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## Naturalness and fine tuning in the NMSSM: implications of early LHC results

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**ABSTRACT:** We study the fine tuning in the parameter space of the semi-constrained NMSSM, where most soft Susy breaking parameters are universal at the GUT scale. We discuss the dependence of the fine tuning on the soft Susy breaking parameters  $M_{1/2}$  and  $m_0$ , and on the Higgs masses in NMSSM specific scenarios involving large singlet-doublet Higgs mixing or dominant Higgs-to-Higgs decays. Whereas these latter scenarios allow *a priori* for considerably less fine tuning than the constrained MSSM, the early LHC results rule out a large part of the parameter space of the semi-constrained NMSSM corresponding to low values of the fine tuning.

**KEYWORDS:** Supersymmetry Phenomenology

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**1 Introduction**

The first motivation for supersymmetric extensions of the Standard Model (SM) stems from the solution of the naturalness or fine tuning problem in the Higgs sector of the SM [1–5] (besides the unification of the gauge couplings and the possibility to explain dark matter): in the SM with an ultraviolet cutoff  $\Lambda$  much larger than the electroweak scale  $M_Z$ , the bare Higgs mass squared  $m_0^2$  must satisfy roughly  $m_0^2 - \Lambda^2 \sim M_Z^2$ . Hence  $m_0^2$  must be of the order  $\Lambda^2$ , but must be finetuned relative to  $\Lambda^2$  with a precision of the order  $M_Z^2/\Lambda^2$ . This fine tuning is enormous for  $\Lambda$  of the order of a GUT scale, but only a tuning of  $\mathcal{O}(1)$  is considered as natural. Within supersymmetric (Susy) extensions of the SM with Susy breaking terms of the order  $M_{\text{Susy}}$ , the necessary tuning between the parameters is of the order of  $M_Z^2/M_{\text{Susy}}^2$ , and hence independent from an ultraviolet cutoff  $\Lambda$ .

First results of searches for Susy by the ATLAS and CMS collaborations at the LHC, based on  $\sim 1 \text{ fb}^{-1}$  of data taken at 7 TeV center-of-mass energy, imply lower bounds on Susy breaking gluino and up/down squark masses in the 1 TeV range [6, 7] (for the latest publications, see the ATLAS and CMS notes on the web pages [8, 9]). These bounds reduce the phenomenologically viable range of parameters in Susy extensions of the SM. However, an obviously interesting question is the impact of these negative results on the necessary tuning between the parameters in the remaining parameter region.

It is well known that the non-observation of a Higgs boson at LEP [10] implies already a “little fine tuning problem” in the Minimal Supersymmetric Standard Model (MSSM) (see e.g. [11–14]), where the field content in the Higgs sector is as small as possible, but large radiative corrections are required in order to lift the mass of the lightest neutral CP-even Higgs boson above the lower LEP bound. Large radiative corrections require relatively large Susy breaking top squark masses compared to the electroweak scale. Via loop diagrams, large top squark masses lead to relatively large soft Susy breaking Higgs mass terms, which require some tuning among the parameters of the MSSM such that the Higgs vacuum expectation values (vevs) are of  $\mathcal{O}(M_Z)$ , well below the scale of the Higgs mass terms. The required tuning among the parameters of the MSSM is typically of the order of a few %.

The “little fine tuning problem” of the MSSM, originating from LEP constraints, is alleviated in certain regions of the parameter space of the Next-to-Minimal Supersymmetric Standard Model (NMSSM). The NMSSM is the simplest 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  $\mu$  is required as in the MSSM, since it is generated dynamically by the vacuum expectation value of a gauge singlet superfield  $S$  (see [15, 16] for recent reviews). 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 and two CP-odd Higgs states in this model.

The additional coupling  $\lambda$  of  $S$  to  $H_u$  and  $H_d$  can lead to a larger mass  $m_H$  of the SM-like neutral Higgs boson  $H$ , and to mixings of the physical CP-even Higgs bosons in terms of the weak eigenstates  $S$ ,  $H_u$  and  $H_d$ , implying reduced couplings of the physical eigenstates to the  $Z$  boson. Both phenomena make it easier to satisfy the LEP bounds [17], and allow to alleviate the little finetuning problem [18]. (See [19] for an evaluation of the upper bound on  $m_H$  of about 140 GeV if  $\lambda$  is required to remain perturbative below the GUT scale; if  $\lambda$  is allowed to be larger,  $m_H$  can be even larger [20].)

Moreover,  $H$  can decay preferably into lighter NMSSM-specific singlet-like Higgs bosons. In this case LEP bounds on  $m_H$  are lower, and again the required fine tuning can be considerably smaller than in the MSSM [18, 21–24]. Consequently it becomes important to study the impact of the recent bounds from the LHC on the fine tuning within the NMSSM, which is the purpose of this paper.

The most frequently used quantitative measure  $\Delta$  for fine tuning is the maximum of the logarithmic derivative of  $M_Z$  with respect to all fundamental parameters  $p_i^{\text{GUT}}$  (if the fundamental Lagrangian is given at the GUT scale) [11, 25–33]:

$$\Delta = \text{Max}\{\Delta_i^{\text{GUT}}\}, \quad \Delta_i^{\text{GUT}} = \left| \frac{\partial \ln(M_Z)}{\partial \ln(p_i^{\text{GUT}})} \right|. \quad (1.1)$$

(See [34, 35] for alternatives; sometimes  $M_Z^2$  instead of  $M_Z$  is used in the argument of the logarithm, which leads to an obvious additional factor of 2. Subsequently we prefer to study linear relations between all masses and couplings.)  $\Delta$  depends on the point in parameter space and is, roughly speaking, inversely proportional to the required fine tuning (as discussed above) between the parameters  $p_i^{\text{GUT}}$ . Hence, for a given point in parameter space,  $\Delta$  should be as small as possible, preferably of  $\mathcal{O}(1)$ . Preferred regions in the parameter space spanned by  $p_i^{\text{GUT}}$  are those where  $\Delta$  is minimal (denoted by  $\Delta_{\text{min}}$ ). In practice, the value of  $\Delta$  depends on the choice of independent fundamental parameters defining the model, and on the implementation of phenomenological constraints as the dark matter relic density, the anomalous magnetic moment of the muon etc.

Including WMAP constraints on the dark matter relic density (but leaving aside the top Yukawa coupling  $h_t$  in the list of  $p_i^{\text{GUT}}$ ),  $\Delta$  has been studied recently within the constrained MSSM (cMSSM, with universal soft Susy breaking terms at the GUT scale) in [30–33]. First investigations of the impact of the early LHC results on the Susy parameter space in the cMSSM have been performed in [36–39], in the cMSSM with non-universal sfermion masses in [40], and within the general MSSM in [38, 39, 41].

