_{SM}} = 125$  GeV, and

$$R_{135}^{bb}(VH) \simeq 3.53 + 1.26 - 1.16 \quad (11)$$

assuming  $M_{H_{SM}} = 135$  GeV [4, 10]. CMS has also observed excesses in this channel [2, 14], but below the expectations for a SM Higgs boson at 125 GeV. Assuming larger values of  $M_{H_{SM}}$ , the excesses observed by CMS are larger (with a peak around  $M_{H_{SM}} \sim 130$  GeV), but have large error bars.

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<sup>1</sup>In the  $\tau\tau + (0/1)$  jets channel, CMS observes a slight excess. The error bar is fairly large, however, and taken together the 0/1 jets and  $VBF$ -tag channels still give a deficit in the  $\tau\tau$  channel. The ATLAS result for  $H \rightarrow \tau\tau$  [13] is based on 7 TeV data only and excludes only about  $(4-5)\times$  the SM rate; it is thus inconclusive for our purpose.

It is clear that the central value of (11) is difficult to explain: the  $VH$  production cross section  $\propto c_V^2$  cannot be enhanced with respect to the SM, and the SM Higgs branching fraction of  $\sim 40\%$  for  $M_{H_{\text{SM}}} = 135$  GeV can be enhanced at most by a factor of 2.5 in the unphysical limit  $c_D \rightarrow \infty$ .

Using the second of Eqs. (2) and the same reduced couplings of Higgs bosons to  $b$ -quarks and  $\tau$ -leptons, one finds

$$R^{bb}(VH) = R^{\tau\tau}(VBF) \quad (12)$$

for all Higgs states. If  $R_1^{\tau\tau}(VBF)$  is as small as observed by CMS, the values for  $R^{bb}(VH)$  measured at the Tevatron should originate primarily from  $H_2$  with  $M_{H_2} \sim 135\text{--}136$  GeV; this possibility is one of the main advantages of the present proposal. However, the contribution of  $H_1$  to the signal rate  $R^{bb}(VH)$  obtained assuming  $M_{H_{\text{SM}}} \sim 135$  GeV can still be sizable, since the production cross section of  $H_1$  is  $\sim 30\%$  larger. Assuming a mass resolution worse than 10 GeV,  $R_{135}^{bb}(VH)$  in (11) would correspond to

$$R_{\text{eff}}^{bb}(VH) \simeq R_2^{bb}(VH) + 1.3 \times R_1^{bb}(VH). \quad (13)$$

(In addition, the contribution from  $H_2$  to the signal rate  $R_{125}^{bb}(VH)$  should be as large as possible.)

In the  $WW^{(*)}$  channel (with  $VH$ -tag), all collaborations have observed excesses over a large mass range up to  $M_H \sim 150$  GeV [1–3, 9]. Given the low mass resolution in this channel and the correspondingly large error bars, the measured values of  $R^{WW^{(*)}}(VH)$  do not impose additional constraints on a scenario with two Higgs bosons at 125–126 and 135–136 GeV.

What are the consequences of the above results on the reduced couplings of the two Higgs bosons proposed here? First, the enhanced signal rate  $R_1^{\gamma\gamma}(ggF)$  at 125–126 GeV, Eq. (6), has to be explained. It has been observed in several publications [15–28] that the branching fraction of a non-standard Higgs boson into  $\gamma\gamma$  is enhanced if its coupling  $c_D$  to down-type quarks is reduced — a reduction of  $c_D$  reduces the (dominant) partial width into  $bb$  and hence the total width  $\Gamma_{\text{Tot}}$ ; in turn, a reduced  $\Gamma_{\text{Tot}}$  in the denominator of (5) will increase the (reduced) branching fraction into  $\gamma\gamma$ . (Furthermore the reduced coupling  $c_{g_1} \sim c_{U_1}$  of  $H_1$  to gluons should not be small.) If  $c_D$  coincides with the reduced coupling to  $\tau$ -leptons, a reduced branching fraction of  $H_1$  into  $\tau\tau$  fits well with the small value of  $R_1^{\tau\tau}(VBF)$  observed by CMS. Of course, due to (12), a reduced signal rate of  $H_1$  into  $bb$  in  $VH$  would be in obvious conflict with the Tevatron results if no other Higgs boson would exist. Thus, the reduced coupling  $c_{D_2}$  of  $H_2$  had better be enhanced.

