Probing minimal supersymmetry at the LHC with the Higgs boson masses

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New Journal of Physics 14 (2012) 073029 (11pp)
Received 24 April 2012
Published 12 July 2012
Online at http://www.njp.org/
doi:10.1088/1367-2630/14/7/073029

Abstract. The ATLAS and CMS collaborations report indications of a Higgs boson at $M_h \sim 125$ GeV. In addition, CMS data show a tenuous bump in the $ZZ$ channel, at about 320 GeV. We make the bold assumption that it might be the indication of a secondary line corresponding to the heaviest scalar Higgs boson of minimal supersymmetry, $H$, and discuss the viability of this hypothesis. We discuss also the case of a heavier $H$. The relevance of the $b\bar{b}$ decay channel is underlined.

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1. Introduction

Indications of a Higgs boson around a mass

\[ M_h \simeq 125 \text{ GeV} \]  

have been presented by the ATLAS [1] and CMS [2] collaborations in the reactions

\[ p + p \rightarrow h + \text{All} \rightarrow \gamma \gamma + \text{All}, \]  

\[ p + p \rightarrow h + \text{All} \rightarrow ZZ + \text{All} \quad (ZZ \rightarrow \text{four charged leptons}), \]

observed at the LHC at center-of-mass energy \( \sqrt{s} = 7 \text{ TeV} \).

The value of the mass, should it be confirmed, is interesting by itself, in that it is compatible with the restrictions posed by the minimal supersymmetric standard model (MSSM) [3, 4]. It is well known that the tree level inequality for the mass of the lightest Higgs boson

\[ M_h^2 \leq \cos^2(2\beta)M_Z^2 \quad \text{(tree level)} \]  

receives radiative corrections, due to the exchange of the top quark and its two scalar partners, \( \tilde{t}_{L,R} \), which may bring the mass up to \( M_h \sim 135 \text{ GeV} \), for 'reasonable' values of the scalar partner masses. Encouraged by this fact, we have investigated the consequences of the next simple prediction of MSSM, namely that there must be two Higgs doublets, one coupled to up and the other to down fermions.

The introduction of a singlet superfield [5, 6] leads to the next-to-minimal supersymmetric standard model (NMSSM), which modifies the tree level inequality (4), thereby reducing the role of the radiative corrections and allowing for lighter scalar top quark partners and better naturalness. However, predictivity in NMSSM is greatly reduced for what concerns the properties of the scalar Higgs particles and we think it wise to stick to the minimal option unless some real contradiction with the data is found.

The mass matrix of the two, CP-even, Higgs particles of the MSSM, \( h \) and \( H \) (with \( h \) the lightest), depends upon four parameters: the vacuum expectation values ratio, parameterized in terms of an angle \( \beta \), the masses of the \( Z \) boson and of the CP-odd Higgs boson, \( A \), and the average mass of the top scalar partners, which appears in the radiative correction mentioned above. Here, we take the usual notation:

\[ \langle 0 | H_0^0 | 0 \rangle = v \sin \beta; \quad \langle 0 | H_0^d | 0 \rangle = v \cos \beta; \quad 0 < \tan \beta < +\infty, \]  

\[ v^2 = (2\sqrt{2}G_F)^{-1} = (174 \text{ GeV})^2. \]

Diagonalizing the mass matrix, we obtain two eigenvectors which express the physical Higgs fields in terms of \( H_0^0 \) and \( H_0^d \) and determine the coupling of \( h \) and \( H \) to quarks, leptons and gauge bosons [8].

Assume now the mass in (1) and assume that we know the other mass, \( M_H \), as well. We can express everything in terms of \( M_{Z,h,H} \) and remain with one unknown parameter only, namely

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4 The implications of a Higgs boson at this mass for MSSM parameters have been considered in [4].
5 A singlet superfield has been considered by many authors, see [5]. For a recent review of the NMSSM, see [6].
6 The ATLAS and CMS signal in NMSSM has been considered by Hall et al [7].
7 The option of a fermiophobic Higgs boson, which does not couple to fermions directly, has also been considered, see [9] and references therein.
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We can derive all the observable quantities, such as the ratios of $\sigma \times BR$ in the MSSM to the one in the SM for the channels observed in (2) and (3), and see (i) how the level of observation of the 125 GeV signal compares to the SM; (ii) what the visibility level of $H$ in channels (2) and (3) is; and (iii) what the best channels for the observation of $H$ are. In addition, we may determine, always in terms of $\tan \beta$, the mass value of the CP-odd boson, $A$, and the mass scale of the top scalar partners.

