Eur. Phys. J. C (2016) 76:286
DOI 10.1140/epjc/s10052-016-4129-2

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Discriminating between SUSY and non-SUSY Higgs sectors through the ratio $H \to b\bar{b}/H \to \tau^+\tau^-$ with a 125 GeV Higgs boson

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Received: 8 July 2015 / Accepted: 7 May 2016

Abstract It is still an open question whether the new scalar particle discovered at the LHC with a mass of 125 GeV is the SM Higgs boson or belongs to models of new physics with an extended Higgs sector, as the MSSM or 2HDM. The ratio of branching fractions $R = \mathrm{BR}(H \to b\bar{b})/\mathrm{BR}(H \to \tau^+\tau^-)$ of Higgs-boson decays is a powerful tool in distinguishing the MSSM Higgs sector from the SM or non-supersymmetric 2HDM. This ratio receives large renormalization-scheme independent radiative corrections in supersymmetric models at large $\tan\beta$, which are insensitive to the SUSY mass scale and absent in the SM or 2HDM. Making use of the current LHC data and the upcoming new results on Higgs couplings to be reported by ATLAS and CMS collaborations and in a future linear collider, we develop a detailed and updated study of this ratio R which improves previous analyses and sets the level of accuracy needed to discriminate between models.

1 Introduction

At present, it is still an open question in the high energy physics community whether the discovered new scalar particle at the Large Hadron Collider (LHC) [1,2] is actually the Higgs boson of the Standard Model of particle physics (SM). This new particle seems to behave as the SM Higgs boson, and the most recent combined measurement of its mass by the ATLAS and CMS collaborations set $m_{H^{\mathrm{SM}}} = 125.09 \pm 0.21\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})$ GeV [3]. However, many more measurements and data will be needed to extract reliable conclusions. It is worth noticing that the study of perturbativity and stability of the SM Higgs-boson potential suggests that, given the measured Higgs-boson mass, new physics must be present before the Planck scale [4–10]. Apart from the introduction of new particles, extensions of the SM scalar sector may affect the properties of the SM-like Higgs boson discovered at the LHC. Experimental data is being used to constrain these extensions. Among the minimal extensions of the SM is the inclusion of additional Higgs bosons. In the two-Higgs-doublet models (2HDM) one additional Higgs doublet is introduced and five physical Higgs bosons are obtained [11]: two CP-even scalars (h and H), one CP-odd scalar (A), and a charged Higgs pair ($H^\pm$); being the lightest Higgs boson very similar to the SM one in the so-called *decoupling limit* [12]. The minimal supersymmetric standard model (MSSM) [13–15], one of the most-predictive frameworks beyond the SM, also contains two Higgs doublets with a light neutral scalar boson compatible with the existing measurements, including the recently discovered Higgs boson. In this letter we approach the question of the existence of an extended Higgs structure beyond the SM by investigating the neutral Higgs sector of various types of models.

We consider in this work the ratio of branching ratios of a neutral Higgs boson H [16],

$$R = \frac{\mathrm{BR}(H \to b\bar{b})}{\mathrm{BR}(H \to \tau^+\tau^-)}, \tag{1}$$

analyzing in detail the Yukawa-coupling effects and their phenomenological consequences. At leading order, in either the SM, the 2HDM or the MSSM, this ratio is given by just the ratio of squared (running) masses:

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$$R = 3\frac{m_b^2(Q)}{m_\tau^2(Q)}. \tag{2}$$

However, this ratio receives large renormalization-scheme independent radiative corrections in supersymmetric (SUSY) models at large $\tan\beta$, the ratio of the vacuum expectation values. These corrections are insensitive to the SUSY mass scale (M_{SUSY}) and absent in the SM or 2HDM. Therefore, this ratio is a discriminant quantity between SUSY and non-SUSY models. The leading radiative corrections to this ratio can be cast into an effective Yukawa SUSY coupling h_{f}, and they can be summarized in a simple correction factor Δm_{f} [16–18]; thus for a down-type quark or a charged lepton one can write

$$h_{\mathrm{f}} = \frac{m_{\mathrm{f}}(Q)}{v_1}\frac{1}{1+\Delta m_{\mathrm{f}}} = \frac{m_{\mathrm{f}}(Q)}{v\cos\beta}\frac{1}{1+\Delta m_{\mathrm{f}}},$$
$$v = (v_1^2+v_2^2)^{1/2}. \tag{3}$$

Here $m_{\mathrm{f}}(Q)$ is the running fermion mass, v_1 and v_2 are the vacuum expectation values (*VEVs*) of the two Higgs doublets; being v_1 the one giving mass to down-type quarks and charged leptons, $\tan\beta = \frac{v_1}{v_2}$ is the ratio of the *VEVs* and $v = (v_1^2+v_2^2)^{1/2}$ is the SM *VEV*. This expression includes all possible $\tan\beta$ enhanced corrections of the type $(\alpha_{(s)}\tan\beta)^n$ [19] correctly resumed. The leading part of the (potentially) non-decoupling contributions proportional to the trilinear soft-SUSY-breaking coupling A_{f} can be absorbed in the definition of the effective Yukawa coupling at low energies and only subleading effects survive [20]. Therefore, expression (3) contains all leading potentially large radiative effects. The resummation of the two-loop dominant corrections for large values of $\tan\beta$ has been calculated in [21,22].

