Naturalness of EWSB in NMSSM and Higgs at 100 GeV

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Abstract. Naturalness of electroweak symmetry breaking in the next-to-minimal supersymmetric model points to scenarios in which the lightest CP-even Higgs boson has SM-like $ZZh$ coupling and mass $m_h \sim 100$ GeV and decays partly via $h \rightarrow b\bar{b}$ but dominantly into two CP-odd Higgs bosons, $h \rightarrow aa$, where $m_a < 2m_b$ so that $a \rightarrow \tau^+\tau^-$ (or light quarks and gluons) decays are dominant. These preferred scenarios correlate well with the observed excess of events at LEP for $m_h \sim 100$ GeV.

In the minimal supersymmetric standard model (MSSM) a generic supersymmetric (SUSY) spectrum that leads to natural electroweak symmetry breaking predicts a mass for the Higgs boson which is already ruled out by LEP data. To satisfy LEP limits the SUSY spectrum has to be either very heavy or very special. However in the next-to-minimal supersymmetric model (NMSSM) the Higgs boson can be where it is predicted from natural EWSB with a generic SUSY spectrum and there is even a hint in LEP data that this might be the case.

The NMSSM is a very attractive model. It provides an elegant solution to the $\mu$ problem of the MSSM via the introduction of a singlet superfield $\hat{S}$. For the simplest possible scale invariant form of the superpotential,

$$\lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3,$$

the scalar component of $\hat{S}$ naturally acquires a vacuum expectation value of the order of the SUSY breaking scale, giving rise to a value of $\mu$ of order the electroweak scale. Its particle content differs from the MSSM by the addition of one CP-even and one CP-odd state in the neutral Higgs sector (assuming CP conservation), and one additional neutralino. We follow the conventions of [5]. The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3.$$  

The final two input parameters are $\tan \beta = h_u/h_d$ and $\mu_{\text{eff}} = \lambda s$, where $h_u \equiv \langle H_u \rangle$, $h_d \equiv \langle H_d \rangle$ and $s \equiv \langle S \rangle$. These, along with $m_Z$, can be viewed as determining the three SUSY breaking masses squared for $H_u$, $H_d$ and $S$ (denoted $m_{H_u}^2$, $m_{H_d}^2$, and $m_S^2$) through the three minimization equations of the scalar potential. Thus, the Higgs sector of the NMSSM is described by the six parameters $\lambda$, $\kappa$, $A_\lambda$, $A_\kappa$, $\tan \beta$, $\mu_{\text{eff}}$.

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1 Scenarios that lead to such a special SUSY spectrum were recently found, see for example mixed anomaly-modulus mediation or gauge mediation with gauge messengers. Both scenarios generate large mixing in the stop sector which maximizes the Higgs mass allowing all experimental limits to be satisfied with a fairly light SUSY spectrum.
We can use naturalness of EWSB to predict the mass of the Higgs boson. Let us define the measure of fine tuning as

\[ F = \text{Max}_p F_p \equiv \text{Max}_p \left[ \frac{d \log m_Z}{d \log p} \right], \tag{3} \]