A reduced total width  $\Gamma_{\text{Tot}}$  of  $H_1$  due to a reduced partial width into  $bb$  can also increase its branching fraction into  $ZZ$ ; together with a slight reduction of  $c_{V_1}$  and  $c_{g_1}$  the SM-like value of  $R_1^{ZZ^{(*)}}(ggF)$  in (7) is a natural result.

For  $H_2$ , the coupling  $c_{g_2} \sim c_{U_2}$  to gluons must be smaller than 1 in order to comply with (8) and (9). However,  $c_{D_2}$  (and hence the branching fraction into  $bb$ ) should be enhanced, and  $c_{V_2}$  should not be small in order to comply with (11) together with (13).

In the next section we will briefly discuss the NMSSM, and present a point in the NMSSM parameter space where  $H_1$  and  $H_2$  have masses of 125 GeV and 136 GeV, respectively, and have the desired reduced couplings. (In the CP-conserving MSSM with its two



CP-even Higgs bosons we were not able to find such points in the much more constrained parameter space.)

### 3 Two Higgs bosons at 125 and 136 GeV in the NMSSM

The NMSSM is the simplest supersymmetric (SUSY) extension of the SM with a scale invariant superpotential, and does not suffer from the  $\mu$ -problem of the MSSM (the presence of a SUSY mass parameter whose value must accidentally be of order  $M_{\text{SUSY}}$ , the mass scale of the soft SUSY breaking terms). The Higgs sector of the NMSSM contains two doublet superfields  $H_u$  and  $H_d$  (with couplings of  $H_u$  to up-type quarks, and couplings of  $H_d$  to down-type quarks and leptons as in the MSSM) and an additional SU(2)-singlet superfield  $S$ . The NMSSM-specific part of the superpotential is

$$W_{\text{NMSSM}} = \lambda S H_u H_d + \frac{\kappa}{3} S^3, \quad (14)$$

where the first term generates an effective  $\mu$ -term with  $\mu_{\text{eff}} = \lambda s$  once the scalar component of  $S$  develops a vacuum expectation value (vev)  $s$ . The vev  $s$  is triggered by the NMSSM-specific soft SUSY breaking terms (from here onwards,  $H_u$ ,  $H_d$  and  $S$  denote the scalar components of the corresponding superfields),

$$\mathcal{L}(\text{soft})_{\text{NMSSM}} = -m_S^2 S^2 - \lambda A_\lambda S H_u H_d - \frac{\kappa}{3} A_\kappa S^3, \quad (15)$$

and is thus naturally of order  $M_{\text{SUSY}}$ . The field content in the Higgs sector of the NMSSM consists of three neutral CP-even bosons  $H_i$ ,  $i = 1 \dots 3$ , two neutral CP-odd bosons  $A_i$ ,  $i = 1 \dots 2$ , and a charged Higgs boson  $H^\pm$ .

The CP-even bosons  $H_i$  are linear combinations of the real components of  $H_u$ ,  $H_d$  and  $S$ . Their masses and mixing angles have to be obtained from the  $3 \times 3$  mass matrix including SUSY terms, soft SUSY breaking terms and radiative corrections. Expressions for the mass matrices of the physical CP-even and CP-odd Higgs states—after  $H_u$ ,  $H_d$  and  $S$  have acquired vevs  $v_u$ ,  $v_d$  and  $s$  and including the dominant radiative corrections—can be found in [12] and will not be repeated here. The Higgs sector of the NMSSM is described by the six parameters

$$\lambda, \kappa, A_\lambda, A_\kappa, \tan \beta = v_u/v_d, \mu_{\text{eff}}. \quad (16)$$

