Detecting the Higgs boson(s) in λSUSY

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Abstract

We reconsider the Higgs bosons discovery potential in the λSUSY framework, in which the masses of the scalar particles are increased already at tree level via a largish supersymmetric coupling between the usual Higgs doublets and a Singlet. We analyze in particular the interplay between the discovery potential of the lightest and of the next-to-lightest scalar, finding that the decay modes of the latter should be more easily detected at the LHC.

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1 Introduction

The quest for the nature of the Electroweak Symmetry Breaking (EWSB) mechanism is reaching its most important phase: with an integrated luminosoty of 2.3 fb^{-1}, the combined CMS-Atlas data exclude at 95% C.L. a Standard Higgs boson mass in the $(141 \div 476)$ GeV range [1].
Of course, since in many extensions of the Standard Model (SM) the Higgs boson is far from being standard (both in its production and decay modes), the presence of such a scalar triggering EWSB is not yet excluded.

Supersymmetry is surely one of the best motivated extension of the SM, since it stabilizes the Electroweak scale against radiative corrections. Despite this, in the Minimal Supersymmetric Standard Model (MSSM), the tree level Higgs boson mass is bounded from above at most by the Z boson mass ($m_h \leq m_Z|\cos 2\beta|$), so that one must rely on considerable radiative corrections in order to satisfy the LEP bound. At the same time, since in wide regions of the parameter space the MSSM Higgs boson has standard couplings, it is now highly constrained by the LHC. This may be an indication that the theory must be augmented with an additional Singlet field, whose coupling λ with the two standard Higgs bosons allows to increase the previous upper bound to $m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$.

This case was studied extensively in the literature, known as Next to Minimal Supersymmetric Standard Model (NMSSM, for comprehensive reviews, see [2, 3]), with a superpotential given by $W = \lambda S H_1 H_2 + (k/3) S^3$. Not only the Singlet field allows one to increase the tree level upper bound on the Higgs boson mass but also the scalars production and decay rates are changed, since in general they will now have a Singlet component that does not interact with the SM matter or gauge fields.

A crucial point for the phenomenology of the model is the value of the trilinear coupling λ. The most studied situation is the one in which perturbativity is retained up to the GUT scale, so that at low energy an upper bound $\lambda \lesssim 0.7$ holds. The mass of the lightest scalar can be below the LEP bound, but we no longer need it to be above 114 GeV since its couplings are no longer standard, both in production and in decay. What is interesting is that there can be a sort of inversion of roles between the lightest and the next-to-lightest scalar, with the latter that can be more similar (in a sense to be made more precise later) to the SM Higgs boson. This "No-Lose" theorem in which at least one of the NMSSM scalars should be discovered at the LHC relies on the assumption that Higgs-to-Higgs or Higgs-to-SUSY decays are kinematically not allowed [4–14], while important violations are possible once one or both the previous assumptions are relaxed [15–18].

Dropping the requirement of perturbativity up to the GUT scale, λ can take larger values at the EW scale (*i.e* requiring perturbativity up to 10 TeV increases the low energy upper bound to $\lambda \lesssim 2$). Since in this case the tree level mass of the scalars can take values up to $(200 \div 250)$ GeV, naturalness is improved. This situation has been recently studied in [19–21], where it has been shown that the behavior of the lightest scalar in this "λSUSY" framework[1] can be quite similar to the one of the usual NMSSM[2].

[1]We call this framework λSUSY to stress the importance of the higher value of the λ coupling.

