

Supersymmetric LHC phenomenology without a light Higgs boson

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Abstract. After a brief discussion of the mass of the Higgs in supersymmetry, I introduce λ SUSY, a model with an extra chiral singlet superfield in addition to the MSSM field content. The key features of the model are: the superpotential $W = \lambda SH_d H_u$ with a large coupling λ and the resulting lightest Higgs with mass above 200 GeV. The main part of my contribution will be about how λ SUSY manifests itself at the LHC. Discoveries of gluino, squarks and in particular of the three lightest neutral Higgs bosons are discussed.

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1 Introduction

Soon the LHC will exploit its potential for a early discovery of a Higgs boson and, in case it is heavier than 140 GeV, the MSSM will be ruled out. The same conclusion applies to the majority of supersymmetric models, which, under the assumption of perturbative gauge coupling unification, cannot have a Higgs heavier than 200 GeV [3]. This generic lightness of the Higgs can receive some support from the EWPT, which find $m_h = 76_{-24}^{+33}$ GeV [1] at 65% C.L in the SM. However, this result could be misleading for beyond standard model (BSM). Indeed the SM result extends to BSM only with the assumption that the new physics, while cutting off top (and gauge boson) loops, does not itself contribute significantly to the EWPT parameters S and T . Scenarios of BSM not respecting this assumption have been realized in simple explicit models [2], finding an interesting and alternative LHC phenomenology. In this contribution I will deal with the phenomenology of one of these alternative scenarios, λ SUSY, which in this discussion seems particularly motivated. In fact it's supersymmetric and has a lightest Higgs naturally above 200 GeV [4].

The field content of λ SUSY is that of the MSSM plus a chiral singlet superfield S . The key feature of the model is the presence of the superpotential interaction

$$W = \lambda SH_d H_u$$

with a large coupling λ . The maximal value of λ is limited by the assumption that it stays perturbative up to about 10 TeV, so that the incalculable contribution to the EWPT from the cutoff can be neglected¹.

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¹ Taking $\lambda = 2$ at the Fermi scale, the Landau pole is at about 50 TeV, which can be interpreted as the composite-

2 The model

The full λ SUSY superpotential and the resulting scalar potential are:

$$W = \mu(S)H_1 H_2 + f(S), \quad \lambda = \mu'(S), \\ V = \sum_i \mu_i^2(S)|H_i|^2 - (\mu_3^2(S)H_1 H_2 + \text{h.c.}) + \\ + \lambda^2 |H_1 H_2|^2 + V(S) + \dots,$$

where the dots stand for negligible D-terms. Assuming the scalar S is heavy and not mixed, the mass eigenstates are the same as in the MSSM: two CP-even bosons, h and H , one CP-odd pseudo-scalar, A , and one charged Higgs, H^\pm ². Using results of [4], the spectrum can be given in terms of m_{H^\pm} , $\tan\beta$ and λ . For $\lambda = 2$, the EWPT, Naturalness and $b \rightarrow s\gamma$ determine the preferred parameter space [4, 8]:

$$1.5 \lesssim \tan\beta \lesssim 3, \quad 350\text{GeV} \lesssim m_{H^\pm} \lesssim 700\text{GeV}. \quad (1)$$

Masses of neutral scalars in this range of parameters are given in Fig. 1. The key feature of the spectrum is that the lightest Higgs boson h is in the 200 – 300 GeV range, hence much heavier than in MSSM or NMSSM. Another notable feature is the fixed ordering of the spectrum: $m_h < m_{H^\pm} < m_H < m_A$ (see Fig. 1).

It should be noticed that this model also has a Higgsino-like DM candidate (see details in [4]).

3 Early (puzzling) discoveries

As in more standard supersymmetric models, also in λ SUSY there are strongly-interacting superpartners.

ness scale of (some of) the Higgs bosons [5], [6]. Ref. [6] also provides a UV completion compatible with gauge coupling unification.

² Analysis of concrete examples shows that singlet admixture in h, H, A typically stays below 0.2 – 0.3.