The interplay between Higgs physics and SUSY, with the inclusion of radiative corrections, has been extensively discussed in the literature; see, e.g., [16–47]. It is also well known that the SUSY radiative corrections to the couplings of the Higgs bosons to bottom quarks can be significant for large values of $\tan\beta$, and that they do not decouple in the limit of a heavy supersymmetric spectrum [17–20,24–30,33–35], opposite to their behavior in electroweak gauge boson physics [48–50]. The partial decay width $\Gamma(h \to b\bar{b})$ of the lightest supersymmetric neutral Higgs particle has received particular attention. The complete one-loop corrections have been studied in [23], and comprehensive studies of the one- and two-loop SUSY-QCD corrections are also available in [24,31]. The effective Lagrangian description of the $hb\bar{b}$ vertex and the implications for Higgs-boson searches from SUSY effects can be found in [17,19,20,27,28]. The decoupling properties of the SUSY-QCD corrections to $\Gamma(h \to b\bar{b})$ have been extensively discussed in [30]. On the other side, the analysis of $\mathrm{BR}(H \to \tau^+\tau^-)$ was presented in [32]. The observable R, as the ratio of the two last mentioned processes, has also been analyzed in [16,29]. Some recent analyses of these two branching ratios and other Higgs decay modes, confronting LHC data with the MSSM predictions, can be found, for example, in [51–53].

The ratio (1) is very interesting from both the experimental and the theoretical sides. It is a clean observable, measurable in a counting experiment, with only small systematic errors since most of them cancel in the ratio. The only surviving systematic effect results from the efficiency of τ- and b-tagging. From the theoretical point of view, it is independent of the production mechanism of the decaying neutral Higgs boson and of its total width. Therefore, new-physics effects affecting the production cross-section do not appear in the ratio and also this observable is insensitive to unknown higher order QCD corrections to Higgs-boson production. Besides, since this ratio only depends on the ratio of the masses (2), there is no other parameter (e.g. $\tan\beta$) that could absorb the large quantum corrections.

As shown in [16], the ratio of the Higgs-boson decay rates into b quarks and τ leptons (1) normalized to the Standard Model expectation R^{SM} is a very efficient quantity to distinguish a general 2HDM from the MSSM, whose Higgs sector could be fully covered at the LHC [54–56]. This normalized value is a function depending only on $\tan\beta$, $\tan\alpha$, Δm_b, and Δm_τ, and encoding all the genuine SUSY corrections. The explicit form of Δm_b and Δm_τ at the one-loop level can be obtained approximately by computing the supersymmetric loop diagrams at zero external momentum ($M_{\mathrm{SUSY}} \gg m_b, m_\tau$) [16]. These two quantities are independent of the SUSY mass scale M_{SUSY} since they only depend on $\tan\beta$ and the ratio A_t/M_{SUSY} [16,19,27]. Therefore, the conclusions about the sensitivity to the SUSY nature of the Higgs sector through the analysis of the ratio R are independent of the scale of the SUSY masses.

Nowadays, the experiments at the LHC become increasingly sensitive to the Higgs-boson couplings. CMS and ATLAS have indeed performed a generic fit to Higgs-boson coupling ratios. In order to carry out this analysis, they define a set of Higgs-boson couplings normalized to the SM ones, $\kappa_x \equiv g_x/g_x^{\mathrm{SM}}$, and the production rate measurements give a measurement of the coupling ratios for two particles:

$$\lambda_{xy} \equiv \frac{\kappa_x}{\kappa_y} \equiv \frac{g_x/g_x^{\mathrm{SM}}}{g_y/g_y^{\mathrm{SM}}}.$$

In the present work, we are interested in the bottom-quark and τ-lepton measurements, for which CMS and ATLAS collaborations provide [57,58]

$$\lambda_{bZ}^{\mathrm{CMS}} = 0.59^{+0.22}_{-0.23}, \quad \lambda_{\tau Z}^{\mathrm{CMS}} = 0.79^{+0.19}_{-0.17}, \quad \lambda_{bZ}^{\mathrm{ATLAS}} = 0.60 \pm 0.27, \quad \lambda_{\tau Z}^{\mathrm{ATLAS}} = 0.99^{+0.23}_{-0.19}. \tag{4}$$

Besides, the expected accuracy for the measurement of the fundamental Higgs couplings $Hb\bar{b}$ and $H\tau^+\tau^-$ in future course of the LHC run corresponds to an uncertainty of 10–

13 % (b quarks) and 6–8 % (τ leptons), going down to 4–7 and 2–5 % for the high luminosity LHC (HL-LHC). At the Linear Collider (LC) the expected uncertainty is smaller, 0.6 % for $Hb\bar{b}$ coupling and 1.3 % for $H\tau^+\tau^-$ coupling [59–61]. In this paper we consider the present experimental results on the Higgs-boson mass and couplings in the analysis of the ratio (1) as well as the expected future precision, and discuss the possibility to discriminate between models at various levels of future accuracy.

