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A Higgs boson near 125 GeV with enhanced di-photon signal in the NMSSM

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Abstract: A natural region in the parameter space of the NMSSM can accomodate a CP-even Higgs boson with a mass of about 125 GeV and, simultaneously, an enhanced cross section times branching ratio in the di-photon channel. This happens in the case of strong singlet-doublet mixing, when the partial width of a 125 GeV Higgs boson into $b\,\bar{b}$ is strongly reduced. In this case, a second lighter CP-even Higgs boson is potentially also observable at the LHC.

Keywords: Higgs Physics, Supersymmetric Standard Model

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Contents

1 Introduction

Based on the analysis of $5\,{\rm fb}^{-1}$ of data at the LHC, the ATLAS [1] and CMS [2] collaborations have presented evidence for a Higgs boson with a mass in the 125 GeV range. The relevant search channels are $H \to \gamma\,\gamma$, $H \to Z\,Z^* \to 4l$, $H \to W\,W^* \to 2l\,2\nu$ and to some extend (at CMS) $H \to \tau\,\tau$. Interestingly, the best fit to the signal strength $\sigma^{\gamma\gamma} = \sigma_{\rm prod} \times {\rm BR}(H \to \gamma\,\gamma)$ in the $\gamma\,\gamma$ search channel is by about one standard deviation larger than expected in the Standard Model (SM) for both collaborations: $\sigma^{\gamma\gamma}/\sigma^{\gamma\gamma}_{\rm SM} \sim 2$ (ATLAS), and $\sigma^{\gamma\gamma}/\sigma^{\gamma\gamma}_{\rm SM} \sim 1.7$ (CMS). Of course, the present evidence for a Higgs boson is not (yet?) sufficiently significant in order to consider its existence as assured, even less is the excess in the $H \to \gamma\,\gamma$ channel a proof for a non-SM-like Higgs boson.

A relatively light Higgs boson (with a mass not too far above the LEP bound of ~ 114 GeV) is a genuine prediction of supersymmetric extensions of the SM which remain consistent up to a Grand Unification (GUT) scale of about 10^{16} GeV, in particular in the Minimal Supersymmetric extension (MSSM) with a minimal Higgs sector consisting of two SU(2) doublets H_u and H_d. In fact, in the MSSM the solution of the fine tuning problem offered by supersymmetry works the better, the lighter is the mostly SM-like Higgs boson.

Still, the parameter space of the MSSM allows to describe a Higgs boson with a mass in the 125 GeV range if certain combinations of the stop masses, stop mixings, $\tan\beta$ and the parameter M_A (essentially the heavy Higgs masses) are large enough [3–12]. This implies a fine tuning within the MSSM parameter space of the order of 1% [13], or extra matter [14]. An enhancement of $\sigma^{\gamma\gamma}/\sigma^{\gamma\gamma}_{\rm SM}$ may be possible in the presence of light staus [8].

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) [15–19] is the simplest supersymmetric (Susy) extension of the SM with a scale invariant superpotential, i.e. where the only dimensionful parameters are the soft Susy breaking terms. No supersymmetric Higgs mass term μ as in the MSSM is required, since it is generated dynamically by the vacuum expectation value (vev) of a gauge singlet superfield S and a coupling $\lambda S H_u H_d$ in the superpotential. Together with the neutral components of the two SU(2) doublet Higgs fields H_u and H_d of the MSSM, one finds three neutral CP-even Higgs states in this model. These three states mix in the form of a 3×3 mass matrix and, accordingly, the physical eigenstates are superpositions of the neutral CP-even components of H_u, H_d and S. In general, the couplings of the physical states to gauge bosons, quarks and leptons can differ considerably from the corresponding couplings of a SM Higgs boson. The possible alleviation in the NMSSM of the "little fine tuning problem" in the Higgs sector of the MSSM has been studied in [21] in the light of $2\,\mathrm{fb}^{-1}$ of data at the LHC, and in the light the recent evidence for a Higgs mass of about 126 GeV in [13] (although mostly for large values of λ, implying new strong interactions below the GUT scale).