Compared to alternative procedures as likelihood scans and/or Bayesian techniques (see [42, 43] for studies within constrained versions of the NMSSM, and [44] for a recent discussion) a disadvantage of  $\Delta$  is that it does not allow to marginalise (i.e. to integrate over) parts of the parameters which, in turn, would allow to determine “most likely” values for given quantities as masses of specific particles, given all present experimental constraints. (Clearly, such predictions for “most likely” masses seem to be of limited use; for instance, they would have failed miserably if applied to the SM-like Higgs mass in the pre-LEP era.)

One can also leave aside the issue of quantitative fine tuning, content oneself with the fact that the fine tuning in Susy is always much smaller than in the SM with a large cutoff  $\Lambda$ , and determine “most likely” values for parameters exclusively from best fits to data from electroweak precision experiments. The impact of recent LHC bounds on such best fits has been studied recently in [43, 45–49].

On the other hand, the constraints from recent or future LHC results on the quantitative fine tuning measure  $\Delta$  can contribute to the discussion on the impact of LHC results on Supersymmetry in general. Hence we will compare these constraints within the parameter space of the semi-constrained sNMSSM (where singlet-specific soft terms are allowed to be non-universal) to the cMSSM, obtained from the sNMSSM in the limit  $\lambda, \kappa \rightarrow 0$ . Therefore we study the dependence of  $\Delta$  on the universal soft Susy breaking parameters  $M_{1/2}$  and  $m_0$  (gaugino and scalar masses, respectively) and on the gluino and up/down squark masses. In particular we investigate the relevance of NMSSM specific scenarios in the Higgs sector for fine tuning, as scenarios with large singlet/doublet mixing and scenarios with dominant  $h \rightarrow A_1 A_1$  decays [16, 21–24, 43].

In the next section we define the model, the procedure for the determination of  $\Delta$ , and discuss some specific properties of  $\Delta$  in the NMSSM. Our results and their discussion are given in section 3, and we conclude with a summary in section 4.

## 2 Fine tuning in the NMSSM and the MSSM

The NMSSM differs from the MSSM by the presence of the gauge singlet superfield  $S$ . The Higgs mass term  $\mu H_u H_d$  in the superpotential  $W_{\text{MSSM}}$  of the MSSM is replaced by the coupling  $\lambda$  of  $H_u$  and  $H_d$  to  $S$  and a self-coupling  $\kappa S^3$ , hence the superpotential  $W_{\text{NMSSM}}$  is scale invariant in this simplest  $Z_3$ -invariant version of the NMSSM:

$$W_{\text{NMSSM}} = \lambda S H_u \cdot H_d + \frac{\kappa}{3} S^3 + h_t H_u \cdot Q T_R^c + h_b H_d \cdot Q B_R^c + h_\tau H_d \cdot L \tau_R^c, \quad (2.1)$$

where we have confined ourselves to the Yukawa couplings of  $H_u$  and  $H_d$  to the quarks and leptons  $Q$ ,  $T_R$ ,  $B_R$ ,  $L$  and  $\tau_R$  of the third generation; a sum over the three generations is implicitly assumed. (In (2.1), for the first and the last time, the fields denote superfields.) Once  $S$  assumes a vev  $s$ , the first term in  $W_{\text{NMSSM}}$  generates an effective  $\mu$ -term

$$\mu_{\text{eff}} = \lambda s. \quad (2.2)$$

The soft Susy-breaking terms consist of mass terms for the gaugino, Higgs and sfermion fields

$$\begin{aligned}
 -\mathcal{L}_{\frac{1}{2}} &= \frac{1}{2} \left[ M_1 \tilde{B} \tilde{B} + M_2 \sum_{a=1}^3 \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^8 \tilde{G}^a \tilde{G}_a \right] + \text{h.c.}, \\
 -\mathcal{L}_0 &= m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + m_Q^2 |Q|^2 + m_T^2 |T_R^c|^2 \\
 &\quad + m_B^2 |B_R^c|^2 + m_L^2 |L|^2 + m_\tau^2 |\tau_R^c|^2,
 \end{aligned} \tag{2.3}$$

as well as trilinear interactions between the sfermion and the Higgs fields, including the singlet field

$$\begin{aligned}
 -\mathcal{L}_{\text{tril}} &= \left( h_t A_t Q \cdot H_u T_R^c + h_b A_b H_d \cdot Q B_R^c + h_\tau A_\tau H_d \cdot L \tau_R^c \right. \\
 &\quad \left. + \lambda A_\lambda H_u \cdot H_d S + \frac{1}{3} \kappa A_\kappa S^3 \right) + \text{h.c.}
 \end{aligned} \tag{2.4}$$

(Again, an effective MSSM-like  $B$ -parameter  $B_{\text{eff}} = A_\lambda + \kappa s$  is generated.)

All parameters in the above Lagrangian depend on the energy scale via the corresponding renormalization group (RG) equations, which account for the dominant radiative corrections involving large logarithms. In the constrained NMSSM, one imposes unification of the soft Susy-breaking gaugino masses, sfermion and Higgs masses as well as trilinear couplings at the grand unification (GUT) scale  $M_{\text{GUT}}$ :

$$\begin{aligned}
 M_1 &= M_2 = M_3 \equiv M_{1/2}, \\
 m_{H_u} &= m_{H_d} = m_Q = m_T = m_B = m_L = m_\tau \equiv m_0, \\
 A_t &= A_b = A_\tau = A_\lambda \equiv A_0.
 \end{aligned} \tag{2.5}$$

Since the singlet superfield could play a special role (its couplings to a hidden sector, responsible for supersymmetry breaking, could differ from the MSSM-like fields), we will allow for non-universal singlet-specific soft terms  $m_S$  and  $A_\kappa$  at the grand unification scale. This is the so-called semi-constrained NMSSM, denoted by sNMSSM subsequently. Including the top quark Yukawa coupling due to its influence on the RG equations, the Lagrangian of the sNMSSM depends on eight parameters  $p_i^{\text{GUT}}$  at the GUT scale:

$$p_i^{\text{GUT}} = M_{1/2}, m_0, A_0, \lambda, \kappa, m_S, A_\kappa \text{ and } h_t. \tag{2.6}$$

The calculation of  $\Delta_i^{\text{GUT}}$  defined in (1.1) proceeds in two steps: first, we compute the variations

$$\Delta_i^{\text{Susy}} = \left| \frac{\partial \ln(M_Z)}{\partial \ln(p_i^{\text{Susy}})} \right| \tag{2.7}$$

with respect to the parameters  $p_i^{\text{Susy}}$  at the Susy scale (the Susy scale is defined to be of the order of the soft Susy breaking terms). Subsequently these variations are contracted with the Jacobian

$$J_{ij} = \left| \frac{\partial \ln(p_i^{\text{Susy}})}{\partial \ln(p_j^{\text{GUT}})} \right| \tag{2.8}$$

which takes care of the renormalization group running of the parameters between the Susy and the GUT scales. Then we obtain

$$\Delta_j^{\text{GUT}} = \sum_i \Delta_i^{\text{Susy}} J_{ij}. \quad (2.9)$$

The parameters  $p_i^{\text{Susy}}$  at the Susy scale are those appearing in the (effective) Higgs potential, whose minimization determines the vevs  $v_u$  of  $H_u$ ,  $v_d$  of  $H_d$  and  $s$  of  $S$ . These vevs determine, in turn, the quantities

$$M_Z^2 = \frac{g_1^2 + g_2^2}{2}(v_u^2 + v_d^2), \quad \tan \beta = \frac{v_u}{v_d} \quad \text{and} \quad \mu_{\text{eff}} = \lambda s. \quad (2.10)$$