In Sect. 2 we present the relevant expressions for our study and analyze the ratio R (Eq. (1)) in view of the present LHC data on Higgs-boson coupling ratios as given in (4). Section 3 is devoted to the analysis of the future sensitivities of this ratio at present and future colliders, and the study of the potential discrimination between SUSY or non-SUSY models. Finally, the conclusions of this work are summarized in Sect. 4.

2 Analysis of present data

In this section we concentrate on the analysis of the ratio R defined in (1) for the cases of the lightest CP-even Higgs boson, h. For the sake of the discussion and the analysis it will be useful to introduce the ratio R (1) normalized to the SM value for equal values of the Higgs-boson mass. For a Higgs boson ϕ we define

$$X(\phi) = \frac{R(\phi)}{R^{\rm SM}(m_{H^{\rm SM}} = m_\phi)}. \tag{5}$$

We can write this normalized ratio for each neutral MSSM Higgs boson in terms of the non-decoupling quantities Δm_b and Δm_τ as [16]

$$X(h) = \frac{R^{\rm MSSM}(h)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(-\cot\alpha\,\Delta m_b + \tan\beta)^2}{(1+\Delta m_b)^2\,(-\cot\alpha\,\Delta m_\tau + \tan\beta)^2}, \tag{6}$$

$$X(H) = \frac{R^{\rm MSSM}(H)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(\tan\alpha\,\Delta m_b + \tan\beta)^2}{(1+\Delta m_b)^2\,(\tan\alpha\,\Delta m_\tau + \tan\beta)^2}, \tag{7}$$

$$X(A) = \frac{R^{\rm MSSM}(A)}{R^{\rm SM}} = \frac{(1+\Delta m_\tau)^2\,(\tan^2\beta - \Delta m_b)^2}{(1+\Delta m_b)^2\,(\tan^2\beta - \Delta m_\tau)^2}. \tag{8}$$

In [16], by assuming a ±21 % measurement of this ratio for the lightest Higgs boson at the LHC [62,63], it was found that one can be sensitive to the SUSY nature of the lightest Higgs boson h for M_A up to ∼1.8 TeV in the most favorable scenario, being up to $M_A \sim 500$ GeV in some other regions. Nowadays, the combination of the LHC coupling measurements of Eq. (4) provides an experimental determination of the normalized ratio (5)

$$X^{\rm exp} = \frac{R^{\rm exp}}{R^{\rm SM}} = \frac{\lambda_{bZ}^2}{\lambda_{\tau Z}^2}. \tag{9}$$

Using the values in Eq. (4) we obtain

$$X^{\rm CMS} = 0.56^{+0.48}_{-0.52}, \quad X^{\rm ATLAS} = 0.37^{+0.36}_{-0.37}. \tag{10}$$

In this work we consider this experimental determination and we discuss their phenomenological consequences through the analysis of the normalized ratio X (5) in different SUSY scenarios. Besides, we also include in our numerical analysis a combined analysis of CMS and ATLAS results. From the generic fit to Higgs coupling ratios given above one can determine the values of these coupling ratios to be

$$\lambda_{bZ}^{\rm Combined} = 0.594^{+0.171}_{-0.174}, \quad \lambda_{\tau Z}^{\rm Combined} = 0.887^{+0.140}_{-0.126}. \tag{11}$$

We obtain these values by using the procedure for combination of results described in [64–66]. As a consequence we get a value for the ratio of

$$X^{\rm Combined} = \frac{R^{\rm Combined}}{R^{\rm SM}} = 0.45^{+0.29}_{-0.30}. \tag{12}$$