In most of the parameter space of the NMSSM, the physical Higgs spectrum contains a heavy CP-even state, a heavy CP-odd state and a charged Higgs boson which are nearly degenerate as in the MSSM with a common mass $\sim M_A$. However, the lighter doublet-like CP-even state (corresponding to the SM-like Higgs boson H_{SM}) can mix strongly with the real part of S and form eigenstates with reduced couplings to gauge bosons, quarks and leptons [15, 16, 19, 20, 22–30]. In this case, possibly both eigenstates are visible at the LHC (see [30], where a second visible state with reduced couplings in the 140–150 GeV range has been studied, and refs. therein).

It is well known that, for small values of $\tan\beta$, the coupling $\lambda S H_u H_d$ in the superpotential leads to a positive contribution to the mass squared of the SM-like Higgs boson H_{SM} relative to the MSSM [15, 16, 19]. However, $H_{\mathrm{SM}} - S$ mixing has an additional impact on the physical spectrum: if the diagonal mass term m^2_{SS} is larger than the one of H_{SM}, the mixing reduces the mass of H_{SM}; if the diagonal mass term m^2_{SS} is smaller than the one of H_{SM}, the mixing leads to an additional increase of the mass of H_{SM}. In this latter case, the mass of the lighter eigenstate H_1 can be well below 114 GeV and compatible with constraints from LEP [31], if its reduced signal strength $\xi_1^2 \equiv \bar{g_1}^2 \times \overline{\mathrm{BR}}(H_1 \to b\bar{b})$ is small enough. (Here $\bar{g_1}$ is the reduced coupling of H_1 to the Z boson normalized with respect to the SM, and $\overline{\mathrm{BR}}(H_1 \to b\bar{b})$ is the branching ratio into $b\bar{b}$ normalized with respect to the SM.)

In addition, $H_{\mathrm{SM}} - S$ mixing can lead to an increase of the branching ratio $\mathrm{BR}(H_i \to \gamma\gamma)$ of one of the eigenstates H_i with respect to the SM: if the coupling to $b\,\bar{b}$ and hence the partial decay width into $b\,\bar{b}$ (which is close to the total width Γ_{Tot}) is strongly reduced with respect to the SM, $\mathrm{BR}(H_i \to \gamma\gamma) = \Gamma(H_i \to \gamma\gamma)/\Gamma_{\mathrm{Tot}}$ is correspondingly enhanced. This phenomenon has been discussed in the context of the lighter eigenstate H_1 in [32], but is equally possible for the heavier eigenstate as will be discussed below. In view of the latest LHC results, the possible enhancement of $\mathrm{BR}(H_i \to \gamma\gamma)$ in the NMSSM was also discussed in [13], and a Higgs mass near 125 GeV in the constrained NMSSM — but without enhancement of $\mathrm{BR}(H_i \to \gamma\gamma)$ — in [33].

In the next section we will study a region of the parameter space of the NMSSM with a scale invariant superpotential, which leads naturally to an eigenstate H_2 after $H_{\mathrm{SM}} - S$ mixing with a mass in the 124–127 GeV range. Its $\mathrm{BR}(H_2 \to \gamma\gamma)$ is always enhanced with respect to the SM. The lighter eigenstate H_1 has a mass in the 70–120 GeV range, compatible with LEP constraints, and is potentially also observable at the LHC. In section 3 we conclude and summarize the possibilities allowing to distinguish this scenario from the SM and/or the MSSM.