Including the dominant top quark/squark induced radiative corrections, the three minimisation equations  $E_i$  are given by [16]

$$\begin{aligned} E_1 : \quad & m_{H_u}^2 + \mu_{\text{eff}}^2 + \lambda^2 v_d^2 + \frac{g_1^2 + g_2^2}{4}(v_u^2 - v_d^2) - \frac{v_d}{v_u} \mu_{\text{eff}}(A_\lambda + \kappa s) + \frac{3h_t^4 v_u^2}{8\pi^2} \ln(M_{\text{stop}}^2/m_{\text{top}}^2) = 0, \\ E_2 : \quad & m_{H_d}^2 + \mu_{\text{eff}}^2 + \lambda^2 v_u^2 + \frac{g_1^2 + g_2^2}{4}(v_d^2 - v_u^2) - \frac{v_u}{v_d} \mu_{\text{eff}}(A_\lambda + \kappa s) = 0, \\ E_3 : \quad & m_S^2 + \kappa A_\kappa s + 2\kappa^2 s^2 + \lambda^2(v_u^2 + v_d^2) - 2\lambda\kappa v_u v_d - \lambda \frac{v_u v_d}{s} A_\lambda = 0, \end{aligned} \quad (2.11)$$

where  $M_{\text{stop}}$  denotes an average value of the top squark masses. (It is not necessary to be more precise here, in contrast to the radiative corrections to the physical Higgs masses.) It is straightforward to express the vevs  $v_u$ ,  $v_d$  and  $s$  in terms of  $M_Z^2$ ,  $\tan \beta$  and  $\mu_{\text{eff}}$  with the help of these equations.

Hence the relevant parameters  $p_i^{\text{Susy}}$  at the Susy scale are given by (leaving aside the electroweak gauge couplings  $g_1$  and  $g_2$ , as well as  $M_{\text{stop}}$  inside the logarithm)

$$p_i^{\text{Susy}} = m_{H_u}, m_{H_d}, m_S^2, A_\lambda, A_\kappa, \lambda, \kappa, \quad \text{and} \quad h_t. \quad (2.12)$$

In order to compute the variations  $\Delta_i^{\text{Susy}}$  (see (2.7)) with respect to these parameters, we use

$$0 = \delta E_j = \sum_i \frac{\partial E_j}{\partial p_i^{\text{Susy}}} \delta p_i^{\text{Susy}} + \frac{\partial E_j}{\partial M_Z} \delta M_Z + \frac{\partial E_j}{\partial \tan \beta} \delta \tan \beta + \frac{\partial E_j}{\partial \mu_{\text{eff}}} \delta \mu_{\text{eff}} \quad (2.13)$$

for  $j = 1, 2, 3$ . Since all partial derivatives of the equations  $E_j$  can be computed explicitly, the three equations (2.13) can be solved for  $\delta M_Z$  (and, separately, for  $\delta \tan \beta$  and  $\delta \mu_{\text{eff}}$ ) as function of all  $\delta p_i^{\text{Susy}}$ , which allows to determine the variations  $\Delta_i^{\text{Susy}}$  in (2.7).

At this stage it is useful to recall the origin of the ‘‘little fine tuning problem’’ in the MSSM. Neglecting the radiative corrections, the minimisation equations (2.11) of the Higgs potential imply, with  $\mu_{\text{eff}} \equiv \mu$  in the MSSM,

$$M_Z^2 \simeq -2\mu^2 + \frac{2(m_{H_d}^2 - \tan^2 \beta m_{H_u}^2)}{\tan^2 \beta - 1}. \quad (2.14)$$

In the absence of fine tuning, all terms on the right hand side of (2.14) should be of comparable magnitude, and no large cancellations should occur; hence both  $\mu^2$  and  $|m_{H_u}^2|$  should not be much larger than  $\mathcal{O}(M_Z^2)$ . However, from the RG equations one typically obtains  $m_{H_u}^2 \sim -M_{\text{stop}}^2$ , which is often required to be much larger (in absolute value) than  $M_Z^2$ : at least within the MSSM, the SM-like Higgs scalar mass increases proportionally to  $\ln(M_{\text{stop}}^2/m_{\text{top}}^2)$  due to top/stop induced radiative corrections. Then, large values for  $M_{\text{stop}}$  are unavoidable in order to satisfy the LEP bound. Albeit large stop masses are consistent with the non-observation of top squarks, they would generate an uncomfortably large value for  $-m_{H_u}^2$  which has to be cancelled by  $\mu^2$  in (2.14).

For large  $|m_{H_u}^2| \sim \mu^2$  one finds for  $\tan^2 \beta \gg 1$ , following (2.7) with  $i = m_{H_u}$  or  $i = \mu$ ,

$$\Delta_{m_{H_u}}^{\text{Susy}} \sim 2 \frac{|m_{H_u}^2|}{M_Z^2} \sim \Delta_{\mu}^{\text{Susy}} \sim 2 \frac{\mu^2}{M_Z^2}. \quad (2.15)$$

Accordingly large values for  $\Delta_i^{\text{Susy}}$  (leading, generally, to large values for  $\Delta_i^{\text{GUT}}$ ) reflect well the necessary fine tuning if  $|m_{H_u}^2|$  and hence  $\mu^2$  are large.

In the NMSSM  $\mu$  is replaced by  $\mu_{\text{eff}} = \lambda s$ . For large  $|m_{H_u}^2| \sim \mu_{\text{eff}}^2$ , the above reasoning remains essentially unchanged: for  $s \gg M_Z$  (valid in most of the parameter space),  $E_3$  in (2.11) gives

$$s \sim \frac{1}{4\kappa} \left( -A_\kappa - \sqrt{A_\kappa^2 - 8m_S^2} \right). \quad (2.16)$$

Replacing  $\mu^2 = \mu_{\text{eff}}^2$  and (2.16) for  $s$  in (2.14), one finds again from (2.7)

$$\Delta_{m_{H_u}}^{\text{Susy}} \sim 2 \frac{|m_{H_u}^2|}{M_Z^2} \sim \Delta_{\lambda}^{\text{Susy}} \sim \Delta_{\kappa}^{\text{Susy}} \sim 2 \frac{\mu_{\text{eff}}^2}{M_Z^2} \quad (2.17)$$

in the NMSSM. Hence, quite obviously, large values for  $|m_{H_u}^2|$  are unnatural as well. However, due to the NMSSM specific contributions to the Higgs masses and mixings or NMSSM specific Higgs decays, LEP bounds on the Higgs sector can be satisfied for smaller top/stop induced radiative corrections, hence for smaller values of  $M_{\text{stop}}$ , allowing for smaller values for  $|m_{H_u}^2|$  and  $\mu_{\text{eff}}^2$ .