Therefore, the one-standard deviation (68 % CL) favored bands on X (5) are

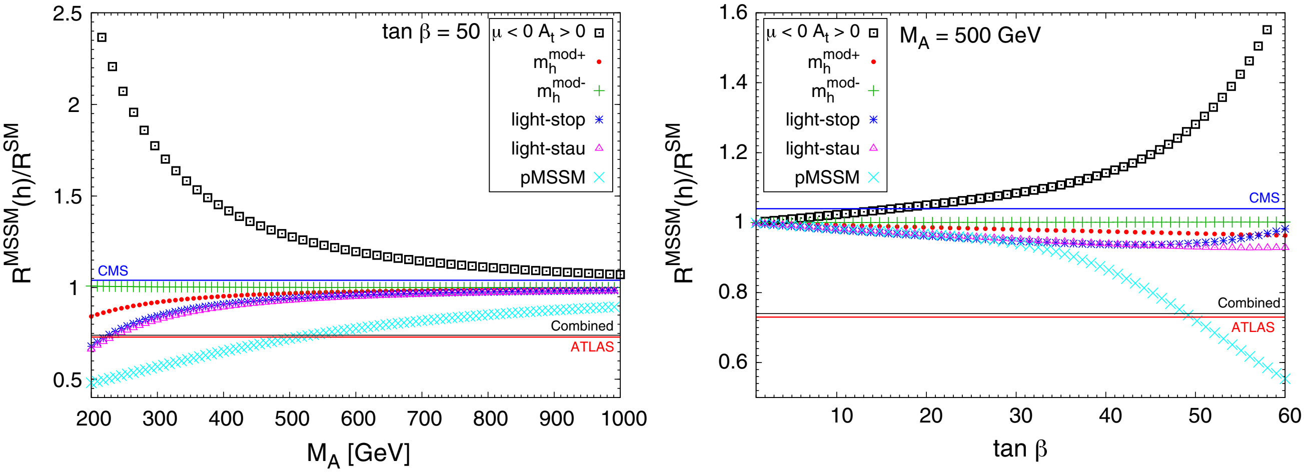
$$\begin{aligned} &0.04 < X^{\rm CMS} < 1.04, \quad 0 < X^{\rm ATLAS} < 0.73,\\ &0.15 < X^{\rm Combined} < 0.74. \end{aligned} \tag{13}$$

While the CMS result includes the SM value ($X = 1$) in its favored region, the ATLAS and our combined results disfavor the SM (at 68 % CL). SUSY can provide the necessary corrections to bring the predicted theoretical value of X inside the ATLAS favored band. Our interest is to explore SUSY scenarios which bring theoretical predictions closer to the experimental result.

For the theoretical numerical analysis, we consider different SUSY scenarios, by checking that those scenarios are compatible with the present experimental value of the Higgs-boson mass, $m_{H^{\rm SM}} = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})$ GeV [3]. The Higgs-boson mass is computed by using `FeynHiggs 2.11` [67]. For completeness, first we consider the four scenarios analyzed in [16] and we find that the SUSY spectra defined in these scenarios provide a Higgs-boson mass value not compatible with the present experimental result. The only exception is the scenario with $\mu < 0$ $A_t > 0$, in which we obtain the result that m_h is around 122 GeV. For the purpose of making contact with the previous results, we include this scenario in the following discussion. Besides, we choose SUSY spectra as defined in [68] for the $m_h^{\rm mod+}$, $m_h^{\rm mod-}$, light-stop, and light-stau scenarios in the MSSM, which are compatible with the Higgs boson mass of the observed signal at the LHC, and the benchmark scenario 2392587 of the phenomenological MSSM (pMSSM) [69], a general version of the R-parity conserving MSSM with 20 input parameters. The SM parameters are fixed to be $m_t = 173.21$ GeV, $m_b = 4.18$ GeV, $m_\tau = 1.777$ GeV [70]. The CP-even mixing angle is computed including the leading corrections up to two-loop order by means of the program `FeynHiggsFast` [71]. The branching ratios of Higgs boson decays into $b\bar{b}$ and $\tau^+\tau^-$ have also been computed with `FeynHiggs 2.11` and we find a perfect agreement with our results for values of $\tan\beta \lesssim 50$. The difference between these two computations for larger values of $\tan\beta$ is around 10 %.

In Fig. 1 we present numerical results for $R^{\mathrm{MSSM}}(h)$ normalized to the SM value, as a function of (a) M_A and (b) $\tan\beta$, for various choices of SUSY scenarios with $\tan\beta = 50$ and $M_A = 500$ GeV, respectively. The horizontal lines show the one-standard deviation experimental upper limit for X (13) by ATLAS (in red), CMS (in blue), and our combined result (in black). The largest deviation with respect to the SM value emerges in the scenario $\mu < 0$ $A_t > 0$. Actually, the present analysis already disfavors this scenario at 68 % CL. In fact, this scenario is excluded by ATLAS, CMS and also the combined analysis (Fig. 1a), and only a small region with $\tan\beta < 10$ and $M_A = 500$ GeV survives the CMS measurement (Fig. 1b). This shows the huge potential of the observable R in SUSY searches/exclusions. We note, however, that this scenario ($\mu < 0$ $A_t > 0$) is also disfavored by the constraints from the measurement of $BR(B_s \to \mu^+\mu^-)$ at large $\tan\beta$ [72]. Actually, the sign of the dominant contribution to the corrections to R is proportional to $-\mathrm{sign}(\mu A_t)$, and since the experimental data on $BR(B_s \to \mu^+\mu^-)$ disfavors $\mu A_t < 0$, it selects negative corrections to R. Furthermore, the $\mu < 0$ scenarios are also disfavored by the muon $g - 2$ [73–76]. For this reason we will not further consider the $\mu < 0$ $A_t > 0$ scenario. The other scenarios provide a prediction for $R^{\mathrm{MSSM}}(h)$ (6) smaller than in the SM, and then the CMS measurement alone cannot exclude any of them (13). However, note that most scenarios have a prediction close the SM one, and therefore the ATLAS result disfavors them (at 68 % CL). The $m_h^{\mathrm{mod}-}$ scenario prediction is practically indistinguishable from the SM one, whereas the $m_h^{\mathrm{mod}+}$ has a largest deviation of a 20 % with respect to the SM value, and both of them are also disfavored by ATLAS. The light-stop and light-stau scenarios provide larger deviations, up to 40 % for small M_A, and this small region is not disfavored by ATLAS. The pMSSM scenario provides larger deviations, and thus has the largest allowed regions, for $M_A \lesssim 500$ GeV and $\tan\beta \gtrsim 50$. These are all 68 % CL constraints; more precise data is needed to obtain more significant constraints.