The couplings of the Higgs states depend on their decompositions into the CP-even weak eigenstates  $H_d$ ,  $H_u$  and  $S$ , which are given by

$$\begin{aligned} H_1 &= S_{1,d} H_d + S_{1,u} H_u + S_{1,s} S, \\ H_2 &= S_{2,d} H_d + S_{2,u} H_u + S_{2,s} S. \end{aligned} \quad (17)$$

Then, the reduced couplings of  $H_i$  are

$$c_{D_i} = \frac{S_{i,d}}{\cos \beta}, \quad c_{U_i} = \frac{S_{i,u}}{\sin \beta}, \quad c_{V_i} = \cos \beta S_{i,d} + \sin \beta S_{i,u}. \quad (18)$$

The loop-induced reduced couplings  $c_{g_i}$  and  $c_{\gamma_i}$  have to be computed including contributions from SUSY particles in the loops, including scalar  $\tau$ -leptons, charginos and more. Below,

$\lambda$	0.617	$\mu_{\text{eff}}$	143
$\kappa$	0.253	$A_\lambda$	164
$\tan\beta$	1.77	$A_\kappa$	337
$M_{H_1}$	125	$M_{A_1}$	95
$M_{H_2}$	136	$M_{A_2}$	282
$M_{H_3}$	289	$M_{H^\pm}$	272

Table 1: NMSSM-specific parameters and Higgs masses of a point with desired properties. (The dimensionful parameters are given in GeV.)

Higgs	$S_{i,d}$	$S_{i,u}$	$S_{i,s}$	$c_{D_i}$	$c_{U_i}$	$c_{V_i}$	$c_{g_i}$	$c_{\gamma_i}$
$H_1$	-0.24	-0.67	0.70	-0.48	-0.77	-0.70	0.77	0.85
$H_2$	0.54	0.51	0.67	1.09	0.58	0.71	0.54	0.66
$H_3$	0.81	-0.54	-0.24	1.64	-0.62	-0.07	0.65	0.28

Table 2: Mixing parameters (17) and reduced couplings of the three CP-even Higgs states.

the calculations of Higgs masses, mixing angles and reduced couplings have been performed by the code NMSSMTools\_3.2.1 [29, 30] including radiative corrections to the Higgs sector from [31].

Next we present a point in the parameter space of the general NMSSM with the desired properties. For the MSSM-like soft SUSY breaking terms we choose bino, wino and gluino masses  $M_1=220$  GeV,  $M_2=400$  GeV and  $M_3=1100$  GeV respectively, squark masses of 1500 GeV for the first two generations and the right-handed  $b$ -squarks, 1000 GeV for sleptons and the other third generation squarks, and finally  $A_t = A_b = -2500$  GeV,  $A_\tau = -1000$  GeV. The NMSSM-specific input parameters are listed in Table 1, together with the resulting masses of the various Higgs states.

The decompositions  $S_{i,j}$  and the reduced couplings of the 3 CP-even Higgs states are given in Table 2. We see that the Higgs states are strongly mixed, both  $H_1$  and  $H_2$  having large SU(2) doublet and singlet components.  $H_1$  has the smallest  $c_D$  component, which leads to an increase of the reduced branching fraction into  $\gamma\gamma$  as discussed above. However, the partial width  $\Gamma(H_1 \rightarrow \gamma\gamma)$  also receives an additional NMSSM-specific contribution of  $\sim 20\%$  from higgsino-like charginos with  $m_{\tilde{\chi}_1^\pm} = 126$  GeV in the loop; this possibility was mentioned previously in [20, 28].

Finally, we give the reduced branching fractions for the CP-even Higgs bosons in Table 3, and their signal rates relative to SM expectations in Table 4.