[2]Although there are also regions in which it is simply a heavier standard Higgs boson (resembling what happens in other realizations of λSUSY, see [22, 23]) and is thus now excluded.

k	Masses (GeV)			BRs				$\frac{\sigma(pp\to s)}{\sigma(pp\to h_{SM})}$	ξ
	m_{A_1}	m_{χ_1}	m_s	A_1A_1	ZA_1	$\chi_1\chi_1$	WW		
-0.2	103	130	252	0.54	0.01	0	0.31	0.38	0.17
			284	0.032	0.324	0.043	0.41	1.06	0.62
	95	77	163	0	0	0.8	0.06	0.56	0.04
			204	0.4	0	0.143	0.33	0.82	0.37
	108	96	173	0	0	0	0.79	0.69	0.57
			243	0.412	0	0.086	0.35	0.70	0.35
-0.6	166	78	160	0	0	0.72	0	0.38	10^{-4}
			194	0	0	0.189	0.61	1	0.8
	195	120	232	0	0	0	0.69	0.04	0.04
			248	0	0	0.001	0.70	1.4	1.3
	168	133	218	0	0	0	0.71	0.52	0.5
			318	0	0.21	0.145	0.44	0.92	0.6

Table 1: Masses and Branching Fractions for some relevant points in parameter space. The first row in each group always refers to s_1, the second one to s_2. The mass of s_3 is always larger than about 500 GeV, while the second pseudoscalar has mass large enough to never be relevant in the decay channels of the particles of interest. The parameters are chosen as follows: $\lambda = 2$, $\tan\beta = 1.5$; for $k = -0.2$ the points refer respectively to $(\mu\ (\text{GeV}), m_H\ (\text{GeV})) = (180, 340),\ (105, 180),\ (130, 200)$, while for $k = -0.6$ they refer to $(\mu\ (\text{GeV}), m_H\ (\text{GeV})) = (105, 180),\ (160, 280),\ (180, 370)$. In the last two columns we present the ratio between the production cross section via gluon-gluon fusion for the relevant scalar and a Standard Model Higgs boson [19, 21] and ξ (Eq. 2.4).

It is then interesting to see whether the "No-lose" theorem, which seems to be valid under certain assumptions for the NMSSM with small λ, can be somehow extended to the λSUSY case. This seems to be possible at least in ample regions of the parameter space, as we will see in more detail in the next Section.

2 Notation and plots

Let us now briefly explain our notation (for a detailed discussion about the scalar potential and the parameter space that we are considering we refer the reader to [19–21, 24]). We define our model through

$$\begin{aligned} W &= \lambda S H_1 H_2 + \frac{k}{3} S^3 , \\ V_{SSB} &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_S^2 |S|^2 - \left(\lambda A S H_1 H_2 + \frac{kG}{3} S^3 + h.c. \right) , \end{aligned} \tag{2.1}$$

with scalar particles defined by

$$H_{1,2} = v_{1,2} + \frac{h_{1,2} + ia_{1,2}}{\sqrt{2}}, \quad S = v_s + \frac{S_1 + iS_2}{\sqrt{2}}. \tag{2.2}$$

The model has 7 parameters (λ, k, m_1^2, m_2^2, m_S^2, A, G), that can be reduced to 6 using the minimum conditions and considering that one combination is fixed by the vev $v = \sqrt{v_1^2 + v_2^2} \simeq$ 174 GeV. We are left with

$$\lambda, \quad k, \quad \tan\beta, \quad \mu, \quad m_H, \quad A/G \tag{2.3}$$

where $\mu = \lambda v_s$ is the higgsino mass parameter and m_H the charged Higgs boson mass. In what follows we will choose for simplicity $A/G = 1$, but we have checked that changing this value does not affect in a consistent way our conclusions.

In the neutralino sector there is also a dependence on the Majorana gaugino masses $M_{1,2}$. For concreteness, in the following we will set $M_2 = 2$ TeV and $M_1 = 200$ GeV having in mind a possible bino-higgsino well-tempered DM candidate [25][3].

We choose to present our results in the (μ, m_H) plane to deal with physical parameters. The allowed regions in parameter space are found considering properly the minimum conditions and the requirement of CP conservation in the scalar sector [19, 21].