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2 Implications of $H_{\rm SM} - S$ mixing in the NMSSM in the light of recent and future LHC results

The NMSSM differs from the MSSM due to the presence of the gauge singlet superfield S. In the simplest Z_3 invariant realisation of the NMSSM, the Higgs mass term $\mu H_u H_d$ in the superpotential $W_{\rm MSSM}$ of the MSSM is replaced by the coupling λ of S to H_u and H_d and a self-coupling κS^3. Hence, in this simplest version the superpotential $W_{\rm NMSSM}$ is scale invariant, and given by:

$$W_{\rm NMSSM} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \dots \,, \tag{2.1}$$

where hatted letters denote superfields, and the dots denote the MSSM-like Yukawa couplings of $\hat{H}_u$ and $\hat{H}_d$ to the quark and lepton superfields. Once the real scalar component of $\hat{S}$ develops a vev s, the first term in $W_{\rm NMSSM}$ generates an effective μ-term

$$\mu_{\rm eff} = \lambda\, s\,. \tag{2.2}$$

A constraint $|\mu_{\rm eff}| \gtrsim 100\,{\rm GeV}$ follows from the non-observation of higgsino-like charginos at LEP.

The soft Susy breaking terms consist of mass terms for the Higgs bosons H_u, H_d and S, and trilinear interactions (omitting squarks and sleptons)

$$-\mathcal{L}_{\rm Soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left(\lambda A_\lambda\, H_u \cdot H_d\, S + \frac{1}{3} \kappa A_\kappa\, S^3 \right) + {\rm h.c.}\,. \tag{2.3}$$

Expressions for the mass matrices of the physical CP-even and CP-odd Higgs states — after H_u, H_d and S have assumed vevs v_u, v_d and s and including the dominant radiative corrections — can be found in [19] in will not be repeated here. As compared to two independent parameters in the Higgs sector of the MSSM at tree level (often chosen as $\tan\beta$ and M_A), the Higgs sector of the NMSSM is described by the six parameters

$$\lambda\,,\ \kappa\,,\ A_\lambda\,,\ A_\kappa\,,\ \tan\beta = v_u/v_d\,,\ \mu_{\rm eff}\,. \tag{2.4}$$

Alternatively, the parameter A_λ can be replaced by the MSSM-like parameter

$$M_A^2 = \frac{2\mu_{\rm eff} B_{\rm eff}}{\sin 2\beta}\,, \tag{2.5}$$

where $B_{\rm eff} = A_\lambda + \kappa s$.

Subsequently we are interested in regions of the parameter space where the soft Susy breaking terms are not very large (in order to avoid large fine tuning), but they have to comply with the present non-observation of sparticles at the LHC. In the gaugino, squark and slepton sectors we make the following choice, motivated to a certain extend by the renormalization group running from the GUT scale down to the weak scale (although the precise values are not very important): bino, wino and gluino masses $M_1 = 175\,{\rm GeV}$, $M_2 = 350\,{\rm GeV}$ and $M_3 = 1000\,{\rm GeV}$ respectively, squark masses of 1200 GeV (but 800 GeV for the third generation), slepton masses of 300 GeV, $A_t = A_b = -1000\,{\rm GeV}$.

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In the Higgs sector we have to keep in mind that the soft Susy breaking masses $m_{H_u}^2$, $m_{H_d}^2$ and m_S^2 are determined implicitely (through the minimization equations of the scalar potential) in terms of M_Z, $\tan\beta$ and μ_{eff}. Large values of $m_{H_u}^2$, $m_{H_d}^2$ and m_S^2 are avoided if μ_{eff}, M_A and $\tan\beta$ are relatively small. (Large values of $\tan\beta$ require small tuned values for B_{eff} in the NMSSM, unless $|m_{H_u}^2|$ and/or $|m_{H_d}^2|$ are large.) Hence we choose $\mu_{\text{eff}} = 140\,\text{GeV}$, $M_A = 300\,\text{GeV}$ and $1.7 < \tan\beta < 2$ leading to $A_\lambda \sim 140$–$200\,\text{GeV}$. Then, the interesting regions of the remaining parameters λ, κ and A_κ are determined by the conditions that i) one of the physical eigenstates in the CP-even Higgs sector (actually always H_2) has a mass in the 124–127 GeV range, and ii) the lighter eigenstate H_1 is not in conflict with LEP constraints. The density of viable points is particularly large for $0.5 < \lambda < 0.6$, $0.3 < \kappa < 0.4$ and $-250\,\text{GeV} < A_\kappa < -200\,\text{GeV}$. Of course, viable points outside this range exist as well, but these will not invalidade our subsequent conclusions.