It remains to express the variations of the parameters at the Susy scale in terms of variations of the parameters at the GUT scale, i.e. to compute the Jacobian  $J_{ij}$  in (2.8), via the integration of the RG equations for the parameters. In the cMSSM (with boundary conditions at the GUT scale as in (2.5)) one can always write

$$m_{H_u}^2 = a^{(1)} m_0^2 + a^{(2)} M_{1/2}^2 + a^{(3)} A_0^2 + a^{(4)} M_{1/2} A_0 \quad (2.18)$$

and

$$\mu^2 = b \mu_0^2, \quad (2.19)$$

where the coefficients  $a^{(i)}$  and  $b$  depend on the gauge and Yukawa couplings.

In the typical case where *all*  $a^{(i)}$  in (2.18) satisfy  $|a^{(i)}| < 1$ , one can verify that all variations  $\partial \ln(m_{H_u}) / \partial \ln(p_i^{\text{GUT}})$ , with  $p_i^{\text{GUT}} = m_0, M_{1/2}, A_0$ , are less than 1. At first sight, due to  $\Delta_{p_i}^{\text{GUT}} < \Delta_{m_{H_u}}$  for these parameters  $p_i^{\text{GUT}}$ , this seems to reduce the necessary fine



tuning in the MSSM. However, due to  $\partial \ln(\mu^2)/\partial \ln(\mu_0^2) \simeq 1$ ,  $\Delta_\mu^{\text{Susy}} \simeq \Delta_\mu^{\text{GUT}}$  remains always large. Moreover,  $h_t^{\text{GUT}}$  should generally be included in the list of parameters  $p_i^{\text{GUT}}$  [27, 50], and the corresponding variation  $\Delta_{h_t}^{\text{GUT}}$  can be large. This holds particularly in the so-called focus point region of the MSSM where  $m_0 \gg M_{1/2}$ ,  $A_0$ , and  $|a^{(1)}| \ll 1$  in (2.18) for specific values of  $h_t^{\text{GUT}}$  (but a large derivative of  $a^{(1)}m_0^2$  with respect to  $h_t^{\text{GUT}}$ ).

In the sNMSSM, additional terms  $\sim m_S^2$  and  $\sim A_\kappa$  appear on the right hand side of (2.18), which have little impact in practice. Instead of (2.19), the RG equations for  $\lambda$ ,  $\kappa$  and  $m_S^2$  will now play some role since, replacing (2.16) for  $s$  in  $\mu_{\text{eff}}$ ,  $\mu_{\text{eff}}$  depends on these parameters (apart from a dependence on  $A_\kappa$ ). In fact one can verify that, in the MSSM limit of the NMSSM where  $\lambda, \kappa \ll 1$ ,  $\mu_{\text{eff}}$  satisfies the *same* RG equation as  $\mu$ . All in all we cannot expect dramatic effects on the fine tuning from the somewhat different running of the parameters between the Susy and the GUT scale in the NMSSM.

In practice our computation of the different variations  $\Delta_i^{\text{GUT}}$  in the space of parameters  $p_i^{\text{GUT}}$  (2.6), in order to find its maximum  $\Delta$  as function of  $i$  (see (1.1)) at a specific point in the parameter space, is performed as follows: for each such point, the code NMSPEC [51] inside NMSSMTOOLS [52, 53] is used in order to compute the Higgs and sparticle spectrum including radiative corrections as described in these references. Constraints from LEP, B-physics and the anomalous magnetic moment of the muon are taken care of according to the latest updates given on the web site <http://www.th.u-psud.fr/NMHDECAY/nmssmtools.html>. (No constraints on the dark matter relic density are imposed; however, in most cases these could be satisfied by giving up the bino mass unification  $M_1 = M_{1/2}$  at the GUT scale, i.e. choosing an appropriate mass for the lightest neutralino-like Susy particle (LSP) without impact on the results relevant here.)

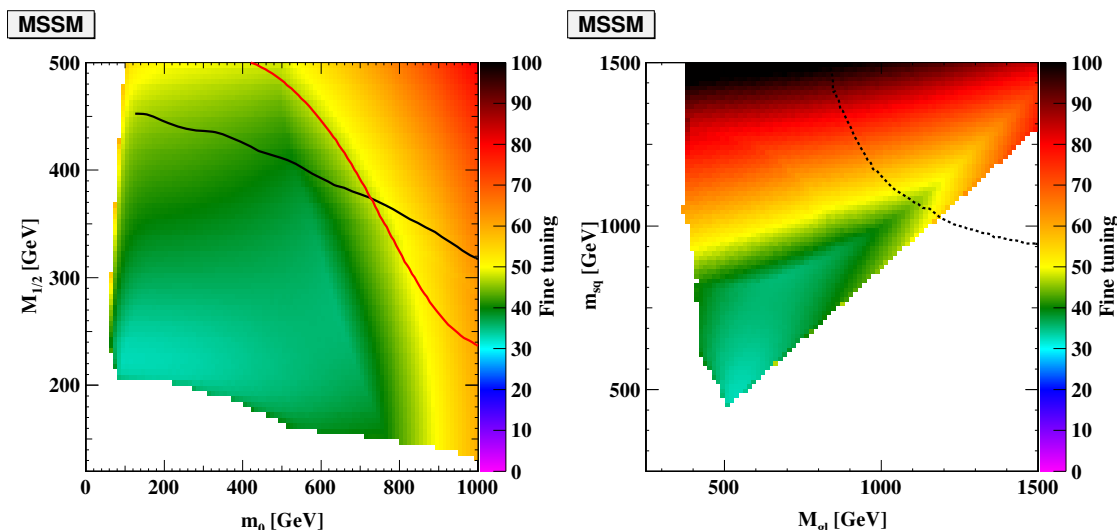
For phenomenologically acceptable points,  $\Delta_i^{\text{Susy}}$  is computed from the three minimization equations  $E_i$  in (2.11), following the procedure described above. The Jacobian  $J_{ij}$ , i.e. the variations of the parameters at the Susy scale in terms of variations of the parameters at the GUT scale, is computed numerically from the two loop RG equations. This allows to obtain the necessary quantities  $\Delta_i^{\text{GUT}}$ , whose maximum with respect to all parameters  $p_i^{\text{GUT}}$  (2.6) defines  $\Delta$ .