Let us now examine the extent to which these signal rates have the desired properties listed in Section 2. We observe that  $R_1^{\gamma\gamma}(ggF)$ ,  $R_1^{ZZ^{(*)}}(ggF)$ ,  $R_2^{\gamma\gamma}(ggF)$  and  $R_2^{ZZ^{(*)}}(ggF)$  satisfy Eqs. (6), (7), (8) and (9), respectively. Note that  $R_1^{\gamma\gamma}(VBF)$  is also enhanced, in agreement with the observations. In the  $\tau\tau$  channel,  $R_1^{\tau\tau}(VBF) = R_1^{bb}(VH)$  is indeed suppressed, as is  $R_1^{\tau\tau}(ggF)$ .  $R_2^{\tau\tau}(VBF)$  is not enhanced but, as discussed in Section 2,  $R_2^{\tau\tau}$  (like  $R_2^{bb}(VH)$ ) can receive a considerable contribution from  $R_1^{\tau\tau}$ . For  $R_{\text{eff}}^{bb}(VH)$  as defined in (13) we obtain  $R_{\text{eff}}^{bb}(VH) \sim 1.20$ , with the dominant contribution from  $R_2^{bb}(VH)$ .



Higgs	$\frac{BR(H_i \rightarrow bb)}{BR(H_{SM} \rightarrow bb)}$	$\frac{BR(H_i \rightarrow VV^{(*)})}{BR(H_{SM} \rightarrow VV^{(*)})}$	$\frac{BR(H_i \rightarrow \gamma\gamma)}{BR(H_{SM} \rightarrow \gamma\gamma)}$
$H_1$	0.73	1.52	2.21
$H_2$	1.46	0.62	0.54
$H_3$	43.45	0.08	1.37

Table 3: Reduced branching fractions for the three CP-even Higgs states. Note that we have  $\frac{BR(H_i \rightarrow \tau\tau)}{BR(H_{SM} \rightarrow \tau\tau)} \sim \frac{BR(H_i \rightarrow bb)}{BR(H_{SM} \rightarrow bb)}$ , and  $\frac{BR(H_i \rightarrow WW^{(*)})}{BR(H_{SM} \rightarrow WW^{(*)})} = \frac{BR(H_i \rightarrow ZZ^{(*)})}{BR(H_{SM} \rightarrow ZZ^{(*)})} \equiv \frac{BR(H_i \rightarrow VV^{(*)})}{BR(H_{SM} \rightarrow VV^{(*)})}$ .

Higgs	$R^{\gamma\gamma}(ggF)$	$R^{\gamma\gamma}(VBF)$	$R^{VV^{(*)}}(ggF)$	$R^{VV^{(*)}}(VH)$	$R^{bb}(VH)$	$R^{\tau\tau}(ggF)$
$H_1$	1.30	1.09	0.90	0.75	0.36	0.42
$H_2$	0.16	0.27	0.18	0.31	0.74	0.43
$H_3$	0.58	0.01	0.04	0.004	0.23	19.6

Table 4: Reduced signal rates for the three CP-even Higgs states. Note that  $R^{VV^{(*)}}(VBF) = R^{VV^{(*)}}(VH)$ , and  $R^{\tau\tau}(VBF) \sim R^{bb}(VH)$ .

This value coincides with the large excess given in (11) (assuming a single Higgs state at 135 GeV) only within about two standard deviations, but at least exceeds the SM value. Finally, the signal rates in the  $WW^{(*)}$  channel via  $VH$  are consistent with the present limits.

The third CP-even Higgs state  $H_3$  with mass of about 290 GeV has properties similar to the heavy scalar Higgs  $H$  in the MSSM, in that it has an enhanced signal rate in the  $gg \rightarrow H_3 \rightarrow bb/\tau\tau$  channels and suppressed couplings to electroweak gauge bosons. However, due to the low value of  $\tan\beta$ , which is typical for NMSSM scenarios such as the one discussed here, the present constraints on such a state from direct searches [32, 33] as well as the  $B$ -physics constraints implemented in NMSSMTools\_3.2.0 are well satisfied.