We note in Fig. 1b the flat evolution of the normalized ratio X with respect to $\tan\beta$ in the $m_h^{\mathrm{mod}+}$, $m_h^{\mathrm{mod}-}$, light-stop, and light-stau scenarios. The reason is manifold: first of all, the resummation procedure softens the $\tan\beta$ evolution; second, at $M_A \simeq 500$ GeV the MSSM Higgs sector is already close to the decoupling limit, with $\tan\alpha$ close to $-1/\tan\beta$ and therefore providing a small effect of the Δm_{f} corrections to $X(h)$ (8); thirdly, those scenarios use as input parameter in the squark sector the non-diagonal element of the squark-mass matrix $X_{t[b,\tau]} = A_{t[b,\tau]} - \mu\cot\beta[\tan\beta]$, and therefore the sfermion-mass matrix is nearly flat as a function of $\tan\beta$, and so are also the sfermion masses. For the pMSSM scenario the first two conditions also apply; however, here the input



(a) **(b)**

Fig. 1 Normalized ratio $X^{\mathrm{MSSM}}(h)$ (6), as a function of: **a** M_A ($\tan\beta = 50$) and **b** $\tan\beta$ ($M_A = 500$ GeV), for various choices of benchmark scenarios. In both plots, the *horizontal lines* show the one-standard deviation experimental upper limit regions for X (13) by ATLAS (*red*), CMS (*blue*), and our combined result (*black*) parameter in the sfermion sector is the soft-SUSY-breaking trilinear coupling $A_{t[b,\tau]}$, therefore the sfermion mass mixing terms changes strongly with $\tan\beta$, and so do also the physical sfermion masses.

As expected, the decoupling behavior with M_A becomes apparent in Fig. 1a for all the SUSY scenarios. Notice that in all the above scenarios the gluino mass is around 1500 GeV. We have also examined numerically the decoupling behavior of the ratio X with the gluino mass, extrapolating the results up to $M_{\tilde{g}} \sim 5000$ GeV. Our results show that there is no decoupling; the ratio X tends to a constant value for all mentioned SUSY scenarios. Therefore, our conclusions are also valid for large values of the gluino mass, in perfect agreement with the present bounds for this mass at the LHC.

We finish this section by discussing the regions of the MSSM parameter space favored by the present experimental values of X (13). Of course, as already told, all the studied scenarios have $X \lesssim 1$, and therefore all of them are allowed by CMS. Furthermore, the $m_h^{\rm mod-}$ scenario has very small deviations with respect to the SM value and it is practically indistinguishable from the SM. Figure 2 shows the contour plots of $X(h)$ (6) in the MSSM for the $m_h^{\rm mod+}$, light-stop, light-stau and pMSSM scenarios. The red [black] line shows the upper (one-standard deviation) limit by ATLAS [our combination] (13), the allowed region is the red area of the curve. We also show the 95 % CL favored regions (shaded blue areas) by the negative searches by ATLAS and CMS for neutral MSSM Higgs bosons decaying into a pair of τ leptons [77,78]. We see that in the $m_h^{\rm mod+}$ roughly the whole explored M_A–$\tan\beta$ plane is disfavored, whereas in the light-stop and light-stau scenarios a small corner of large $\tan\beta$ and low M_A is favored. The region favored in the pMSSM scenario is much larger, allowing large values of M_A with large $\tan\beta$. In all the cases, the favored regions fall completely inside the excluded region for the CMS and ATLAS direct searches for Higgs bosons decaying into τ-lepton pairs, which means that there is a tension (albeit a very soft one) between the experimental determination of the Higgs boson couplings and the direct search for Higgs boson decaying into τ-lepton pairs.