2. Details of the calculation

In the basis $(H_d, H_u)$, the mass matrix of the CP-even Higgs fields is given by:

$$M_2^2 = M_Z^2 \left( \begin{array}{cc} \cos^2 \beta & - \cos \beta \sin \beta \\ - \cos \beta \sin \beta & \sin^2 \beta \end{array} \right) + M_A^2 \left( \begin{array}{cc} \sin^2 \beta & - \cos \beta \sin \beta \\ - \cos \beta \sin \beta & \cos^2 \beta \end{array} \right) + \left( \begin{array}{cc} 0 & 0 \\ 0 & \delta \end{array} \right),$$

with $\delta$ the radiative correction

$$\delta = \frac{3\sqrt{2}}{\pi^2 \sin^2 \beta} G_F (M_t)^4 t; \quad t = \log \left( \frac{\sqrt{M_{\tilde{t}} M_{\tilde{t}}}}{M_t} \right).$$

The first term in $M_2^2$ arises from the so-called Fayet–Iliopoulos term [10] determined by gauge interaction. In the radiative corrections we have kept only the top-stop contribution which is by far the most dominant one.

We also note that in MSSM

$$M_{H^\pm}^2 = M_A^2 + M_W^2.$$  \hspace{1cm} (8)

We eliminate $M_A^2$ from (7) equating the trace of $M_2^2$ to the sum of the eigenvalues, $M_h^2 + M_H^2$, and obtain $t$ as a function of $\tan \beta$ from the difference. One obtains two real solutions:

$$t = F(\pm)(\tan \beta),$$

only for

$$\tan \beta \geq 0.89,$$

which therefore provides an absolute lower bound, roughly compatible with the border of the shaded exclusion region in $\tan \beta$ (for the definition of the exclusion regions, see the results section).

The function in (9) is plotted versus $\tan \beta$ in figure 1 for the two guiding values of $M_H$. The solid (dotted) lines correspond to $F^-(F^+)$). We shall choose $F^-$, which minimizes the size of the radiative correction. In correspondence, we plot in figure 2 the values of $M_A$, solid (dotted) lines referring to the solid (dotted) line solution in figure 1.

Substituting this function back into (7), we compute the two eigenvectors

$$S_h(\tan \beta) = (S_{hd}, S_{hu}),$$

$$S_H(\tan \beta) = (S_{Hd}, S_{Hu}),$$

with the physical fields given by

$$h = S_{hi} H_i, \quad H = S_{Hi} H_i \quad (i = d, u).$$

New Journal of Physics 14 (2012) 073029 (http://www.njp.org/)
Couplings of $h$ and $H$ to exclusive channels, e.g. $WW$, $t\bar{t}$ etc, are given by the SM coupling multiplied by factors which depend upon the components of the eigenvectors in (11) and $\beta$, see table 1. The two components of $S_h$ are positive and about equal for $\tan \beta \sim 2$, while the components of $S_H$ have opposite sign, which considerably suppresses the coupling of $H$ to the $VV$ channels.

3. Decay rates

To determine the decay rates, we used the program HDECAY [11] that gives the decay rates of the SM Higgs boson in exclusive decays, and multiplied them by the appropriate factors\(^8\) taken from tables 1–3.

\(^8\) In the usual notation, one defines: $S_{hd} = \cos \alpha$ and $S_{hu} = \sin \alpha$ and the couplings of $h$ and $H$ to $WW$ are $\cos(\beta - \alpha)$ and $\sin(\beta - \alpha)$, respectively.
Table 1. Ratios of the couplings of $h$ and $H$ to the SM Higgs boson couplings, for different exclusive channels.

| Channel | Ratio |
|---------|-------|
| $WW = ZZ$ | $i\bar{t} = c\bar{c}$ |
| $\bar{t}t = \tau^+\tau^-$ | $(\sin \beta)^{-1} S_{1u}$ |
| $b\bar{b} = \tau^+\tau^-$ | $(\cos \beta)^{-1} S_{1d}$ |
| $i = h, H$ | $\cos \beta S_{1d} + \sin \beta S_{1u}$ |

Table 2. Ratios of the couplings of $A$ to the SM Higgs boson couplings for different exclusive channels.

| Channel | Ratio |
|---------|-------|
| $hZ$ | $\sin \beta S_{1d} - \cos \beta S_{1u}$ |
| $\bar{t}t = \tau^+\tau^-$ | $\cos \beta$ |
| $b\bar{b} = \tau^+\tau^-$ | $\sin \beta$ |

Table 3. Ratios of the couplings of $H^+$ to the SM Higgs boson couplings for different exclusive channels.

| Channel | Ratio |
|---------|-------|
| $hW^+$ | $t\bar{b} = c\bar{s} = \nu_\tau\tau^+$ |
| $H^+$ | $\cos \beta S_{1u} - \sin \beta S_{1d}$ |
| | $-\sin \beta$ |

Decay rates in $\gamma\gamma$ are dominated by $WW$ and $i\bar{t}$ loops. We take from [12] the separate SM loop amplitudes and rescale them with the appropriate couplings given in the previous table.