Finally we have also attempted to look for similar scenarios in the Higgs sector of the semi-constrained NMSSM [23, 27, 34], where one requires universal soft SUSY breaking terms at the GUT scale except for the Higgs soft-SUSY-breaking mass terms and the NMSSM-specific trilinear couplings  $A_\lambda$  and  $A_\kappa$ . In fact, one can find scenarios where  $H_1$  and  $H_2$  have masses of about 125 and 136 GeV, respectively. However, we did not find any points where the constraints (6) to (9) are all satisfied simultaneously; at least one of the conditions on  $R_1^{\gamma\gamma}(ggF)$ ,  $R_2^{\gamma\gamma}(ggF)$  or  $R_2^{ZZ^{(*)}}(ggF)$  has to be relaxed to find valid points. For example, we can satisfy Eqs. (6), (7), (9) (and (10)), but then  $R_2^{\gamma\gamma}(ggF)$  turns out too low,  $R_2^{\gamma\gamma}(ggF) \lesssim 0.06$ . Or we can satisfy (7)–(10), but then  $R_1^{\gamma\gamma}(ggF) \lesssim 1.3$ . Moreover,  $R_2^{bb}(VH)$  is never large, making it difficult to explain the Tevatron result in this channel.

## 4 Conclusions

In the present paper we propose that the best fit to the Tevatron results in the  $bb$  channel and to the mild excesses at CMS in the  $\gamma\gamma$  channel at 136 GeV and in the  $\tau\tau$  channel above 132 GeV could point towards a second Higgs state with this mass. In the NMSSM, where

an enhanced signal rate of a 125 GeV Higgs boson in the  $\gamma\gamma$  channel can be explained by a strong mixing between the SU(2) doublet and the singlet states, one indeed expects at least one additional state with a mass not too far from 125 GeV. We have shown an example of such a point in the parameter space of the general NMSSM. However, an enhanced signal rate in the  $VH \rightarrow bb$  coinciding with the central value of about 3.5 ( $\pm 1.2$ ) as measured by the CDF and D0 collaborations at the Tevatron is practically impossible to obtain even if one assumes that it is due to a superposition of two distinct Higgs states; nevertheless, signal rates above the SM value for a 136 GeV Higgs boson are possible in such a scenario.

The scenario proposed here can be verified by measurements in the  $\gamma\gamma$  and  $ZZ$  channels with high mass resolution; however, the sensitivities to the signal rates of a 136 GeV Higgs boson have to be about 4–5 times better than for a SM Higgs boson of such mass. Further tests of the scenario involve searches for the heavy Higgs doublet-like  $H_3$ , which cannot be too heavy here since it participates in the mixing. Note however that  $H_3$  and  $A_2$  can have large branching fractions into the lighter Higgs states and/or neutralino pairs so that non-standard search channels need to be exploited.

The NMSSM also predicts the presence of SUSY particles like squarks, gluinos and charginos/neutralinos. The colored sparticles should eventually be observed at the LHC, although their decay channels are possibly more complicated than in the MSSM, see e.g. [22, 35]. Furthermore, scenarios with an enhanced di-photon rate for the Higgs are typically associated with small values of  $\mu_{\text{eff}}$  implying light higgsino-like charginos/neutralinos that can be accessible in direct production at the LHC. Note, however, that the pure higgsino-LSP (lightest SUSY particle) case is extremely difficult to detect at the LHC [36].

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## References

- [1] G. Aad *et al.* [ATLAS Collaboration], “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” arXiv:1207.7214 [hep-ex].
- [2] S. Chatrchyan *et al.* [CMS Collaboration], “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” arXiv:1207.7235 [hep-ex].
- [3] ATLAS Collaboration, “Observation of an Excess of Events in the Search for the Standard Model Higgs Boson in the  $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$  Channel with the ATLAS Detector,” ATLAS-CONF-2012-098.