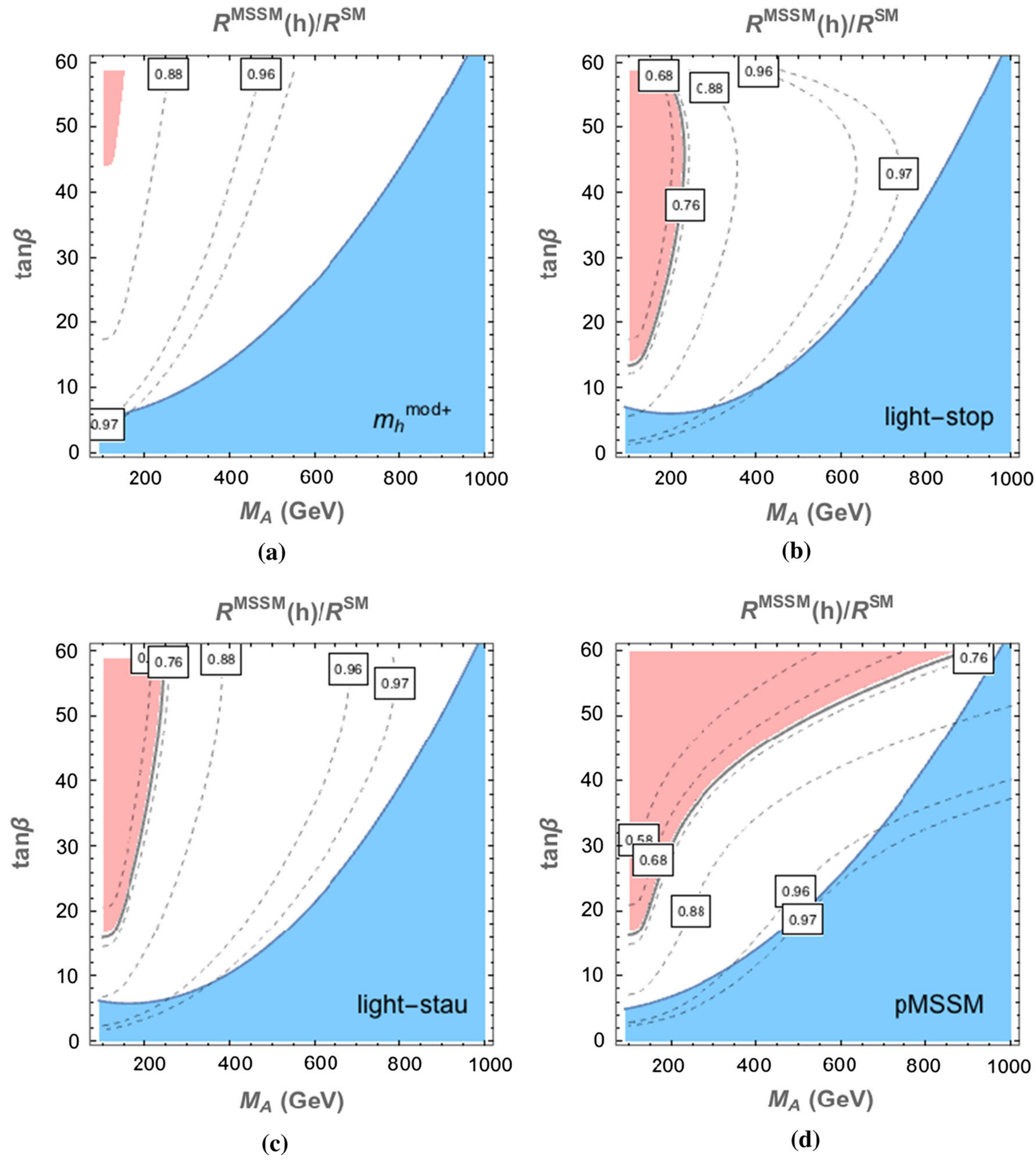
The direct searches for charged Higgs bosons provide also model-dependent constraints in the M_A–$\tan\beta$ plane [26,79–82]. Present data [83,84] exclude most of the parameter space for $m_{H^\pm} < 160$ GeV ($M_A < 140$ GeV), except for a small wedge around $\tan\beta \sim 6$, and also exclude a region for $\tan\beta > 50$ and $m_{H^\pm} = 200$–400 GeV ($M_A = 180$–225 GeV). No results exist for the intermediate region $m_{H^\pm} = 160$–200 GeV. These results are also in tension with the ones of Fig. 2, although not as severe as the neutral Higgs-boson ones, since they only cover the region of smallest M_A, and, moreover, there is still an unexplored region.

3 Future prospects

In this section we study the prospects for finding deviations in the ratio R (1) in future colliders. In order to define the different sensitivity regions we show in Table 1 the expected accuracies with which the fundamental Higgs couplings $Hb\bar{b}$ and $H\tau^+\tau^-$ and our derived observable R (1) can be measured at the LHC/HL-LHC, the LC, and in combined analyses of the HL-LHC and the LC [59–61]. Note that Table 1 shows the accuracy expected on absolute coupling measurements, whereas for the purpose of the present work relative coupling measurements, like the ones in Eq. (4), are sufficient, and these have better accuracies.