A corresponding scan in parameter space is performed with the help of the code NMSSMTools [17, 34]; we employed the version 3.0.2 which is includes radiative corrections to the Higgs sector from [35]. Only points respecting constraints on the Higgs sector from LEP and from B physics are retained. We find that about 50% of all points in this region of parameter space respect these phenomenological constraints, and $\sim$ 5–6% ($\sim$ 550 out of 10000) lead to a Higgs boson H_2 with a mass in the 124–127 GeV range. (Of course, measurements always reduce the allowed regions in parameter space.)

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

$$\begin{aligned} H_1 &= S_{1,d}\, H_d + S_{1,u}\, H_u + S_{1,s}\, S\,, \\ H_2 &= S_{2,d}\, H_d + S_{2,u}\, H_u + S_{2,s}\, S\,. \end{aligned} \tag{2.6}$$

Then the reduced tree level couplings (relative to a SM-like Higgs boson) of H_i to b quarks, τ leptons, t quarks and electroweak gauge bosons V are

$$\begin{aligned} \frac{g_{H_i bb}}{g_{H_{\text{SM}} bb}} &= \frac{g_{H_i \tau\tau}}{g_{H_{\text{SM}} \tau\tau}} = \frac{S_{i,d}}{\cos\beta}\,, \qquad \frac{g_{H_i tt}}{g_{H_{\text{SM}} tt}} = \frac{S_{i,u}}{\sin\beta}\,, \\ \bar{g}_i \equiv \frac{g_{H_i VV}}{g_{H_{\text{SM}} VV}} &= \cos\beta\, S_{i,d} + \sin\beta\, S_{i,u}\,. \end{aligned} \tag{2.7}$$

For the low values of $\tan\beta$ considered here, the couplings of Higgs bosons to gluons (relevant for their production) and to photons are induced by loop diagrams dominated by top-quark loops. As stated above, the branching ratios into two photons can be enhanced, if the coupling to b-quarks is reduced, which is the case if $S_{i,d}$ is small.

Subsequently we are interested in the signal strength $\sigma_2^{\gamma\gamma} = \sigma_{\text{prod}} \times \text{BR}(H_2 \to \gamma\,\gamma)$ relative to the SM, $R_2^{\gamma\gamma} = \sigma_2^{\gamma\gamma}/\sigma_{\text{SM}}^{\gamma\gamma}$. $R_2^{\gamma\gamma}$ is the product of two factors: i) the reduced coupling of H_2 to gluons, which is essentially given by $g_{H_2 tt}/g_{H_{\text{SM}} tt}$ (but contributions from non-SM particles in the loop are taken into account), and ii) the $\overline{\text{BR}}(H_2 \to \gamma\,\gamma)$, the branching ratio of H_2 into $\gamma\,\gamma$ normalized with respect to the corresponding branching