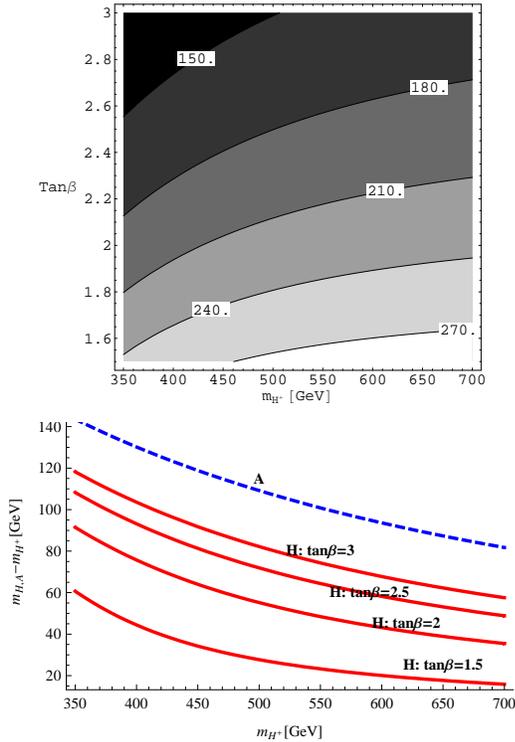


Fig. 1: m_h (up) and the mass differences $m_H - m_{H^\pm}$ (down, solid red lines, $\tan\beta = 1.5, 2, 2.5, 3$) and $m_A - m_{H^\pm}$ (down, dashed blue line) as a function of m_{H^\pm} and $\tan\beta$ in the preferred region (1) of the parameter space for $\lambda = 2$.

The $O(\text{pb})$ cross section makes them interesting candidates for early discovery of SUSY at the LHC. As explained below, also the Higgs boson h should be discoverable in the early phase.

Glino and stop Naturalness can be used to bound gluino and stop masses. According to [4] they have to satisfy

$$m_{\tilde{t}} \lesssim 800\text{GeV}, \quad m_{\tilde{g}} \lesssim 1.6\text{TeV},$$

while the masses of the electroweak gauginos, sleptons and all the other squarks, do not have significant bounds. Even assuming the less favorable scenario where only \tilde{t} and \tilde{g} are light enough to be produced, we expect an early discovery of these superpartners through their usual cascade decays [13, 14]. For a rough estimate of the discovery potential we can use the existing study [9] valid in the case of effective supersymmetry [10]. We conclude that 10fb^{-1} of integrated luminosity (\mathcal{L}) should be enough for a discovery of SUSY in the entire range of stop and gluino masses suggested by Naturalness.

The lightest Higgs The light Higgs mass is about 200-300 GeV and its coupling to SM particles are very close to the SM Higgs value. In [7] has been found that the impact of couplings to superpartners is very limited. Thus, we estimate the discovery potential of this Higgs boson using standard model studies [13], [14]. We expect an early discovery of this Higgs boson in the “gold-plated” channel $h \rightarrow ZZ \rightarrow l^+l^-l^+l^-$, with $\mathcal{L} = 5\text{fb}^{-1}$.

For what we have said in the Introduction, the discovery of such a heavy Higgs boson together with the discovery of superpartners could be puzzling. λSUSY is a possible solution to this puzzle, therefore we should look closer to the heavier scalars and ask ourselves if their detection can give an experimental evidence for this model. To this aim we assume h , \tilde{g} and \tilde{t} have been observed and m_h is known, then we turn to study the discovery reach for H and A.

4 Investigation of λSUSY

The heavy CP-even scalar From Fig. 1 we see that the heavy CP-even Higgs boson H has mass in the 500-800 GeV range. Interactions of H are described in [7] where the following results were found. The H is a quite narrow resonance, its width ranges from 5 to 40 GeV. Whenever it is kinematically available, there is a dominance of the $H \rightarrow hh$ decay mode. This can be ascribed to the large λ , which enters quadratically in the expression for the Hhh coupling. The stop gets decoupled as it gets heavier and assuming $m_{\tilde{t}_1} > 400\text{GeV}$ one can neglect couplings to stop. In [4, 7] interactions with Higgsinos have been studied. They depend on μ and on the mass of the heavy scalar S. In our concrete study we take a small value for the $H\chi\chi$ coupling, that is we maximize the branching fraction of H into standard model particles. This can be thought as a favorable condition for H discovery³.