### 3 Results for the cMSSM and the sNMSSM

To start with, we apply our procedure to the cMSSM, which allows for comparisons with the sNMSSM and the available literature. The relevant parameters  $p_i^{\text{GUT}}$ (cMSSM) at the GUT scale are

$$p_i^{\text{GUT}}(\text{cMSSM}) = M_{1/2}, m_0, A_0, \mu_0, B_0, \text{ and } h_t. \tag{3.1}$$

As usual,  $\mu$  and  $B$  (and hence  $\mu_0$  and  $B_0$ ) are determined by  $M_Z$  and  $\tan \beta$ , but they still contribute to the definition of  $\Delta$ . Next we scan over a grid of values of  $M_{1/2}$  and  $m_0$ . For each set of these values, we scan over  $A_0$  and  $\tan \beta$ . Keeping only sets of parameters consistent with all phenomenological constraints, we look for values of  $A_0$  and  $\tan \beta$  which minimize  $\Delta$  as defined in (1.1) for fixed  $M_{1/2}$  and  $m_0$ . The resulting minimal values of  $\Delta$  can be represented in the plane  $M_{1/2}-m_0$ , or in the plane  $M_{\text{gluino}}-m_{\text{squark}}$  (where  $m_{\text{squark}}$  refers to squarks of the first generation) in figures 1.



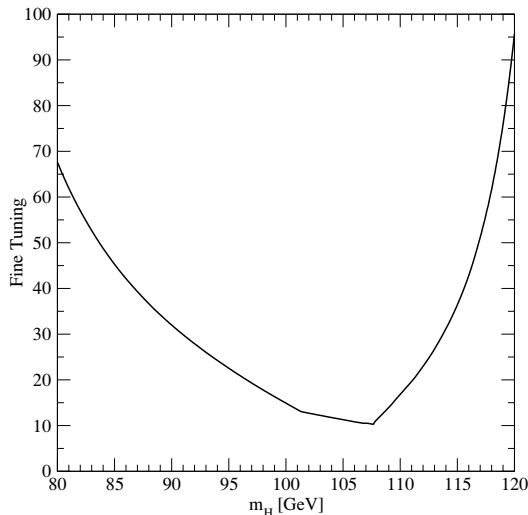
**Figure 1.** The minimal fine tuning  $\Delta$  in the cMSSM. For each set of  $M_{1/2}$  and  $m_0$ ,  $\Delta$  is minimized with respect to  $A_0$  and  $\tan\beta$ . Left panel:  $\Delta$  in the plane  $M_{1/2}$ - $m_0$ . Right panel:  $\Delta$  in the plane  $M_{\text{gluino}}$ - $m_{\text{squark}}$ . Bounds within specific cMSSM scenarios from ATLAS [6] are indicated as black lines, and from CMS [7] as red lines (see text).

In order to guide the eye, we have indicated lower bounds from ATLAS and CMS notes on analyses of jets and missing  $E_T$ , based on an integrated luminosity  $L^{\text{int}} \simeq 1 \text{ fb}^{-1}$ : in the plane  $M_{1/2}$ - $m_0$ , lower bounds from ATLAS [6] (interpreted within the cMSSM with  $\tan\beta = 10$ ,  $A_0 = 0$ ) are shown as a black line, and lower bounds from CMS [7] are shown as a red line. In the plane  $M_{\text{gluino}}$ - $m_{\text{squark}}$ , lower bounds from ATLAS [6] are shown as a black line. (The latter bounds from ATLAS are obtained in a simplified model where squarks decay only into quarks + a neutralino with a branching ratio of 100%.)

In the white regions in figures 1, phenomenological constraints cannot be satisfied for any values of  $A_0$  and  $\tan\beta$ : either a stau would be the LSP (left hand side of the left panel), or a charged slepton, chargino, neutralino or a CP-even Higgs boson is excluded by LEP2/Tevatron (lower part of the left panel), or squarks are excluded by CDF/D0 (left hand side of the right panel) or are theoretically inaccessible (right hand side of the right panel).

Note that, for  $M_{1/2} \lesssim 350 \text{ GeV}$  and  $m_0 \lesssim 700 \text{ GeV}$  in the left panel,  $\Delta$  decreases hardly with decreasing Susy breaking parameters  $M_{1/2}$  and  $m_0$ ; the minimal value of  $\Delta$  in the pre-LHC allowed region is about  $\sim 33$ . In this region of the parameter space we observe the "little fine tuning problem" of the MSSM due to the LEP bound on the SM-like Higgs mass, which hardly depends on  $M_{1/2}$  and  $m_0$ . The impact of the LEP bound becomes clear once we minimize the fine tuning  $\Delta$  for fixed lightest Higgs mass  $m_H$  (without imposing LEP constraints on the Higgs sector) as a function not only of  $A_0$  and  $\tan\beta$ , but also of  $M_{1/2}$  and  $m_0$ . The result is shown in figure 2.

We see the strong increase of  $\Delta$  with  $m_H$  for  $m_H \gtrsim 108 \text{ GeV}$ . Accordingly the LEP constraint  $m_H \gtrsim 114 \text{ GeV}$  implies  $\Delta \gtrsim 33$  in agreement with figures 1 (for low values of



**Figure 2.**  $\Delta$  as function of the SM-like Higgs mass  $m_H$  in the cMSSM, without imposing LEP constraints on the Higgs sector.

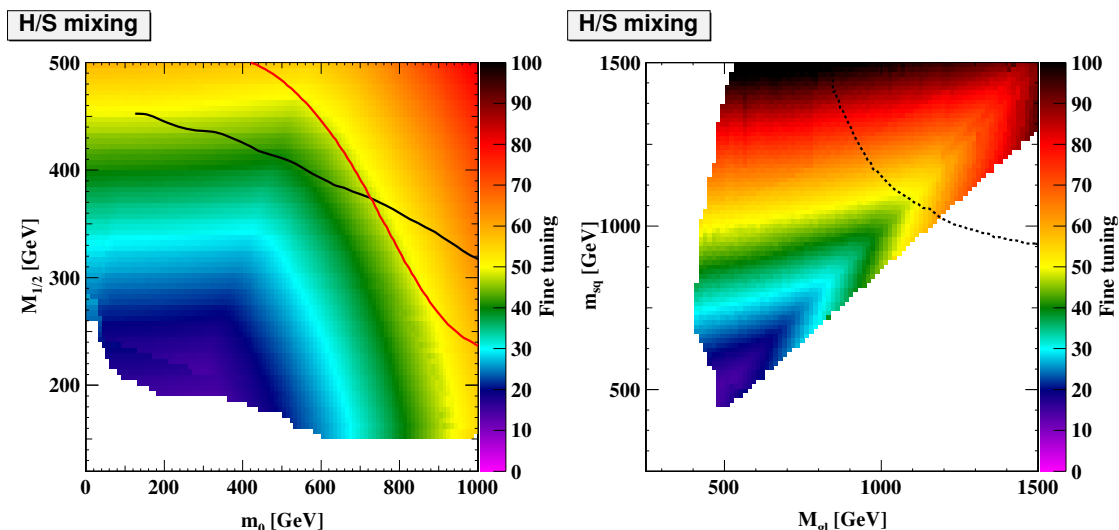
$M_{1/2}$  and  $m_0$ ). In fact,  $m_H$  is always just above 114 GeV in the entire planes in figure 1, once  $A_0$  and  $\tan\beta$  are chosen such that  $\Delta$  is minimized for fixed  $M_{1/2}$  and  $m_0$ , but LEP constraints are applied.

