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Higgs bosons in the Next-to-Minimal Supersymmetric Standard Model

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We discuss how decays of Higgs bosons into light pseudoscalars A_1 reduce the required fine tuning in the parameter space of the constrained NMSSM as compared to the MSSM, notably for $M_{A_1} \sim 10$ GeV where $A_1 - \eta_b$ mixing is relevant. Due to the induced dominant $A_1 \to gg$ decays, the search for jet substructures seems to be the only hope for Higgs discovery at the LHC in such a scenario.

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The first motivation for supersymmetric extensions of the Standard Model (SM) stems from the solution of the naturalness or finetuning problem in the Higgs sector of the SM. Since LEP has established a lower bound of about 114 GeV on the mass M_h of a SM-like Higgs boson, it has become clear that the Minimal Supersymmetric Standard Model (MSSM) suffers from a so-called “little hierarchy problem”.

The origin of the little hierarchy problem can be understood as follows. The Lagrangian of the MSSM in the Higgs sector contains two doublets H_u and H_d, soft supersymmetry (Susy) breaking mass terms $m_{H_u}^2$ and $m_{H_d}^2$ for these scalars, additional *supersymmetric* mass terms μ^2 (whose origin is difficult to understand), and quartic couplings depending on the electroweak gauge couplings g_1 and g_2. In the approximation $\langle H_u\rangle \gg \langle H_d\rangle$ (neglecting terms $\sim \tan^{-2}\beta$), the tree level potential V reads simply

$$V \simeq \left(m_{H_u}^2+\mu^2\right)|H_u|^2+\frac{g_1^2+g_2^2}{8}|H_u|^4\,. \tag{1}$$

From $M_Z^2=\left\langle H_u^2\right\rangle \frac{g_1^2+g_2^2}{2}$ we find the condition

$$-2(m_{H_u}^2+\mu^2)\stackrel{!}{=}M_Z^2\,. \tag{2}$$

In the absence of any finetuning, we should have $M_Z^2 \approx \mu^2 \approx -m_{H_u}^2$. However, the SM-like Higgs mass M_h is approximately given by

$$M_h^2 \sim M_Z^2+\frac{3m_{top}^2}{4\pi^2\left\langle H_u\right\rangle^2}\ln\left(\frac{M_{stop}^2}{m_{top}^2}\right)+\dots \tag{3}$$

For $M_h \gtrsim 114$ GeV we need $M_{stop} \gtrsim 1$ TeV, and but large values for M_{stop} induce $m_{H_u}^2 \sim -M_{stop}^2$ via radiative corrections between the weak and the GUT scale. $m_{H_u}^2 \sim 1$ TeV^2 requires to tune μ^2 in Eq. (2) with a precision of $\approx 1\%$.

In the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [1], an additional gauge singlet superfield S generates an effective μ_{eff}-term through its vacuum expectation value, $\mu_{eff} = \lambda\left\langle S\right\rangle$, where λ is a Yukawa coupling. Apart from generating automatically a μ-term of the desired order, the NMSSM has more physical states in the (neutral) Higgs sector as the MSSM: 3 neutral CP-even, and two neutral CP-odd states. The lightest CP-odd state A_1 can be quite light ($0 < M_{A_1} \lesssim 50$ GeV) without contradicting any bounds. In this case the SM-like Higgs boson h would decay dominantly as $h \to A_1A_1$, and LEP constraints on M_h are alleviated: essentially one is left with constraints on $h \to 4b$ (if $M_{A_1} \gtrsim 10.5$ GeV) from DELPHI/OPAL [2, 3], and on $h \to 4\tau$ (if $M_{A_1} \lesssim 10.5$ GeV) from ALEPH [4].