4. Cross sections

The total production cross section for the Higgs particles is dominated by gluon–gluon fusion, which in turn is dominated by the top quark loop. However, CMS searches also for $\gamma\gamma$ events in the central region, accompanied by two backward and forward hadron jets. In these conditions, vector boson fusion (VBF) is favored but, given the CMS cuts, it is not 100%. The ATLAS analysis enhances VBF as well, but we will focus on the CMS set of cuts.

We split the cross section for Higgs production accompanied by two jets into four different categories, which we label $gg$, $gq$, $qq$ and VBF, see figure 3, diagrams (a)–(d), respectively. To compute them we use the libraries in [13].

We give in table 4 the values of the SM cross sections for $h+2$ jets ($M_h = 125$ GeV) and $H+2$ jets ($M_H = 320$ GeV), separately for two cases: (i) the minimal cuts, where we require only a maximum value of jets pseudorapidity, $\eta_{\text{max}} = 4.7$, and a minimum value of the jets transverse momentum, $(p_T)_{\text{min}} = 20$ GeV; and (ii) CMS-cuts, where we enforce the cuts applied by CMS to the diphoton events of their fifth category [14]. The CMS requirements are

- $E_T$ thresholds for the two jets of 30 and 20 GeV;
- pseudorapidity separation between jets greater than 3.5;
- jet–jet invariant mass greater than 350 GeV;
- difference between the average pseudorapidity of the two jets and the pseudorapidity of the diphoton system (i.e. the Higgs boson) of less than 2.5.
Figure 3. Feynman diagrams contributing at parton level to the process $p + p \rightarrow H + 2$ jets. Full triangles: the gluon–gluon–Higgs effective vertex induced by the top loop, full dot: $VV$–Higgs vertex.

Table 4. Cross sections (pb) for: $p + p \rightarrow$ Higgs + 2 jets.

|            | $gg$  | $gq$  | $qq$  | VBF   |
|------------|-------|-------|-------|-------|
| $h$, $M_h = 125$ GeV | 0.827 | 0.674 | 0.062 | 0.826 |
| minimal cuts | 0.026 | 0.056 | 0.018 | 0.361 |
| CMS cuts    | 0.026 | 0.056 | 0.018 | 0.361 |
| $H$, $M_H = 320$ GeV | 0.162 | 0.137 | 0.014 | 0.164 |
| minimal cuts | 0.005 | 0.013 | 0.005 | 0.102 |
| CMS cuts    | 0.005 | 0.013 | 0.005 | 0.102 |

The final requirement imposed by CMS is automatically enforced in Monte Carlo calculations.

Our results show that the CMS cuts indeed favor VBF considerably over the gluonic channels, which, however, survive the cuts to a non-negligible extent. To get a more quantitative estimate, we also considered the inclusion of the so-called $K$-factors, that provide for a consistent part of the higher-order corrections, not included in $^{[13]}$. For example, we use estimates$^9$ which assume the numerical values

$$K_{gg} = 1.72; \quad K_{qq} = 1.23,$$

and compute the corrected cross sections by multiplying the values in table 4 by the appropriate factors:

$$\sigma_{g\text{ cor}} = K_{gg} \sigma_{gg} + \sqrt{K_{gg} K_{qq} \sigma_{gq}^2} + K_{qq} \sigma_{qq},$$

$$\sigma_{VBF\text{ cor}} = K_{qq} \sigma_{VBF}.$$  \hspace{1cm} (14)

The results for $h$ and $H$ are shown in table 5. For reference we have computed with the same libraries $^{[13]}$ the total cross section for the SM inclusive Higgs production at LHC as a

\hspace{1cm} $^9$ http://www.pa.msu.edu/~huston/Kfactor/Kfactor.pdf.
Table 5. Same as table 4, with cross sections rescaled by $K$-factors, see equation (14).