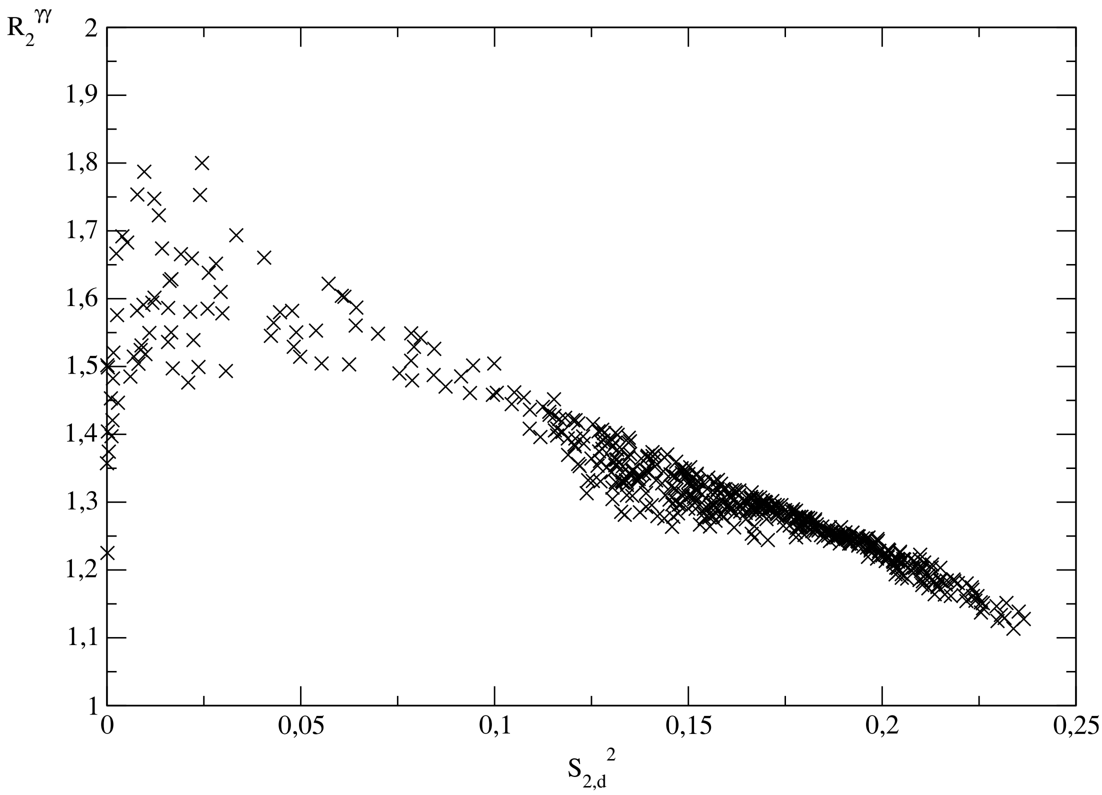

Figure 1. The relative signal rate $R_2^{\gamma\gamma} = \sigma_2^{\gamma\gamma}/\sigma_{\rm SM}^{\gamma\gamma}$ as function of $S_{2,d}^2$, for H_2 with a mass in the 124–127 GeV range for about 550 points in the parameter space of the NMSSM described in the text.

ratio of a SM-like Higgs boson of the same mass.[1] $\overline{\rm BR}(H_2 \to \gamma\gamma)$ can be considerably larger than 1. In figure 1 we show $R_2^{\gamma\gamma}$ as function of $S_{2,d}^2$ for $\sim$ 550 points in the region of the parameter space of the NMSSM described above, in which M_{H_2} is in the 124–127 GeV range. We see that $R_2^{\gamma\gamma}$ is *always* larger than 1.1, with an expected dependence on $S_{2,d}^2$.

If one modifies somewhat the soft Susy breaking squark and slepton masses (and trilinear couplings A) at the weak scale, the parameters can be mapped to a semi-constrained version of the NMSSM together with non-universal soft Higgs masses at the GUT scale as studied in [33] (where additional regions in the parameter space of the NMSSM with M_{H_1} or $M_{H_2} \sim 124 \ldots 127$ GeV have been found). One obtains $M_{1/2} \sim 500$ GeV, $m_0 \sim 500 \ldots 700$ GeV, $A_0 \sim -900 \ldots -950$ GeV, for the soft terms involving the singlet $m_S \sim 1$ TeV, $A_\lambda \sim -400$ GeV, $A_\kappa \sim -300$ GeV, and for the soft Higgs masses $m_{H_u} \sim 1.5$ TeV, $m_{H_d} \sim m_0$. Due to the low value of $\tan\beta$ (leading to a relatively large value of the top Yukawa coupling h_t) and the large values of λ, κ at the weak scale, all 3 Yukawa couplings

[1] The branching ratios of SM-like Higgs bosons are computed in a subroutine hadecay.f within NMSSM-Tools, such that radiative corrections are included at the same level of accuracy. In fact, QCD corrections cancel in the ratio of branching ratios NMSSM/SM. The routines for the branching ratios of NMSSM- and SM-like Higgs bosons are based on modified versions of HDECAY [36].