To assess LHC’s potential for H discovery we choose a rather generic point of the parameter space (1):

$$\tan\beta = 2, \quad m_{H^\pm} = 500\text{GeV}, \quad (2)$$

and study possible detection strategies. Relevant particle properties for the choice of parameters Eq. (2) are given in Table 1. For plots of these quantities in the whole parameter space Eq. (1) we refer to [7].

σ_H^{GF}	m_H	Γ_H	m_h	Γ_h
150 fb	555 GeV	21 GeV	250 GeV	3.8 GeV
σ_H^{VBF}	$\frac{g_{Htt}^2}{g_{Htt,SM}^2}$	$\frac{g_{HVV}^2}{g_{HVV,SM}^2}$	$\mathcal{B}_{(H \rightarrow hh)}$	$\mathcal{B}_{(H \rightarrow VV)}$
27 fb	0.058	0.060	0.76	0.2
σ_A^{GF}	m_A	Γ_A	$\mathcal{B}_{(A \rightarrow hZ)}$	$\mathcal{B}_{(A \rightarrow t\tilde{t})}$
0.7pb	615GeV	11 GeV	0.2	0.76

Table 1: Particle properties at the point Eq. (2). VBF means vector boson fusion. \mathcal{B} means branching fraction. $g_{,SM}$ are the couplings of a same mass SM Higgs boson.

From Table 1 we see that H is mainly produced via gluon fusion (GF), thus, in the following we will consider only this channel.

Once produced, most of the H s will decay into hh and then into $4V$, resulting in $\sigma_{tot}(gg \rightarrow H \rightarrow 4V) = 110\text{fb}$ (V means both Z and W). To have a sizeable final state cross section we cannot demand more than one leptonic decay of these weak bosons. Our choice

³ Inclusion of H decays into Higgsinos lessens the final result at worse by a factor 0.5.

for a quantitative study is therefore:

$$gg \rightarrow H \rightarrow hh \rightarrow 2Z2V \rightarrow l^+l^-6J, \quad (3)$$

Signal is defined with $J = \{u, d, c, s, b, g\}$ and has been produced with MADGRAPH [15], which yields

$$\sigma \times BR = 2.67\text{fb}.$$

For the H mass values we are interested in, the relevant background (BG) sources of l^+l^-6J events are the $Z6J$ and $t\bar{t}Z$ ⁴. The latter has been simulated with MADGRAPH while for $Z6J$ we used specific ALPGEN [17] codes for $Z6j$ and $ZQ\bar{Q}4j$ ($Q = b, c$).

Restricting event invariant mass in a $O(100\text{GeV})$ interval around m_H , the total BG cross section is a factor 2000 bigger than that of the signal. To increase the S/B ratio we exploit the presence of intermediate resonances (h, W, Z) in the signal. Thus we enforce *reconstruction cuts* on both signal and BG, i.e. we require that the intermediate state resonances be reconstructed by final state jets and leptons. This is the main tool we use in our analysis.

All samples are analyzed with ROOT [16]. We don't do neither showering nor jet reconstruction simulation, in fact our analysis is completely partonic. We also ignore flavor tagging and trigger issues, but our inclusive definition of jet, J , and final selection cuts Eq. (4), respectively, make these simplifications fully justified. However, in order to make the analysis more realistic, we do introduce a smearing of energies of individual jets. The smearing coefficient is generated using the expression⁵ $\sigma/E = 0.5/\sqrt{E/\text{GeV}} + 0.03$. After smearing, we impose the kinematical cuts:

$$\begin{aligned} \Delta R_{JJ} > 0.7, \quad p_T^J > 20\text{GeV}, \quad \eta_J < 2.5, \quad (4) \\ \Delta R_{lJ} > 0.4, \quad p_T^l > 10\text{GeV}, \quad \eta_l < 2.5, \\ |m_{ll} - m_Z| < 10\text{GeV}, \end{aligned}$$

where m_{ll} denotes leptons pair invariant mass.

The signal events passing these cuts correspond to 0.42(1) fb cross section while BG's cross section is still orders of magnitudes larger. Finally, we impose the *reconstruction cuts*, proceeding as follows.