|                | $\sigma_{g\text{ corr}}$ | $\sigma_{VBF\text{ corr}}$ | $\sigma_{TOT\text{ corr}}$ |
|----------------|--------------------------|----------------------------|-----------------------------|
| $h$, $M_h = 125$ GeV | minimal cuts 2.48         | 1.02                       | 3.50                        |
|                 | CMS cuts                 | 0.149                      | 0.444                       | 0.593                       |
| $H$, $M_H = 320$ GeV | minimal cuts 0.495        | 0.202                      | 0.697                       |
|                 | CMS cuts                 | 0.035                      | 0.125                       | 0.160                       |

sum of the cross sections for Higgs production with 0, 1 and 2 jets. Including the $K$-factors (13) and compared with more accurate calculations available. For $M_h = 125$ GeV, we obtain

$$\sigma (0 + 1 + 2 \text{ jets}) \sim 17 \text{ pb},$$

to be compared with the inclusive Higgs cross section at the same mass [15, 16]:

$$\sigma (\text{inclusive}) = 19.49 \text{ pb (dFG)},$$

$$\sigma (\text{inclusive}) = 20.69 \text{ pb (ABHL)}.$$

We find that the CMS cuts indeed favor VBF considerably over the gluon channels, which, however, survive to a non-negligible extent. In the case of $h$ we obtain

$$\left(\frac{\sigma_{VBF\text{ corr}}}{\sigma_{g\text{ corr}}}\right)_{h} \simeq 3 : 1,$$

which agrees with what is stated in [14]. For $H$, at $m_H = 320$ GeV

$$\left(\frac{\sigma_{VBF\text{ corr}}}{\sigma_{g\text{ corr}}}\right)_{H} \simeq 3.5 : 1.$$ (18)

Ratios of production cross sections to the SM ones can now be computed upon specifying the dominant mechanism:

$$R_{gg}(h) = \frac{\sigma (gg \to h)_{\text{MSSM}}}{\sigma (gg \to h)_{\text{SM}}} = \frac{S_{hs}^2}{\sin^2 \beta},$$

$$R_{VBF}(h) = \frac{\sigma (VV \to h)_{\text{MSSM}}}{\sigma (VV \to h)_{\text{SM}}} = (\cos \beta S_{hd} + \sin \beta S_{hs})^2,$$ (19)

and similarly for $H$.

5. Results

In the numerical calculations, we take as guiding values for $M_H$:

- the value $M_H = 320$ GeV, in correspondence with which an ‘excess’ can be seen in CMS data, albeit with small significance at about 1/3 with respect to SM [14];
- the value $M_H = 500$ GeV, to exemplify the behavior above the $tt$ threshold.

The results are summarized in figures 1, 2 and 4–7. The shaded areas in the figures indicate the presently excluded regions of tan $\beta$ corresponding to: (i) the region where the $(\sin \beta)^{-1}$ factor would make the $t$ quark Yukawa coupling run out of the perturbative region before the grand unification scale is reached [17] and (ii) the limit on tan $\beta$ derived (see [18] and references therein, [19]) from the non-observation of flavor-changing neutral current decays of $B$ mesons such as $B_s \to \mu^+ \mu^-$ [20].

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Figure 4. Values of $\frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$ in the $ZZ$ and $\gamma\gamma$ channels for $h$, $M_h = 125$ GeV and $H$, $M_H = 320$ GeV. Gluon–gluon fusion is assumed for $ZZ$ and VBF, to the degree allowed by the CMS cuts for $\gamma\gamma$. The lower dashed curve $\text{VBF} \rightarrow H \rightarrow \gamma\gamma$ is obtained by assuming 100% VBF.

Figure 5. Values of $\frac{\sigma \times BR}{\sigma_{SM}}$ for $h$, $M_h = 125$ GeV and $M_H = 320$. For comparison, the same ratios in SM are shown by the dots in the right-hand corner.

5.1. $h(125)$

For $M_H = 320$ GeV, we find that the light Higgs boson $h$ behaves in a manner rather close to that of the SM Higgs boson in both $ZZ$ and $\gamma\gamma$ channels, figure 4. For $M_H = 500$ GeV the decoupling limit is reached and $h$ is essentially an SM Higgs boson. We adopt the gluon–gluon fusion mechanism for the $ZZ$ channel and for $\gamma\gamma$ we use the cross sections in table 5 with CMS cuts, with the gluon fusion and VBF appropriately rescaled with supersymmetric (SUSY) couplings.

We show in figure 5 the values of $\frac{\sigma \times BR}{\sigma_{SM}}$ for SUSY $h$, $M_h = 125$ GeV and $M_H = 320$ GeV. The value of $\sigma \times BR$ is obtained by multiplying the SM cross section for a Higgs boson of the same mass. For comparison, the same ratios in SM are shown by the dots in the right-hand corner.
Figure 6. Values of $\frac{\sigma \times BR}{\sigma_{SM}}$ for $H$, $M_H = 320$ GeV. SM values shown in the right corner.