Hence, for low values of  $M_{1/2}$  and  $m_0$  (in the region  $M_{1/2} \lesssim 350$  GeV and  $m_0 \lesssim 700$  GeV),  $\Delta$  is determined by the LEP constraints on  $m_H$  (implying the little fine tuning problem of the MSSM) and not much affected by the lower bounds on gluino and squark masses from early LHC searches: in the region above the ATLAS/CMS bounds, the minimal value of  $\Delta$  increases only to  $\sim 40$ – $50$ .

We also see in figure 2 that  $\Delta$  does not decrease systematically with  $m_H$ , once lower bounds on sparticle masses from LEP and the Tevatron are imposed: in order to minimize  $\Delta$ , preferred values of  $m_H$  would be in the range 100–110 GeV which is excluded in the MSSM, but not in the NMSSM (see below).

For larger values of  $M_{1/2}$  or  $m_0$ , the origin of the required fine tuning is different: here it is simply the fact that the weak scale (determined essentially by  $-2(\mu^2 + m_{H_u}^2)$ ) is small compared to the Susy breaking scale, which requires some tuning between the parameters. Since  $m_{H_u}$  at the Susy scale is closely related to the squark masses,  $\Delta$  increases rapidly with  $m_{\text{squark}}$  (for  $m_{\text{squark}} \gtrsim 1$  TeV) as it is visible in the right panel in figures 1.

The fine tuning in the cMSSM has recently been analysed in [30–33]. The procedure and precision in these papers is similar to ours, except that constraints on the dark matter relic density are applied in [30–33], but contributions to  $\Delta$  from the top Yukawa coupling  $h_t$  are left aside. From figure 7d in [31] we find, once LEP constraints are applied, a minimal value of  $\Delta \sim 70$  for not too large values of  $m_0$ . Given that  $\Delta$  in [31] is twice as large as our  $\Delta$  defined in (1.1), this coincides well with the left panel of figures 1 for moderate values of  $M_{1/2}$ . However, for  $m_0 \gtrsim 800$  GeV,  $\Delta$  decreases to  $\sim 10$  in [31], whereas  $\Delta$  increases with  $m_0$  in the left panel of figures 1. In fact, for larger values of  $m_0$ ,  $\Delta$  is dominated by contributions from  $h_t$  whose absence in [30–33] explains the different results for  $\Delta$  in this region.



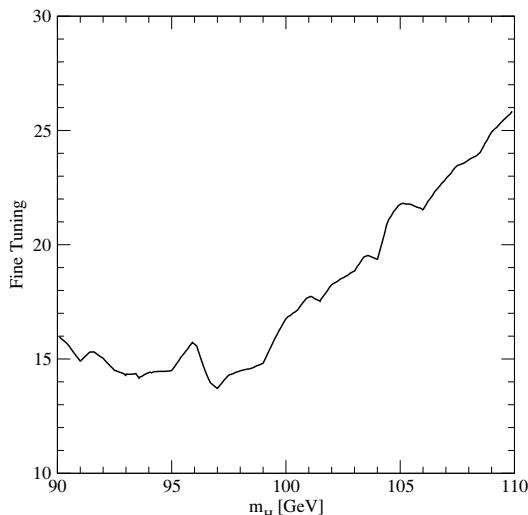
**Figure 3.** The minimal fine tuning  $\Delta$ , defined as in figures 1 for the cMSSM, in the sNMSSM scenario (1).

Next we turn to the sNMSSM. In various regions of the parameter space of the sNMSSM, unconventional properties of the Higgs sector allow to alleviate the LEP bounds, lowering the minimal possible values of  $\Delta$ . We found it interesting to study these lower bounds on  $\Delta$  separately for different scenarios in the NMSSM Higgs sector (see also [18]), since these will have very different implications for future Higgs searches at the LHC. Hence we distinguish subsequently the following two scenarios:

- (1) The lightest CP even Higgs boson  $H_1$  has a large singlet component (H/S mixing). This implies a reduced coupling to the  $Z$  boson, and allows for  $H_1$  masses well below 114 GeV [10].
- (2) A CP-even Higgs boson  $H$  decays dominantly into a pair of lighter CP-odd bosons,  $H \rightarrow AA$ , allowing again for  $H_1$  masses well below 114 GeV [10]. (We omit the index 1 of  $A_1$  in the following.)

The search for the minimal fine tuning  $\Delta$  in each of these scenarios is performed similar to the procedure in the cMSSM: again we scan over a grid of values of  $M_{1/2}$  and  $m_0$ . Now, for each set of these values, we scan over  $A_0$ ,  $\tan\beta$ ,  $\lambda$  and  $A_\kappa$  ( $\kappa$  and  $m_S$  are determined by  $M_Z$  and  $\tan\beta$ , but included in the definition of  $\Delta$ ) using a Monte Carlo Markov Chain (MCMC) technique. Keeping only sets of parameters consistent with all phenomenological constraints, we look for values of  $A_0$ ,  $\tan\beta$ ,  $\lambda$  and  $A_\kappa$  which minimize  $\Delta$  as defined in (1.1) for fixed  $M_{1/2}$  and  $m_0$ , allowing us to represent the resulting minimal values of  $\Delta$  in the plane  $M_{1/2}$ – $m_0$ , or in the plane  $M_{\text{gluino}}$ – $m_{\text{squark}}$ . (In order to distinguish the scenarios above, we require essentially  $\text{BR}(H_1 \rightarrow bb) > 0.7$  for scenario (1), but  $\text{BR}(H_1 \rightarrow AA) > 0.2$  for scenario (2).)

In the scenario (1) (H/S mixing), the corresponding results for  $\Delta$  are shown in figures 3. Now the constraint on the left hand side in the left panel from the absence of a stau LSP has disappeared, since a singlino-like neutralino can be the LSP. From here onwards, the



**Figure 4.**  $\Delta$  as function of the mass  $m_{H_1}$  of the dominantly singlet-like Higgs state in the mixing scenario (1) described above, including constraints from LEP.

bounds from ATLAS and CMS are indicative only, since the signals for supersymmetry in the NMSSM can be different notably in the case of a singlino-like LSP [54].

Compared to the fine tuning in the cMSSM in figures 1, we see that  $\Delta$  can be considerably smaller for not too large values of the Susy breaking parameters  $M_{1/2}$  and  $m_0$  [18]: a large singlet component of  $H_1$  (in the range 0.8–0.85) allows for lighter  $H_1$  masses compatible with LEP constraints, which reduces the required fine tuning, see figure 4 discussed below. The mass of the second mostly SM-like CP-even Higgs boson  $H_2$  is always just above 114 GeV. This is now easier to satisfy than in the MSSM, since the doublet/singlet mixing shifts the mass of the mostly doublet-like Higgs boson upwards. The values of the NMSSM-specific coupling  $\lambda$  do not have to be large to this end; its value is always  $\lesssim 0.01$ .