where the parameters \( p \) comprise the GUT-scale soft-SUSY-breaking parameters. We randomly generate NMSSM scenarios with fixed \( \tan \beta = 10 \) and \( M_3(m_Z) = 300 \) GeV and plot fine tuning vs. the Higgs mass, see Fig. 1 (left). Scenarios that satisfy the experimental constraints on superpartner masses are labeled by green circles. Scenarios labeled by blue squares have in addition \( m_{h_1} > 114.4 \) GeV and/or large \( \text{Br}(h_1 \to a_1a_1) \) (typically, the lightest CP-odd Higgs boson is mostly singlet). If \( m_{a_1} > 2m_b \) the later scenarios are further constrained by \( Zh \to Za \to Zb \bar{b}b \bar{b} \) limits and those with full strength \( ZZh \) coupling are ruled out unless \( m_{h_1} \gtrsim 110 \) GeV. However, there are no limits on the \( Zh \to Za \to Z \tau^+ \tau^- \tau^+ \tau^- \) final state for \( m_h \gtrsim 87 \) GeV and so the scenarios with \( m_{a_1} < 2m_b \) satisfy all experimental constraints. These scenarios (orange stars in Fig. 1) are among the scenarios with the very lowest fine tuning one can find given the current constraints on superpartners. Naturalness of EWSB in NMSSM clearly points to scenarios in which the Higgs boson with SM-like \( ZZh \) coupling and mass \( m_{h_1} \sim 100 \) GeV decays partly via \( h_1 \to b \bar{b} \) but dominantly into two CP-odd Higgs bosons, \( h_1 \to a_1a_1 \), where \( m_{a_1} < 2m_b \) so that \( a_1 \to \tau^+ \tau^- \) (or light quarks and gluons) decays are dominant. Further, since the \( ZZh \) and \( WWh \) couplings are very SM-like, these scenarios give excellent agreement with precision electroweak data.

Quite interestingly, the largest excess of events in the search for the SM Higgs boson at LEP is for a test Higgs mass of \( m_h \sim 100 \) GeV [6]. This excess cannot be interpreted as the SM Higgs boson (a SM Higgs boson with a mass of 100 GeV would lead to \( \sim 10 \) times larger excess). However, in the orange scenarios discussed above, the Higgs boson has SM-like \( ZZh \) coupling, but highly reduced \( \text{Br}(h \to b \bar{b}) \); such scenarios can...
naturally explain the observed excess. In Fig. 1 (right) we plot $C^{2b}_{eff}$ limits and $C^{2b}_{eff}$ predictions for NMSSM scenarios that appeared in our original (low density) scan [3] that give fine-tuning measure $F < 25$ and $m_{a1} < 2m_b$. All these points are consistent with the experimental and theoretical constraints built into NMHDECAY [5] as well as with limits from the preliminary LHKG full confidence level/likelihood analysis (we thank P. Bechtle for doing this analysis). The eight points with the lowest fine tuning, $F < 10$, cluster near $m_{h1} \sim 98 \pm 105$ GeV (see also Fig. 3 of [3]). A detailed description of these eight points, including precise masses and branching ratios of the $h_1$ and $a_1$, can be found in Ref. [4]. A significant fraction of the $F < 10$ points with low fine tuning are very consistent with the observed event excess.

Finally, let us discuss conditions under which scenarios with $m_{a1} < 2m_b$ and large $\text{Br}(h_1 \to a_1 a_1)$ occur in the NMSSM. In the NMSSM, one of the CP-odd Higgses is massless in the Peccei-Quinn symmetry limit, $\kappa \to 0$, or in the R-symmetry limit, $A_k, A_\lambda \to 0$ [7]. The masslessness of $a_1$ in the limit $A_k, A_\lambda \to 0$ can be understood as a consequence of a global $U(1)_R$ symmetry of the superpotential under which the charge of $S$ is half of the charge of $H_uH_d$. In the limit $A_k, A_\lambda \to 0$ it is also a symmetry of the scalar potential. This symmetry is spontaneously broken by the vevs of $H_u$, $H_d$ and $S$, resulting in a (massless) Nambu-Goldstone boson in the spectrum. Soft trilinear couplings explicitly break $U(1)_R$ and thus lift the mass of the $a_1$. For small trilinear couplings, the mass of the lightest CP-odd Higgs boson is approximately given as:

$$m_{a1}^2 \simeq 3s \left( \frac{3\lambda A_\lambda \cos \theta_A}{2\sin2\beta} - \kappa A_k \sin^2 \theta_A \right),$$

where $\cos \theta_A$ measures the doublet component of the lightest CP-odd Higgs mass eigenstate, $a_1 = \cos \theta_A A_{MSSM} + \sin \theta_A A_S$. In the limit of large $\tan \beta$ or $|s| \gg v$, $\cos \theta_A$ can be approximated by $\cos \theta_A \simeq 2v/s\tan \beta$, which indicates that in these limits the lightest mass eigenstate is mostly singlet.