R1. For each event we try to group the 6 final jets into 3 pairs so that the jets in each pair *reconstruct* a W or a Z . By this we mean that the invariant mass m_{inv} of each pair has to satisfy the requirement:

$$|m_{inv} - M_V| \leq \delta_V, \quad \delta_V = 8\text{GeV}, \quad V \in \{W, Z\} \quad (5)$$

R2. If a grouping into jet pairs reconstructing a W or a Z each is found, we proceed to impose a further condition that two h 's be reconstructed by four jets from two of these three pairs, say pair 1 and 2, and by two jets of pair 3 and the two leptons. In this case the precise reconstruction cut that we used is

$$\begin{aligned} |m_{pair_1+pair_2} - m_h| \leq \delta_h, \quad \delta_h = 18\text{GeV}, \quad (6) \\ |m_{pair_3+l+l^-} - m_h| \leq \delta_h/\sqrt{2}, \end{aligned}$$

⁴ All the details about the identification of relevant BG sources and their simulation can be found in [7].

⁵ This is one of the values discussed in Table 9-1 of [13].

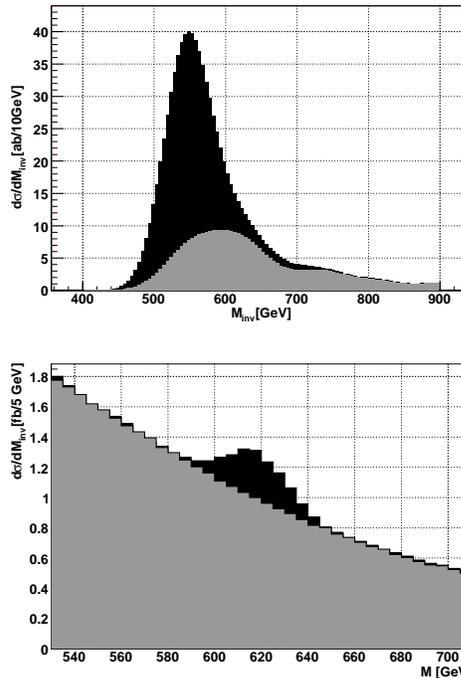


Fig. 2: Differential cross section against event invariant mass. Black is λ SUSY at the benchmark point (2), while grey is the SM background. The upper plots refer to the process (3), while the lower plot refers to the process (7).

where $m_{pair_1+pair_2}$ and $m_{pair_3+l+l^-}$ are the invariant masses of the $4J$ and $2Jl^+l^-$ final states⁶. We also check that the gauge boson reconstructed by the jets of pair 3 is a Z , while the two gauge bosons reconstructed by the jets of pairs 1 and 2 are of the same type (both W or both Z). If no grouping of 6 jets into 3 pairs satisfying both R1 and R2 can be found (we go over all combinations), the event is rejected.

We ran the reconstruction analysis on the signal sample and on each of the relevant BG samples. Resulting total cross sections *after the reconstruction cuts* are 0.286(9)fb and 0.40(1)fb, respectively. Distribution of the signal+BG and of BG-only cross section versus the total invariant mass of the event is shown in the upper panel of Figure 2. From this figure it is apparent that the rejection efficiency of our procedure is high enough to unveil the signal. In particular, we see that signal and BG peak in the same invariant mass range. The discovery of H will thus come from an overall excess of events compared to the SM prediction, as well as from the enhanced prominence of the SM peak. For $\mathcal{L} = 100\text{fb}^{-1}$, the expected number of events passing all the cuts is 20 in the SM, and 49 in λ SUSY at the benchmark point (2), giving 3.4σ if one uses the significance estimator given in Eq. (A.3) of [14]. Of course, once this global excess is found, it is worth to scan the invariant mass range to find where the excess is localized. For instance, for $510\text{ GeV} < M_{inv} < 590\text{ GeV}$ we have 3 events in the SM, and 23 events in λ SUSY, 7.2σ

⁶ The used value of $\delta_h(\delta_V)$ is motivated by the natural width of $h(V)$ and jet energy resolution.

away from the SM. When going beyond benchmark-point analysis (something out our aim), such localized excess can be used to determine m_H .