The region 9.5 GeV $\lesssim M_{A_1} \lesssim$ 10.5 GeV is particularly interesting: here A_1 would mix with the CP-odd $b\bar{b}$ bound states $\eta_b(nS)$. The mass of the only observed state $\eta_b(1S)$ by BaBar [5, 6] is actually somewhat below expectations from QCD for the hyperfine splitting $M_{\Upsilon(1S)}-M_{\eta_b(1S)}$. This could be explained by $A_1-\eta_b(1S)$ mixing, if M_{A_1} is in the above range [7]. However, the width for any decay $\eta_b(nS)\to gg$ is much larger than the width $A_1\to\tau^+\tau^-$. Consequently a tiny $A_1-\eta_b(nS)$ mixing angle suffices such that the physical eigenstate decays dominantly into gg [8], and the ALEPH constraints do not apply.

In general, $h \to A_1A_1$ decays alleviate the lower bounds on M_h from LEP and hence the little fine tuning problem [9, 10, 11]. Taking possible $A_1-\eta_b(nS)$ mixing into account, the corresponding remaining finetuning in the constraint NMSSM (cNMSSM) has been studied in [12] and

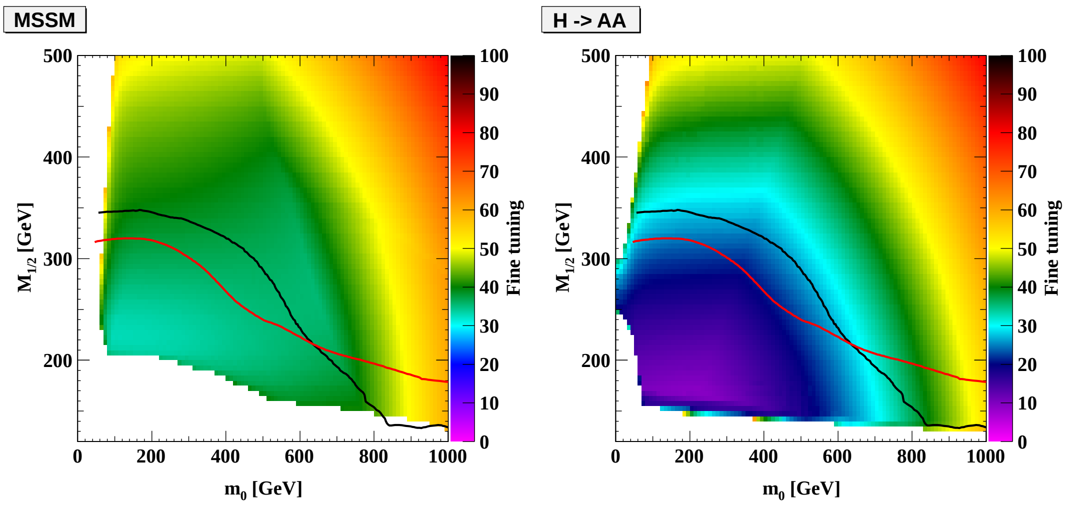

Figure 1: Δ in the plane $m_0 - M_{1/2}$ for the cMSSM and the cNMSSM. Bounds within specific cMSSM scenarios from ATLAS [13] are indicated as black lines, and from CMS [14] as red lines.

compared to the cMSSM. Here, the finetuning measure is defined as

$$\Delta = Max\left\{\left|\frac{\partial \ln(M_Z)}{\partial \ln(p_i^{\mathrm{GUT}})}\right|\right\}, \tag{4}$$

where p_i^{GUT} are the parameters at the GUT scale:

$$p_i^{\mathrm{GUT}} = m_0,\ M_{1/2},\ A_0,\ h_t,\ \ldots \tag{5}$$

For fixed m_0, $M_{1/2}$ (universal scalar and gaugino masses) we look for the minimum of Δ as function of A_0, $\tan(\beta)$, $\ldots$; the minimal value of Δ can be represented in the plane m_0, $M_{1/2}$ for the cMSSM and the cNMSSM: We see in Fig. 1 that, for $M_{1/2} \lesssim 400$ GeV and $m_0 \lesssim 800$ GeV, the amount of finetuning in the cNMSSM ($\gtrsim 10$) can be considerably less than in the cMSSM ($\gtrsim 33$) due to lower possible values of M_h due to allowed $h \to A_1 A_1$ decays, although most of this region is now excluded by fruitless searches for supersymmetry with low M_{Susy} at the LHC. (However, these negative results are not necessarily applicable to the cNMSSM, notably for a singlino-like LSP.)