- [4] Tevatron New Physics Higgs Working Group and CDF and D0 Collaborations, “Updated Combination of CDF and D0 Searches for Standard Model Higgs Boson Production with up to  $10.0 \text{ fb}^{-1}$  of Data,” arXiv:1207.0449 [hep-ex].
- [5] ATLAS Collaboration, “Observation of an excess of events in the search for the Standard Model Higgs boson in the  $\gamma\gamma$  channel with the ATLAS detector,” ATLAS-CONF-2012-091.
- [6] CMS Collaboration, “Evidence for a new state decaying into two photons in the search for the standard model Higgs boson in pp collisions,” CMS PAS HIG-12-015.
- [7] ATLAS Collaboration, “Observation of an excess of events in the search for the Standard Model Higgs boson in the  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$  channel with the ATLAS detector,” ATLAS-CONF-2012-092.
- [8] CMS Collaboration, “Search for the standard model Higgs boson in the  $H \rightarrow ZZ \rightarrow 2\ell 2\nu$  channel in pp collisions at  $\sqrt{s} = 7$  and 8 TeV,” CMS PAS HIG-12-023.
- [9] CMS Collaboration, “Search for the Standard Model Higgs boson in the  $H \rightarrow WW \rightarrow \ell\nu jj$  decay channel in pp collisions at  $\sqrt{s} = 8$  TeV,” CMS PAS HIG-12-021.
- [10] T. Aaltonen *et al.* [CDF and D0 Collaborations], “Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson searches at the Tevatron,” arXiv:1207.6436 [hep-ex].
- [11] CMS Collaboration, “Search for the standard model Higgs boson decaying to tau pairs in pp collisions,” CMS PAS HIG-12-018;  
erratum: <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12018TWiki>
- [12] U. Ellwanger, C. Hugonie and A. M. Teixeira, “The Next-to-Minimal Supersymmetric Standard Model,” Phys. Rept. **496** (2010) 1 [arXiv:0910.1785 [hep-ph]].
- [13] G. Aad *et al.* [ATLAS Collaboration], “Search for the Standard Model Higgs boson in the  $H \rightarrow \tau^+\tau^-$  decay mode in  $\sqrt{s} = 7$  TeV pp collisions with ATLAS,” arXiv:1206.5971 [hep-ex].
- [14] CMS Collaboration, “Search for the standard model Higgs boson produced in association with  $W$  or  $Z$  bosons, and decaying to bottom quarks (ICHEP 2012),” CMS PAS HIG-12-019.
- [15] M. S. Carena, S. Mrenna and C. E. M. Wagner, “The Complementarity of LEP, the Tevatron and the CERN LHC in the search for a light MSSM Higgs boson,” Phys. Rev. D **62** (2000) 055008 [hep-ph/9907422].
- [16] U. Ellwanger, “Enhanced di-photon Higgs signal in the Next-to-Minimal Supersymmetric Standard Model,” Phys. Lett. B **698** (2011) 293 [arXiv:1012.1201 [hep-ph]].
- [17] M. Carena, S. Gori, N. R. Shah and C. E. M. Wagner, “A 125 GeV SM-like Higgs in the MSSM and the  $\gamma\gamma$  rate,” JHEP **1203** (2012) 014 [arXiv:1112.3336 [hep-ph]].