Figure 7. Values of $\frac{\sigma \times BR}{\sigma_{SM}}$ for $H$, $M_H = 500$ GeV. SM values shown in the right corner.

corner, for different channels. The $b\bar{b}$ branching ratio is $\sim 1.5$ larger than the SM one, due to the factor $(\cos \beta)^{-1}$ in the Yukawa coupling.

5.2. $H(320/500)$

The VBF $VV \rightarrow H \rightarrow ZZ$ gives a negligible result and we are left with $gg$ fusion as the production mechanism. For $\gamma \gamma$ we use the results of table 5 with CMS cuts. Not surprisingly, a large difference is made by being below or above the top quark threshold.

For $M_H = 320$ GeV, the ratios of $\sigma \times BR(H \rightarrow ZZ)$ and $\sigma \times BR(H \rightarrow \gamma \gamma)$ in SUSY over the same in SM drop very quickly at the increase of $\tan \beta$, see figure 4. In a window around $\tan \beta = 2$, $H$ would appear as a subdominant companion of $h$ in both $VV$ and $\gamma \gamma$ channels. Note that the assumption of pure VBF would give a very small result for $\gamma \gamma$, see figure 4. For $\tan \beta \geq 4$, the $VV$ and $\gamma \gamma$ decay branching ratios drop and the $b\bar{b}$ channel takes over, due to the $(\cos \beta)^{-1}$ factor, figure 6.
Taking seriously the bump at $M_H = 320 \text{ GeV}$, we get from figure 4:

$$\frac{\sigma \times BR(H \rightarrow ZZ)^{\text{MSSM}}}{(\sigma \times BR)^{\text{SM}}} \sim 0.3, \quad \text{at} \quad \tan \beta \sim 2$$ (20)

and, in correspondence, see also figures 1 and 2 and equation (8):

$$\frac{\sigma \times BR(h \rightarrow \gamma \gamma)^{\text{MSSM}}}{(\sigma \times BR)^{\text{SM}}} \sim 0.8, \quad \text{at} \quad \tan \beta \sim 2, \quad \text{CMS cuts},$$ (21)

$$\frac{\sigma \times BR(H \rightarrow \gamma \gamma)^{\text{MSSM}}}{(\sigma \times BR)^{\text{SM}}} \sim 0.26 \quad \text{at} \quad \tan \beta = 2,$$

$$M_A = 310 \text{ GeV}; \quad M_{H^\pm} = 320 \text{ GeV},$$ (23)

$$\sqrt{M_{\tilde{t}_R} M_{\tilde{t}_L}} = 3.9 \text{ TeV}.$$ (24)

For $M_H = 500 \text{ GeV}$, the $t\bar{t}$ channel is dominant up to $\tan \beta \sim 5$ and the observation of $H$ is related to the ability to detect top quarks. For $\tan \beta \geq 2$ the $b\bar{b}$ channel is also significant.

The ratios $\frac{\sigma \times BR}{\text{SM}}$ give a measure of the visibility of the different channels for $H$. We plot these ratios for $H$ below and above the $t\bar{t}$ threshold in figures 6 and 7.

5.3. $A$ and $H^\pm$

Given the masses of the CP-odd neutral $A$ and of the charged $H^\pm$ bosons, given in (23), one can foresee the dominant decays $[11] A \rightarrow b\bar{b}, \tau \bar{\tau}, Zh$, with branching ratios $(0.43, 0.06, 0.36)$ respectively and $H^+ \rightarrow t\bar{b}, hW^+$ $(0.99, 0.007)$.

6. Conclusions

A clear prediction of supersymmetry is the presence of two Higgs field doublets, one coupled to $u$ and the other to $d$ quarks. If the 125 GeV signal is confirmed, the next thing to look for is the presence of a secondary line in $VV, \gamma \gamma$ and $b\bar{b}$. We have shown that these signals are viable for $M_H$ below the $t\bar{t}$ threshold and in the rather narrow region of $\tan \beta$ allowed at present. An $H$ at 320 GeV seen in $ZZ$ and $\gamma \gamma$ would fit very well into MSSM with $\tan \beta \sim 2$ and this calls for close scrutiny of this region. Clear signatures for the CP-odd $A$ and the charged $H^\pm$ are the $b\bar{b}$ and $t\bar{b}$ decays, respectively. In all the cases we have considered, a scalar top mass around 4 TeV is predicted.

Acknowledgments

We are grateful to R Barbieri, D Del Re, C Dionisi, F Gianotti, G Organtini and G Tonelli for illuminating discussions.
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