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are of $\mathcal{O}(1)$ at the GUT scale: $h_t \sim 1.2 \ldots 1.3$, $\lambda \sim 1.3 \ldots 1.7$, $\kappa \sim 0.7 \ldots 1.0$.[2] The fact that all 3 Yukawa couplings are close to (but just below) a Landau singularity at the GUT scale is intriguing.

Next we turn to the lighter Higgs boson H_1 in this scenario. Its mass is in the 70–120 GeV range. The most relevant search channels in this mass range are again the $\gamma\gamma$ mode, but also $H_1 \to \tau\tau$ (with H_1 produced by vector boson fusion, VBF) and, to some extent, $H_1 \to b\bar{b}$ with H_1 produced in association with W or Z bosons. The reduced signal strength in the $\gamma\gamma$ mode, $R_1^{\gamma\gamma} = \sigma_1^{\gamma\gamma}/\sigma_{\mathrm{SM}}^{\gamma\gamma}$, can be obtained as above. The reduced signal strength in the $\tau\tau$ mode and VBF, $R_1^{\tau\tau} = \sigma_1^{\tau\tau}/\sigma_{\mathrm{SM}}^{\tau\tau}$, is the product of the reduced coupling $\bar{g}_1^2$ of H_1 to the electroweak gauge bosons, and the $\overline{\mathrm{BR}}(H_1 \to \tau\tau)$, the branching ratio of H_1 into $\tau\tau$ normalized with respect to the corresponding branching ratio of a SM-like Higgs boson of the same mass. (The reduced signal strength in the $b\bar{b}$ mode is practically the same as $R_1^{\tau\tau}$, since it is again proportional to the coupling to electroweak gauge bosons, and the branching ratio into $b\bar{b}$ remains proportional to the branching ratio into $\tau\tau$.)

In figure 2 we show $R_1^{\gamma\gamma}$ and $R_1^{\tau\tau}$ as function of M_{H_1}. We see that $R_1^{\gamma\gamma}$ is not enhanced, but mostly strongly reduced due to the small coupling of H_1 to two gluons, which is *not* compensated by an enhanced branching ratio into two photons in this case. Hence, except perhaps for $M_{H_1} \gtrsim 110$ GeV, the prospects for a discovery of H_1 in this channel are not rosy. Likewise, $R_1^{\tau\tau}$ ($\simeq R_1^{b\bar{b}}$) is not enhanced, but not as small as $R_1^{\gamma\gamma}$. Actually the upper bound on $R_1^{\tau\tau}$ coincides with the upper LEP bound on $\xi_1^2 \equiv \bar{g}_1{}^2 \times \overline{\mathrm{BR}}(H_1 \to b\bar{b})$ as function of M_H [31], which is not astonishing given that $\overline{\mathrm{BR}}(H_1 \to b\bar{b}) \sim \overline{\mathrm{BR}}(H_1 \to \tau\tau)$. Hence, although a discovery of H_1 in the $\tau\tau$ channel (or $b\bar{b}$ mode) is not guaranteed, this is not excluded in particular after future high luminosity runs of the LHC or if its mass is in the 110–120 GeV range.

3 Conclusions

We have presented a natural region in the parameter space of the NMSSM, where the NMSSM-specific coupling λ and mixing effects push up the mass of a CP-even Higgs boson into the 124–127 GeV range without the need for excessive radiative corrections from heavy sparticles. The relative signal rate in the $\gamma\gamma$ channel is always enhanced by a factor 1.1–1.8 with respect to a SM-like Higgs boson of the same mass. This Higgs boson complying with recent evidence from the ATLAS and CMS collaborations is accompagnied by a lighter CP-even neutral Higgs state.