It is interesting to study the dependence of the finetuning Δ on M_{A_1} in the cNMSSM in Fig. 2. We see that Δ is particularly low for $M_{A_1} \sim 10$ GeV (where h can be light due to the absence of constraints from $h \to 4\tau$), and for 30 GeV $\lesssim M_{A_1} \lesssim 50$ GeV where the constraints on M_h from $H \to 4b$ are weak.

It is clear that, for any value of M_h and M_{A_1}, the search for a SM-like Higgs boson decaying as $H \to A_1 A_1 \to \ldots$ is a challenge at the LHC (see [15] and references therein). Notably the interesting case $M_{A_1} \approx 10$ GeV, where $A_1 \to gg$ dominates, seems hopeless at first sight.

However, the search for jet substructures can be applied to such a situation [16, 17, 18, 19, 20]. Here one concentrates on associate h production with a $W^{\pm}$, and triggers on an isolated lepton from $W^{\pm} \to l^{\pm} + \nu$. Then one studies $h \to A_1 A_1 \to 2$ (fat) jets j from each A_1. Typically one requires jet transverse momenta $p_{T_j} > 100$, 50 GeV (or 200 GeV) allowing to study a boosted Higgs. Then

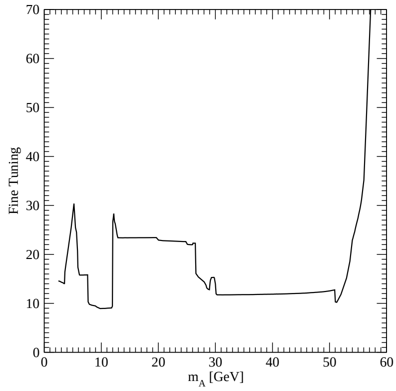

Figure 2: Dependence of the finetuning Δ on M_{A_1} in the cNMSSM

one looks for substructures in jets j with $m_j \lesssim 12$ GeV, which are supposed to originate from an A_1 decay into 2 gluons: Undoing the last recombination step of the clustering algorithm from j_1, j_2 to j, one requires $m_{j_1} \sim m_{j_2} \ll m_j$. Finally one looks for a peak in the dijet mass $m_{jj} \sim m_h$. A possible result (from [16], with $m_h = 120$ GeV, 30 fb^{-1} luminosity) is shown in Fig. 3. Hence, as also indicated in [17, 18, 19, 20], such a search seems feasible.

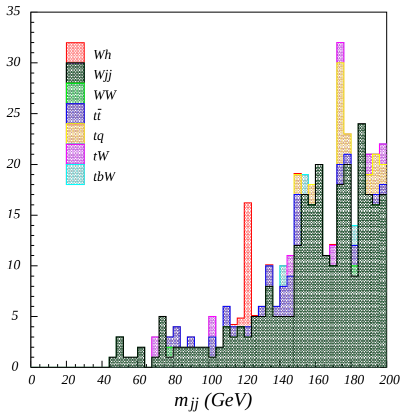

Figure 3: Possible result for the dijet mass m_{jj} for $m_h = 120$ GeV, from [16]

To summarize, the scenario with a light pseudoscalar A_1 with $M_{A_1} \approx 10$ GeV in the NMSSM is particularly interesting, and particularly challenging: due to $A_1 - \eta_b(1S)$ mixing and the resulting dominant $A_1 \to gg$ decays, bounds from LEP on $h \to A_1 A_1$ are particularly weak. This allows for scenarios with particularly low finetuning in the (c)NMSSM. But, precisely this final state in Higgs decays is very difficult to detect. In this scenario, the search for jet substructures seems to be the only hope for a Higgs discovery at the LHC.

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