Respecting just the pre-LHC phenomenological constraints, the fine tuning measure  $\Delta$  can be as small as 14 for low values of  $M_{1/2}$  and  $m_0$  in this scenario, but this is precisely the region which is constrained by the first unsuccessful searches for Susy at the LHC. (As stated above, these constraints depend on the decay properties of the u/d-squarks and gluinos. Additional bino  $\rightarrow$  neutralino decay processes can reduce  $E_T^{\text{miss}}$  signature in all sparticle decay cascades. Applying nevertheless the bounds for the cMSSM scenarios studied by the ATLAS and CMS collaborations to the sNMSSM, we find that the smallest admissible value of  $\Delta$  becomes  $\sim 44$  for  $M_{1/2} \sim 400$  GeV,  $m_0 \sim 600$  GeV, similar to the smallest admissible value of  $\Delta$  in the cMSSM.)

For larger values of  $M_{1/2}$  and  $m_0$ , the fine tuning within this scenario (1) of the sNMSSM becomes similar to the one within the cMSSM: as explained above, the origin of the fine tuning is now the smallness of the weak scale with respect to  $M_{\text{Susy}}$  and not the LEP constraints on the Higgs mass; hence the possibility to alleviate the LEP constraints within the sNMSSM is less relevant.

In figure 4 we show  $\Delta$  as function of the mass  $m_{H_1}$  of the dominantly singlet-like Higgs state, minimizing  $\Delta$  as a function of  $m_0$ ,  $M_{1/2}$ ,  $A_0$ ,  $\tan\beta$  taking into account LEP

constraints from Higgs and sparticle searches. (The irregular structures originate from the LEP constraints on  $H_1 \rightarrow b\bar{b}$ , which lead to irregular upper bounds on the coupling of  $H_1$  to the  $Z$  boson as function of  $m_{H_1}$ .) Again,  $\Delta$  does not decrease systematically with decreasing  $m_{H_1}$  given the phenomenological constraints on sparticle masses, but the behaviour is somewhat different from the dependence of  $\Delta$  on the SM-like Higgs mass in the MSSM. Here we find that  $\Delta$  is minimal for  $m_{H_1}$  below  $\sim 100$  GeV which coincides with the Higgs mass range where a  $2.3 \sigma$  excess in  $H \rightarrow b\bar{b}$  is observed at LEP 2 [10]. (This excess could be explained here since, although  $H_1$  is dominantly a gauge singlet, it still has a nonvanishing — but reduced — coupling to the  $Z$  boson, and will decay dominantly into  $b\bar{b}$ .)

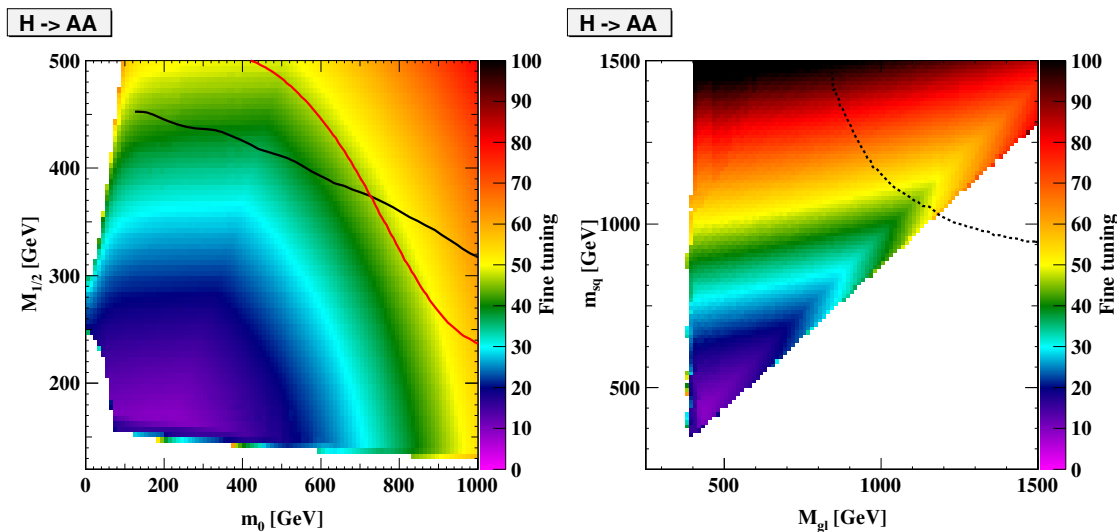
Next we turn to the sNMSSM scenario (2) involving light pseudoscalars  $A$ , into which the SM-like CP-even Higgs boson  $H$  can decay. Again the required fine tuning is reduced [21, 22], since LEP constraints allow for smaller  $H$  masses than 114 GeV. These constraints depend on  $m_A$ :

- a) For  $m_A \gtrsim 10.5$  GeV,  $A$  will dominantly decay into a pair of  $b\bar{b}$  quarks. This signature has been studied by the OPAL and DELPHI groups at LEP [55, 56] implying  $m_H \gtrsim 105$ –110 GeV if  $H$  has SM-like couplings to the  $Z$  boson [10]. Still, this lower bound on  $m_H$  allows for lower values of  $\Delta$ .
- b) For  $m_A \lesssim 10.5$  GeV,  $A$  decays dominantly into a pair of  $\tau$  leptons. The signature  $H \rightarrow AA \rightarrow 4\tau$  has recently been re-analysed by the ALEPH group [57] for  $m_A < 12$  GeV, implying again lower limits on  $m_H$ . However, for  $m_A$  in the range  $9 \text{ GeV} \lesssim m_A \lesssim 10.5 \text{ GeV}$ ,  $A$  can and will mix strongly with the CP-odd  $\eta_b(nS)$  states [58] which implies a considerable reduction of the  $\text{BR}(A \rightarrow \tau^+\tau^-)$  [59]. Hence bounds on  $H \rightarrow AA \rightarrow 4\tau$  hardly constrain  $m_H$  in this case; now we find that the dominant constraints result from the lower limits on  $m_H$  depending on remaining sub-dominant  $\text{BR}(H \rightarrow b\bar{b})$  [10].

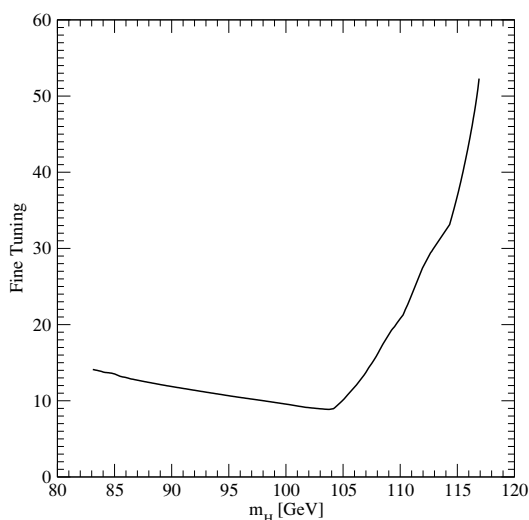
Our results for the minimal fine tuning  $\Delta$  in the sNMSSM scenario (2) are shown in figures 5 in the same planes as before. Similar to the sNMSSM scenario (1), respecting just the pre-LHC constraints, the fine tuning measure  $\Delta$  can be as small as 9 for low values of  $M_{1/2}$  and  $m_0$ . Applying naively the bounds for the cMSSM scenarios studied by the ATLAS and CMS collaborations to the sNMSSM, we find that the smallest admissible value of  $\Delta$  becomes  $\sim 39$  for  $M_{1/2} \sim 375$  GeV,  $m_0 \sim 700$  GeV, hence below the smallest admissible value in the cMSSM.