Under the following circumstances it might be possible to distinguish this scenario from the SM and/or the MSSM:

- the enhanced signal rate in the $\gamma\gamma$ channel is confirmed, and incompatible with a SM-like Higgs boson;

[2] For such large Yukawa couplings, the solution of renormalization group equations for the running parameters with boundary conditions both at the weak *and* the GUT scale is a delicate issue leading to convergence problems. In fact, the public version of the code NMSPEC inside NMSSMTools [37] has to be modified for a study of this region.

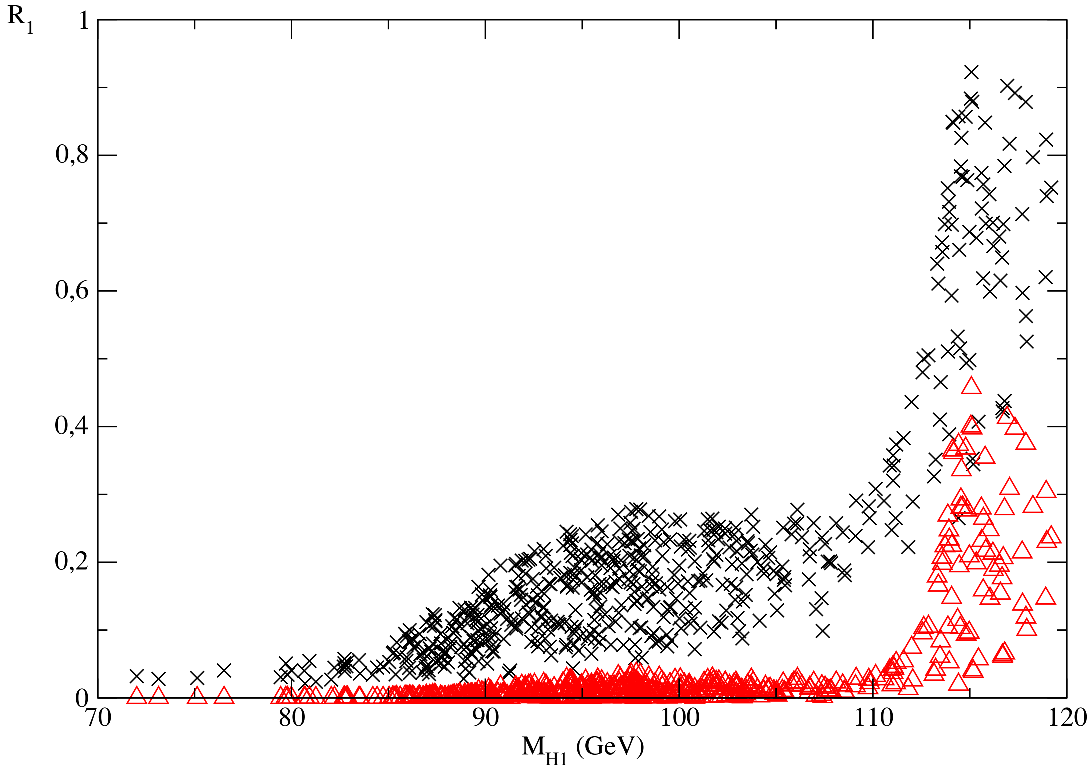

Figure 2. The relative signal rate $R_1 = R_1^{\gamma\gamma} = \sigma_1^{\gamma\gamma}/\sigma_{\mathrm{SM}}^{\gamma\gamma}$ (red triangles) and $R_1 = R_1^{\tau\tau} = \sigma_1^{\tau\tau}/\sigma_{\mathrm{SM}}^{\tau\tau}$ (black crosses) as function of M_{H_1}, for about 550 points in the parameter space of the NMSSM described in the text.

- sparticles are detected, and their masses turn out to be incompatible with the necessarily large radiative corrections to the Higgs mass in the MSSM;
- the lighter CP-even state H_1 is discovered.

Of course, first of all the present evidence for a Higgs boson into the 124–127 GeV range should be confirmed by more data; then the same data can give us possible hints for non-SM-like properties of the Higgs sector along the lines discussed here.

Acknowledgments

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