We reanalyze, from the point of view of the sensitivity to the SUSY nature of the neutral MSSM Higgs bosons, the results of Fig. 2, where the regions in the M_A–$\tan\beta$ plane in which the MSSM prediction for the normalized ratio X (5) is larger than the expected sensitivities of Table 1 are depicted. Figure 2 shows these sensitivity regions on $X(h)$ (6) for the $m_h^{\rm mod+}$, light-stop, light-stau, and pMSSM scenarios, respectively, for 42, 32, 24, 12, 4, and 3 % accuracy measurements. The sensitive regions are the ones above and to the left of the corresponding curve. The sensitivity regions for the $m_h^{\rm mod-}$ scenario are not shown here, since as can be inferred from the results of Fig. 1, it is not possible to distinguish its predictions from the SM ones. Indeed, in order to measure a deviation with respect the SM value in this scenario, an accuracy of at least ~ 0.5 % would be required.

The SUSY nature of the discovered Higgs boson of 125 GeV is testable within these four scenarios with the expected accuracies for the current LHC runs or for its high luminosity phase. Unfortunately the corresponding sensitivity regions lie mainly outside the shaded blue areas and thus are excluded by the ATLAS and CMS direct searches. Only in the pMSSM scenario with a 12 % measurement (corresponding to the HL-LHC accuracy) one can have sensitivity to SUSY in a favored area for large values of M_A (around 800–1000 GeV) and $\tan\beta \gtrsim 50$. If we turn to the LC and combined HL-LHC+LC accuracies, the possibility of detecting a deviation with respect to the SM value becomes more favored. In that case, within the $m_h^{\rm mod+}$ scenario, one could have sensitivity to SUSY in the region with very low values of $\tan\beta$ and M_A, up to $M_A \sim 200$ GeV. On the other hand, within the light-stop and light-stau scenarios the LC sensitivities are kept up to $M_A \simeq 400$ GeV. From this value of M_A, the sensitivity regions lie in the area of exclusion and are not allowed. The contour lines for the LC accuracies in the pMSSM scenario are allowed for any value of M_A, depending on the value of $\tan\beta$. Then, if this class of scenarios is realized in nature, one would be able to observe deviations with respect the SM predictions at a possible future LC, which would mean a clear hint of SUSY.



(a) (b) (c) (d)

Fig. 2 Contour plots in the M_A–$\tan\beta$ plane for the normalized ratio X (13), in the **a** $m_h^{\text{mod+}}$, **b** light-stop, **c** light-stau, and **d** pMSSM scenarios. The *red* (*black*) *curve* shows the upper (one-standard deviation) limit from ATLAS (our combination) (13), the favored region is shown in *red*. Sensitivity regions on $X(h)$ (6) with the different expected accuracies defined in Table 1 are also included. The sensitivity regions are the ones to the *left* of the corresponding curve. Shown in *blue* is the 95 % CL allowed regions by the negative searches by ATLAS and CMS for neutral MSSM Higgs bosons decaying to a pair of τ leptons [77,78]

Table 1 Expected accuracies for the measurements of the Higgs-boson couplings $Hb\bar{b}$ and $H\tau^+\tau^-$ [59–61] and the ratio R (1) at the LHC/HL–LHC, LC, and in combined analyses of the HL–LHC and LC

Observable	LHC (%)	HL–LHC (%)	LC (%)	HL–LHC + LC (%)
$Hb\bar{b}$	10–13	4–7	0.6	0.6
$H\tau^+\tau^-$	6–8	2–5	1.3	1.2
R	32–42	12–24	4	3

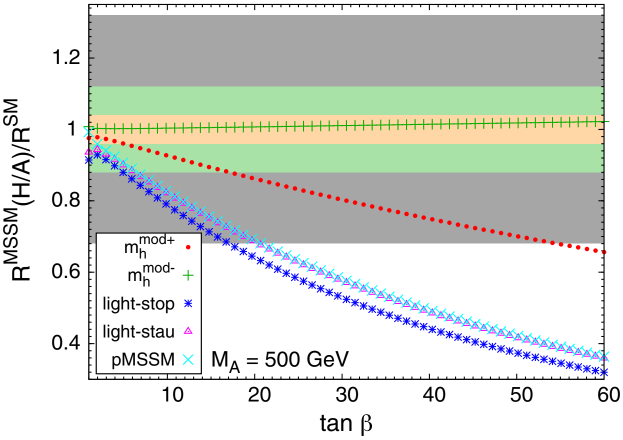


Fig. 3 Deviation of $R^{\text{MSSM}}(H/A)$ with respect to the SM value, as a function of $\tan\beta$ for various choices of benchmark scenarios. The *shaded gray region* shows the ±32 % deviation whit respect to the SM, the *shaded green one* the ±12 %, and the *shaded orange one* the ±4 %