The CP-odd pseudo-scalar A has mass in the 500-800 GeV range, as the heavy scalar H , but it is always heavier than H (see Fig. 1). The expression for its couplings to the SM fermions are the same as in the MSSM and can be found in [12]. By CP-invariance AVV couplings vanish, therefore the only relevant production mechanism is gluon fusion via the top loop.

Its total width ranges between 5 and 30 GeV and is dominated by $A \rightarrow t\bar{t}$ and $A \rightarrow hZ$ decays. Although the branching ratio of $A \rightarrow t\bar{t}$ is almost always dominant, it is not usable to discover A [11]. Therefore, we focus on $A \rightarrow hZ$, whose BR is smaller, but still significant.

Most of the produced h 's will decay into vectors, yielding $\sigma_{tot}(gg \rightarrow A \rightarrow ZVV) \sim 100\text{fb}$ over all the parameter space. Such a cross section will give too small event rate if more than one V is allowed to decay leptonically. Therefore we concentrate on the signature

$$gg \rightarrow A \rightarrow hZ \rightarrow VVZ \rightarrow 4Jl^+l^- \quad (\text{signal}). \quad (7)$$

We fix the point of parameter space Eq. (2) and compute total cross section for signal (7)

$$\sigma \times BR(\text{signal}) = 6.9\text{fb}.$$

Signal events has been produced with MADGRAPH.

The relevant BG sources of l^+l^-4J events are the $Z4J$ process and $ZW2J$. The latter has been simulated with MADGRAPH while $Z4J$ has been simulated through a specific ALPGEN code for $Z4j$. Restricting event invariant mass in a $O(100\text{GeV})$ interval around m_A , the total BG cross section is factor 2000 larger than the signal.

To increase the S/B ratio we analyse events in a quite analogous way to what was done for H . First we smear jets energy as described above. Then we impose the kinematical cuts

$$\Delta R_{JJ,lJ,U} > 0.4, \quad p_T^J > 20\text{GeV}, \quad \eta_J < 2.5, \quad (8)$$

$$|m_U - m_Z| < 10\text{GeV}, \quad p_T^l > 10\text{GeV}, \quad \eta_l < 2.5.$$

The signal events passing these cuts correspond to $3.02(4)\text{fb}$ cross section while BG cross section is still orders of magnitudes larger. Thus we impose *reconstruction cuts*. Namely, we require that the 4 final jets can be divided into 2 pairs reconstructing 2 vector bosons of the same type. If they are both W , then we require that they reconstruct an h . If they are both Z , we require that out of the 3 final Z 's (the two from jets and the one reconstructed by the leptons) we should find a pair reconstructing an h . Reconstruction parameters are the same as in the case of H , Eq. (5) and (6). After these reconstruction cut signal cross section is 2.2 fb. Unfortunately the total BG cross section is still one order of magnitude larger. However, it's interesting to look closer at the differential cross sections of BG and signal+BG versus the event invariant mass, plotted in Fig. 2. We see that the signal distribution presents a

well visible peak above the BG. The discovery significance can be optimized choosing a range with largest S/\sqrt{B} ratio. For example, assuming $\mathcal{L} = 100\text{fb}^{-1}$, in the 595 – 635 GeV range we expect 816 events in the SM, and 989 events in λSUSY at the benchmark point (2), which amounts to 6.1σ discovery significance.

5 Conclusions

Our conclusion is that λSUSY signal (3) is indeed observable at the LHC with 100fb^{-1} of integrated luminosity. If observed, it can provide clean evidence for the heavy scalar H as well as for the $H \rightarrow hh$ dominant decay chain. Moreover, we have shown that the CP-odd Higgs boson A has a clear experimental signature (7), which allows for its discovery at the LHC with 100fb^{-1} of integrated luminosity. Remarkably, the peaked shape of the signal distribution should allow BG extraction from data and an easy mass measurement. Even though the $A \rightarrow Zh$ decay mode is less distinctive of λSUSY than the $H \rightarrow hh$, its signature seems simpler and cleaner, and it could be the easiest channel to pursue when looking for λSUSY .

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