- [18] L. J. Hall, D. Pinner and J. T. Ruderman, “A Natural SUSY Higgs Near 126 GeV,” JHEP **1204** (2012) 131 [arXiv:1112.2703 [hep-ph]].
- [19] U. Ellwanger, “A Higgs boson near 125 GeV with enhanced di-photon signal in the NMSSM,” JHEP **1203** (2012) 044 [arXiv:1112.3548 [hep-ph]].
- [20] S. F. King, M. Muhlleitner and R. Nevzorov, “NMSSM Higgs Benchmarks Near 125 GeV,” Nucl. Phys. B **860** (2012) 207 [arXiv:1201.2671 [hep-ph]].
- [21] J. -J. Cao, Z. -X. Heng, J. M. Yang, Y. -M. Zhang and J. -Y. Zhu, “A SM-like Higgs near 125 GeV in low energy SUSY: a comparative study for MSSM and NMSSM,” JHEP **1203** (2012) 086 [arXiv:1202.5821 [hep-ph]].
- [22] D. A. Vasquez, G. Belanger, C. Boehm, J. Da Silva, P. Richardson and C. Wymant, “The 125 GeV Higgs in the NMSSM in light of LHC results and astrophysics constraints,” arXiv:1203.3446 [hep-ph].
- [23] U. Ellwanger and C. Hugonie, “Higgs bosons near 125 GeV in the NMSSM with constraints at the GUT scale,” arXiv:1203.5048 [hep-ph].
- [24] K. S. Jeong, Y. Shoji and M. Yamaguchi, “Singlet-doublet Higgs mixing and its implications on the Higgs mass in the PQ-NMSSM,” arXiv:1205.2486 [hep-ph].
- [25] K. Blum, R. T. D’Agnolo and J. Fan, “Natural SUSY Predicts: Higgs Couplings,” arXiv:1206.5303 [hep-ph].
- [26] R. Benbrik, M. G. Bock, S. Heinemeyer, O. Stal, G. Weiglein and L. Zeune, “Confronting the MSSM and the NMSSM with the Discovery of a Signal in the two Photon Channel at the LHC,” arXiv:1207.1096 [hep-ph].
- [27] J. F. Gunion, Y. Jiang and S. Kraml, “Could two NMSSM Higgs bosons be present near 125 GeV?,” arXiv:1207.1545 [hep-ph].
- [28] K. Schmidt-Hoberg and F. Staub, “Enhanced  $h \rightarrow \gamma\gamma$  rate in MSSM singlet extensions,” arXiv:1208.1683 [hep-ph].
- [29] U. Ellwanger, J. F. Gunion and C. Hugonie, “NMHDECAY: A Fortran code for the Higgs masses, couplings and decay widths in the NMSSM,” JHEP **0502** (2005) 066 [arXiv:hep-ph/0406215].
- [30] U. Ellwanger and C. Hugonie, “NMHDECAY 2.0: An Updated program for sparticle masses, Higgs masses, couplings and decay widths in the NMSSM,” Comput. Phys. Commun. **175** (2006) 290 [arXiv:hep-ph/0508022].
- [31] G. Degrandi and P. Slavich, “On the radiative corrections to the neutral Higgs boson masses in the NMSSM,” Nucl. Phys. B **825** (2010) 119 [arXiv:0907.4682 [hep-ph]].
- [32] S. Chatrchyan *et al.* [CMS Collaboration], “Search for neutral Higgs bosons decaying to  $\tau$  pairs in pp collisions at  $\sqrt{s} = 7$  TeV,” Phys. Lett. B **713** (2012) 68 [arXiv:1202.4083 [hep-ex]].

- [33] ATLAS Collaboration, “Search for neutral MSSM Higgs bosons in  $\sqrt{s} = 7$  TeV pp collisions with the ATLAS detector”, ATLAS-CONF-2012-094.
- [34] J. F. Gunion, Y. Jiang and S. Kraml, “The Constrained NMSSM and Higgs near 125 GeV,” Phys. Lett. B **710** (2012) 454 [arXiv:1201.0982 [hep-ph]].
- [35] D. Das, U. Ellwanger and A. M. Teixeira, “Modified Signals for Supersymmetry in the NMSSM with a Singlino-like LSP,” JHEP **1204** (2012) 067 [arXiv:1202.5244 [hep-ph]].
- [36] H. Baer, V. Barger and P. Huang, “Hidden SUSY at the LHC: the light higgsino-world scenario and the role of a lepton collider,” JHEP **1111** (2011) 031 [arXiv:1107.5581 [hep-ph]].