In what follows we will always take $\lambda = 2$, $|k| \lesssim 0.7$ and $\tan\beta = 1.5$. Such a large value for λ is the characteristic feature of our model, since it allows to increase the Higgs boson mass up to $(200 \div 250)$ GeV. We are then requiring semiperturbativity up to 10 TeV or so, and this motivates the upper bound on k (for $k \simeq 0.7$ at the EW scale this coupling becomes semiperturbative at 10 TeV). The rather low value for $\tan\beta$ is instead due to requirement of consistency with the ElectroWeak Precision Tests. In what follows, we will choose two representative values for k, $k = -0.2$ and $k = -0.6$: for intermediate values the overall conclusion is similar, although a few details may change.

The physical scalar particles will be called $s_{1,2,3}$ in the CP-even sector and $A_{1,2}$ in the CP-odd sector, all named in increasing order of masses. For our discussion, s_3 and A_2 are not significant, since the mass of the heaviest scalar is always above 500 GeV while the mass of A_2 is large enough to be irrelevant in the decays of the two lightest scalars.

The crucial quantity we want to analyze is

$$\xi_i = \frac{\sigma(pp \to s_i)\mathrm{BR}(s_i \to VV)}{\sigma(pp \to h_{SM})\mathrm{BR}(h_{SM} \to VV)} \tag{2.4}$$

with h_{SM} the usual Standard Model Higgs particle and V any of the vector bosons, since these channels are the most sensitive for the range of masses of interest.

Our results are summarized in Figs. 1, 2, where we show the masses of the first two scalar and the isolines of ξ in the allowed parameter space. For the lightest scalar, $\xi \lesssim 0.5$ in most of the parameter space, while this is not the case for the next-to-lightest scalar, for which $\xi \gtrsim 0.3$. The reasons for such a behavior are rather clear and are summarized in Table 1, where we present the relevant quantities choosing some representative points in parameter space.

[3]This can be justified since the singlino component of the LSP is always below 10% for our choice of parameters.

The lightest scalar s_1 has a reduced coupling to $t\bar{t}$ that suppresses the production cross section via gluon-gluon fusion, and at the same time it prefers to decay into $b\bar{b}b\bar{b}$ (through the intermediate decay into a pair of lightest pseudoscalars) or into a pair of neutralinos $\chi_1\chi_1$. On the contrary, s_2 has a production cross section much more similar to the Standard Higgs boson (in some cases even higher) that compensates possible depletions in the branching fraction into vectors due to decays into $A_1 A_1$ or $\chi_1\chi_1$, so that the overall effect is to increase the value of ξ with respect to the one of the lightest scalar.

3 Conclusions

With an integrated luminosity of about 2 fb^{-1}, the LHC is probing ample mass regions not only of the Standard Higgs boson, but also of many interesting SM extensions. In this paper we focused on λSUSY with a scale invariant superpotential, showing the typical values of ξ (the key quantity probed by the experiments) for the lightest and the next-to-lightest scalars.

The message is quite clear: the next-to-lightest scalar is more similar to a standard Higgs boson than the lightest one, and gives in general larger values of ξ, although its behavior depends on k, the cubic self coupling of the Singlet. Since the sensitivity of the LHC in the vector channels has allowed to already probe values down to $\xi \simeq (0.5 \div 0.6)$ [1], it is clear that the parameter space is becoming more and more constrained. Our plots seems to indicate that higher values of k are by now disfavored, while some regions in parameter space are still allowed for lower values of k, so that the Peccei-Quinn symmetric limit $k = 0$ seems to be still viable. It is plausible that the LHC will be able to probe other regions of parameter space in the next two years, so we will learn more on the nature of the Electroweak symmetry breaking rather soon.