Naively, an arbitrarily small mass for the $a_1$ is achievable provided small values of $A_k$ and $A_\lambda$ are generated by a SUSY breaking scenario. However, $A_k$ and $A_\lambda$ receive radiative corrections from gaugino masses ($A_k$ only at the two-loop level) and we should naturally expect $A_\lambda(m_Z) \simeq 0(M_2(m_Z)) \gtrsim 100$ GeV and $A_k(m_Z) \gtrsim \text{few GeV}$. Much smaller values would require cancellations between the values of $A_\lambda$, $A_k$ coming from a particular SUSY breaking scenario and the contributions from the radiative corrections.

Eq. (4) indicates that the contribution from $A_\lambda \gtrsim 100$ GeV to $m_{a1}^2$ is highly suppressed if the lightest CP-odd Higgs is mostly singlet. We define a measure of the tuning in $A_\lambda(m_Z)$ and $A_k(m_Z)$ necessary to achieve $m_{a1} < 2m_b$ as $F_{MAX} = \max \{ |d \log m_{a1}^2/d \log A_\lambda(m_Z)|, |d \log m_{a1}^2/d \log A_k(m_Z)| \}$ which is to be evaluated for given choices of $A_\lambda(m_Z)$ and $A_k(m_Z)$ that yield a given $m_{a1}$ [8]. This definition reflects the fact that $m_{a1}$ is completely determined by these parameters for fixed $\lambda, \kappa, \mu_{eff}, \tan \beta$. The dependence of $F_{MAX}$ on $A_k$ and $A_\lambda$ is given in Fig. 2. As expected, the smallest fine tuning or sensitivity is achieved for as small $A_k$ and $A_\lambda$ as possible. Of course, as we discussed earlier, very small values of $A_k$ and $A_\lambda$ would require cancellations between the bare values and the RGE-induced radiative corrections and this kind of cancellation would not be visible from the definition of $F_{MAX}$. However, this is not a concern given that very small values of $A_k$ and $A_\lambda$ do not in any case lead to sufficiently large $\text{Br}(h_1 \to a_1 a_1)$ that $\text{Br}(h_1 \to b\bar{b})$ is adequately suppressed, see Fig. 2. Thus, in the
region of parameter space where soft trilinear couplings are at least of order the typical RGE-induced contributions, which is also the region where Br($h_1 \rightarrow a_1a_1$) is large, the tuning of the soft trilinear couplings can be as small as $O(5\%-10\%)$. Finally, we would like to note that $F_{MAX}$, typically substantially overestimate the magnitude of fine tuning with respect to GUT scale parameters. For scenarios in which gaugino masses and soft-trilinear couplings are correlated (not free parameters but rather calculable from a SUSY breaking scale) there is in principle no tuning associated with the SUSY breaking necessary to achieve $m_{a_1} < 2m_b$ [8].

In conclusion, we reemphasize that in the NMSSM the SM-like Higgs boson can be where it is predicted on the basis of natural EWSB and that the LEP event excess in the $Z + b$'s channel for a reconstructed Higgs mass of $m_h \sim 100$ GeV is consistent with a scenario in which the $h$ decays mainly via $h \rightarrow aa \rightarrow \tau^+\tau^-\tau^+\tau^-$ ($2m_\tau < m_a < 2m_b$) or 4 jets ($m_a < 2m_\tau$) leaving an appropriately reduced rate for $h \rightarrow b\bar{b}$. We speculate that similar results will emerge in other supersymmetric models with a Higgs sector that is more complicated than that of the CP-conserving MSSM. This suggests that the strategy for Higgs searches at the Tevatron and LHC should be modified.

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