We turn now our attention to the heavy neutral Higgs bosons H and A. In case of these heavy states are found at the LHC, one still has to answer the question whether they belong to a simple 2HDM, or whether they belong to a SUSY extension of the SM. The ratio of branching ratios R (1) can be useful in this task. Figure 3 shows the normalized ratio $X(H/A)$ (5) as a function of $\tan\beta$ for the $m_h^{\text{mod+}}$, light-stop, light-stau, and pMSSM scenarios with $M_A = 500$ GeV. Note that once we are close to the decoupling limit ($M_A \gg M_Z$) the couplings of H/A are indistinguishable, and, furthermore, the ratio $R(H/A)$ becomes independent of M_A. We show through different shaded regions the expected accuracies for the future measurement of R (1), ±32 % (shaded gray area), ±12 % (shaded green area), and ±4 % (shaded orange area). For the sake of readiness, we only show the smallest accuracies reported in Table 1. We see that, given a large enough value of $\tan\beta$, all the scenarios (except the $m_h^{\text{mod}-}$) provide a value for $X(H/A)$ (5) larger than the expected experimental accuracies. Within the $m_h^{\text{mod+}}$ scenario, it would be possible to observe at the LHC 32 % deviations with respect to the SM value for $\tan\beta \gtrsim 55$. At the HL-LHC, we could be sensitive to SUSY within this scenario for a 12 % deviation from values of $\tan\beta \gtrsim 20$. The results for the light-stop, light-stau, and pMSSM scenarios are very similar and even more favorable in order to detect any SUSY deviation with respect to the SM value. The LHC could observe 32 % deviations for values of $\tan\beta$ larger than 20 and the HL-LHC would be sensitive to SUSY with 12 % deviations for $\tan\beta \gtrsim 5$. If an accuracy of 4 % is achieved at a future LC, it would be possible to probe the SUSY nature of H and A Higgs bosons for $\tan\beta \gtrsim 5$ in any of these four scenarios. Therefore, if a new heavy Higgs scalar or pseudoscalar is discovered, and its couplings to bottom quarks and τ leptons are measured with a moderate level of precision, it would be possible to distinguish between SUSY and non-SUSY Higgs sectors at the LHC.

The measurements of the light Higgs boson (Fig. 2) and the heavier ones (Fig. 3) are complementary. For large values of M_A the contributions to $R^{\text{MSSM}}(h)$ (Fig. 2) decouple, whereas the contributions to $R^{\text{MSSM}}(H/A)$ do not decrease. In addition, for intermediate values of M_A we could find ourselves in the lucky situation in which both $R^{\text{MSSM}}(h)$ and $R^{\text{MSSM}}(H/A)$ might be measured, and show a deviation with respect to R^{SM}. For example, in the pMSSM scenario with $M_A = 500$ GeV, and $\tan\beta = 40$, $R^{\text{MSSM}}(h)/R^{\text{SM}} \simeq 0.88$ and $R^{\text{MSSM}}(H/A)/R^{\text{SM}} \simeq 0.5$, both deviations are measurable at the HL-LHC 1.

4 Conclusions

In this work, we have updated the analysis of the observable $R = \text{BR}(H \to b\bar{b})/\text{BR}(H \to \tau^+\tau^-)$ (1) in order to look for a strong evidence for, or against, the SUSY nature of the Higgs boson. We have considered more realistic MSSM scenarios with a lightest Higgs-boson mass m_h compatible with the current value of the Higgs-boson mass $m_{H^{\text{SM}}} \simeq 125$ GeV. We have compared the theoretical prediction in the MSSM with the current experimental determination of Higgs-boson couplings to fermions at the LHC (4). We find that the SM prediction for R agrees well with current CMS data, but using ATLAS data we obtain a (one-standard deviation) upper limit below the SM prediction. By contrast, the SUSY contributions can provide a prediction that agrees with the experiment at the one-standard deviation level. Current accuracy already allows one to disfavor (at least at the one-standard deviation level) portions of the parameter space, showing the potential of the observable R to discriminate among different models of new physics. It is also important to mention that the parameter space regions that are favored by the determination of the Higgs-boson couplings to fermions are in tension with the direct searches for MSSM neutral Higgs boson decaying into τ-lepton pairs.

We have also looked at the prospects for future measurements of the Higgs-boson couplings. We find that, in wide regions of the parameter space, a moderate accuracy of the couplings would signal the presence of SUSY in the Higgs-boson data. This analysis allows the use of relative couplings, which can improve significantly the accuracy in the experimental determination of R.

Finally, we have moved our attention to the heavier Higgs bosons of the MSSM, H and A. If one or both of these heavy neutral Higgs bosons are discovered, one would still need to determine whether they belong to a generic 2HDM or to a SUSY model. A moderate accuracy determination of their couplings to b quarks and τ leptons, by means of the analysis of the ratio R, would be sufficient to discern the SUSY nature of such particles.

Acknowledgments The work of E. A. is funded by a grant from the Spanish Consolider-Ingenio 2010 Program CPAN (CSD2007-00042). E. A. and S. P. are financially supported by the Spanish DGIID-DGA Grant No. 2013-E24/2, the Spanish MINECO Grants No. FPA2012-35453 and CPAN (CSD2007-00042). J.G. has been supported by MINECO (Spain) (FPA2013-46570-C2-2-P), by DURSI (2014-SGR-1474) and CPAN (CSD2007-00042).

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