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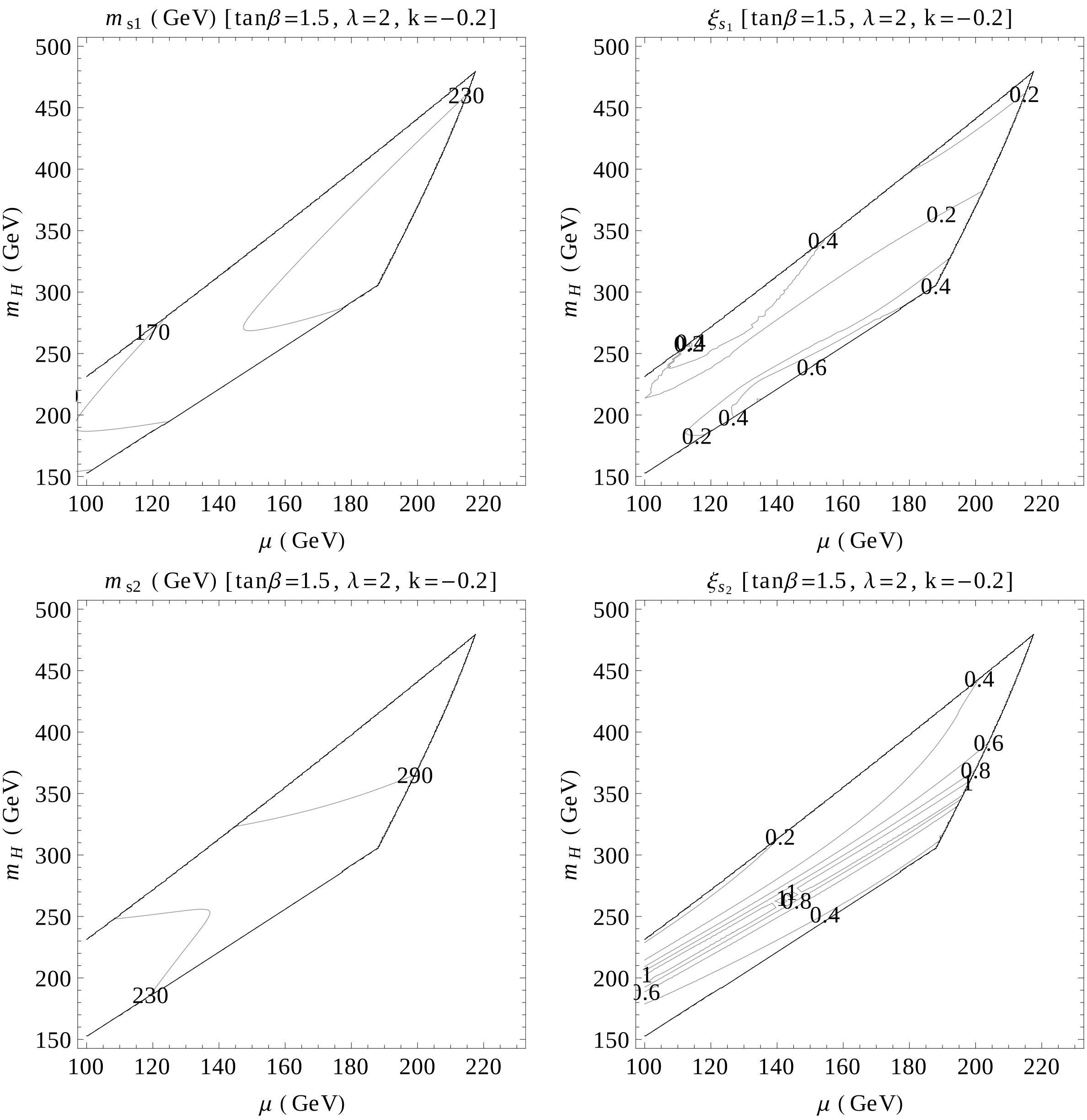

Figure 1: Isolines of the mass (left panels) and of ξ (right panels) for the two lightest scalars in the $k = -0.2$ case. The other parameters are fixed as: $\lambda = 2$, $\tan\beta = 1.5$, $M_1 = 200$ GeV, $M_2 = 2$ TeV.