In the region of low  $\Delta$ , the  $\text{BR}(H \rightarrow AA)$  is larger than 80%. Again, the values of the NMSSM-specific coupling  $\lambda$  do not have to be large in order to favour  $H \rightarrow AA$  decays once these are kinematically allowed; the value of  $\lambda$  varies between 0.02 and 0.16 in figures 5.

In figure 6 we show the minimal value of  $\Delta$  as function of the mass  $m_H$  of the now SM-like state  $H$ , imposing LEP constraints. Again the preferred value of  $m_H$  is not always as small as possible; now the minimal fine tuning is obtained for  $m_H$  in the range 100–105 GeV, and increases again strongly for larger values of  $m_H$ .



**Figure 5.** The minimal fine tuning  $\Delta$ , defined as in figures 1 for the cMSSM, in the sNMSSM scenario (2).

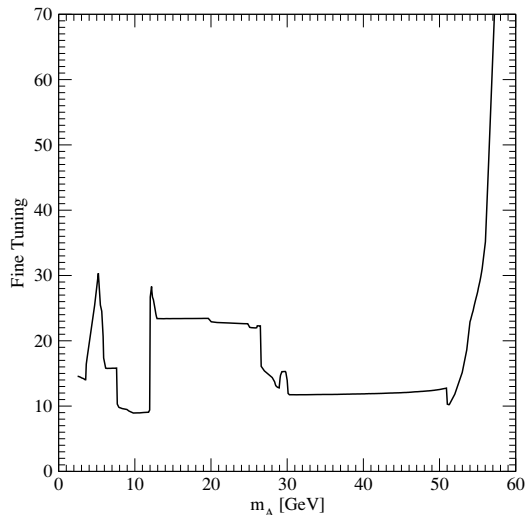


**Figure 6.**  $\Delta$  as function of  $m_H$  in the scenario (2), once LEP constraints are imposed.

It is also interesting to study the dependence of the fine tuning on  $m_A$ . At first sight,  $\Delta$  depends hardly on  $m_A$  within the sNMSSM, where  $A_\kappa$  differs from  $A_0$  at the GUT scale: a variation of  $m_A$  from 0 to  $\sim 50$  GeV (still allowing for  $H \rightarrow AA$  decays) corresponds to a variation of  $|A_\kappa|$  from  $\sim 5$  GeV to  $\sim 40$  GeV at the GUT scale, which has practically no effect on the fine tuning measure  $\Delta$ . However, different values for  $m_A$  correspond to different lower LEP bounds on  $m_H$ ; lower bounds  $m_H$ , in turn, affect  $\Delta$  as in figure 6. The resulting minimal values of  $\Delta$  as function of  $m_A$  are shown in figure 7.

The structures in figure 7 can be explained as follows: for  $m_A \gtrsim 11$  GeV, LEP bounds on  $H_2 \rightarrow H_1 H_1 \rightarrow 4b$  (here with  $H_2 \sim H$ , and  $H_1 \sim A$ ) apply, see figures 3 in [10].





**Figure 7.**  $\Delta$  as function of  $m_A$  in the scenario (2), once LEP constraints are imposed.

The corresponding lower bounds on  $m_H$  are somewhat weaker for  $m_A \gtrsim 30$  GeV than for  $11 \text{ GeV} \lesssim m_A \lesssim 30 \text{ GeV}$ , leading to a lower fine tuning for  $m_A \gtrsim 30$  GeV where  $m_H \gtrsim 106$  GeV. (For  $m_A \sim 51$  GeV, the lower bound on  $m_H$  has a dip implying a dip in  $\Delta$ . For  $m_A \sim 57$  GeV,  $\Delta$  increases since  $m_H > 2m_A > 114$  GeV is required for kinematic reasons; here this scenario is obviously not preferred.) For  $m_A \lesssim 11$  GeV, strong lower bounds on  $m_H$  from ALEPH [57] on the BR( $H \rightarrow AA \rightarrow 4\tau$ ) apply at first sight. However, due to a reduced branching ratio for  $A \rightarrow 2\tau$  from  $A - \eta_b$  mixing [59], the window  $9 \text{ GeV} \lesssim m_A \lesssim 11 \text{ GeV}$  is hardly affected by these constraints, allowing for  $m_H$  to assume values for which  $\Delta$  is minimal according to figure 6. (For  $m_A \sim 5$  GeV, parameters have to be tuned in order to satisfy constraints from  $B_s \rightarrow \mu^+ \mu^-$ .) Hence we find two distinct regions for  $m_A$  where  $H \rightarrow AA$  decays allow for a considerable reduction of the fine tuning.

#### 4 Conclusions

We have studied the amount of fine tuning in the parameter space of the semi-constrained NMSSM, and compared it to the cMSSM. Representing the minimal fine tuning in the plane  $M_{1/2} - m_0$  allowed us to study the impact of early LHC results. First we verified quantitatively, to what extent the NMSSM-specific scenarios in the Higgs sector allow to alleviate the LEP constraints with respect to the MSSM. We found indeed that a considerable reduction of the fine tuning is possible in scenarios where the lightest CP-even Higgs state is dominantly singlet like, or in scenarios where  $H \rightarrow AA$  decays are possible, notably for  $m_A \sim (10 \pm 1) \text{ GeV}$  and  $30 \text{ GeV} \lesssim m_A \lesssim 55 \text{ GeV}$ .

If one applies naively the early LHC constraints on the cMSSM in the  $M_{1/2} - m_0$ -plane to the sNMSSM, the impact on the minimal fine tuning is stronger in the sNMSSM since these constraints affect in particular the region of smaller Susy breaking terms where the fine tuning in the sNMSSM can be relatively small. Still, the necessary fine tuning in the sNMSSM in scenarios where  $H \rightarrow AA$  decays are possible is smaller than in the cMSSM,



but only if the Susy breaking terms are not too large (hence if sparticles are not too heavy). Otherwise, if the Susy breaking terms are larger, the fine tuning does not originate from LEP constraints on the Higgs sector, but from the smallness of the weak scale with respect to the Susy scale. This hardly depends on details of the Higgs sector of the Susy model, as long as the fundamental parameters are defined at the GUT scale and influence each other through the renormalization group running between the GUT and the weak scale. Hence the same question should be re-analysed in the NMSSM with gauge mediated supersymmetry breaking [60], where the Susy breaking parameters can originate from much lower scales, and where the Susy breaking Higgs mass terms can differ considerably from squark mass terms.

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