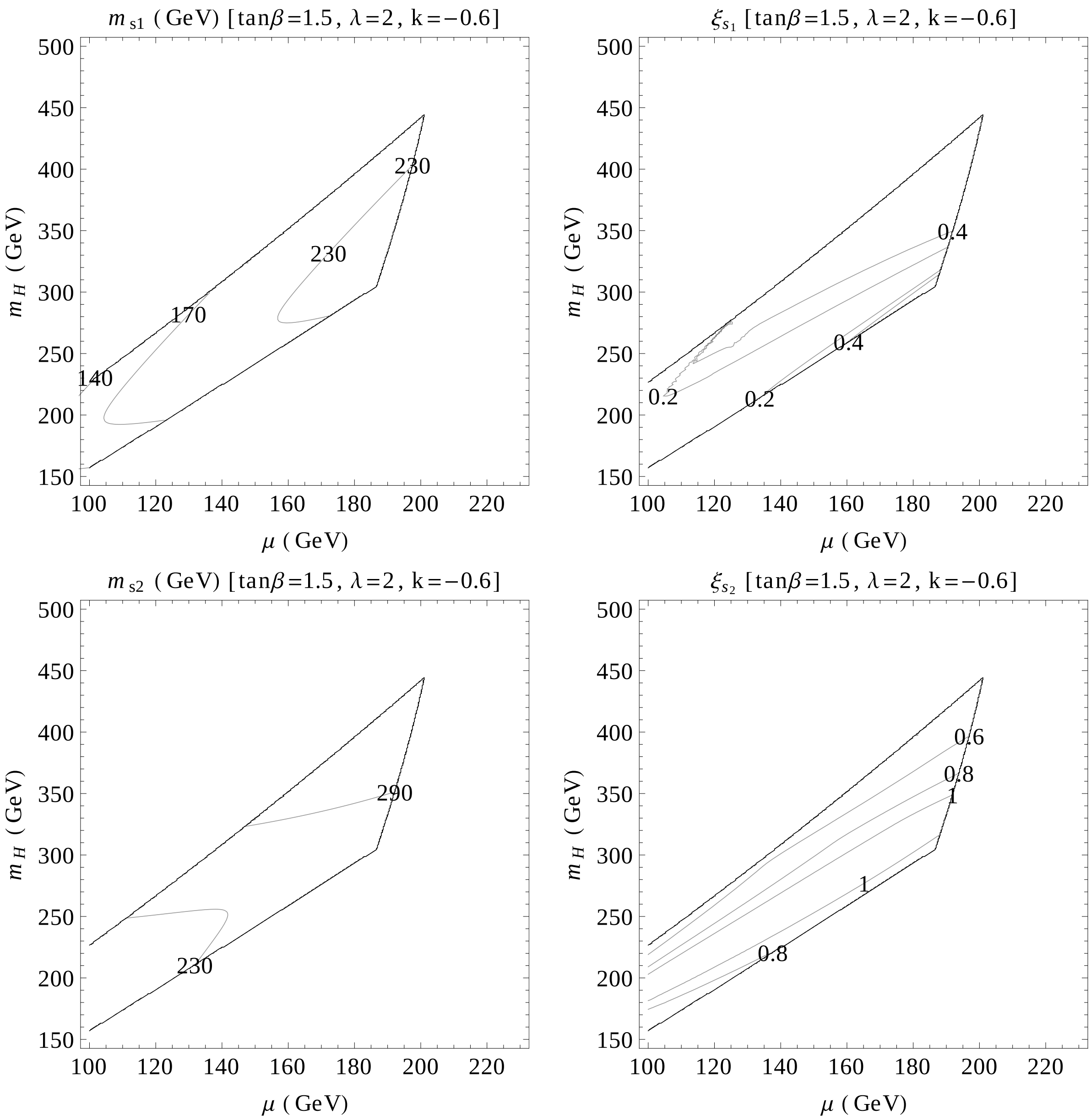

Figure 2: Isolines of the mass (left panels) and of ξ (right panels) for the two lightest scalars in the $k = -0.6$ case. The other parameters are fixed as: $\lambda = 2$, $\tan\beta = 1.5$, $M_1 = 200$ GeV, $M_2 = 2$ TeV.