Constrained Next-to-Minimal Supersymmetric Standard Model

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(Received 3 March 2008; published 2 September 2008)

We consider the fully constrained version of the next-to-minimal supersymmetric extension of the standard model (cNMSSM) in which a singlet Higgs superfield is added to the two doublets that are present in the minimal extension (MSSM). Assuming universal boundary conditions at a high scale for the soft supersymmetry-breaking mass parameters as well as for the trilinear interactions, we find that the model is more constrained than the celebrated minimal supergravity model. The phenomenologically viable region in the parameter space of the cNMSSM corresponds to a small value for the universal scalar mass m_0: in this case, one single input parameter is sufficient to describe the model's phenomenology once constraints from collider data and cosmology are imposed.

DOI: 10.1103/PhysRevLett.101.101802 PACS numbers: 12.60.Jv, 12.10.−g, 12.60.Fr

Supersymmetric extensions of the standard model of particle physics are motivated by the solution of the hierarchy problem, the unification of the scale dependent gauge couplings at a common grand unification scale M_{GUT}, and the possibility to explain the presence of dark matter in the form of the lightest supersymmetric (SUSY) particle (LSP). Unfortunately, general supersymmetric extensions do not make precise predictions for the spectrum of the Higgs scalars and the additional supersymmetric particles (so-called sparticles), since they involve a large number of unknown parameters, in particular, numerous soft SUSY-breaking mass terms and couplings. Hopefully, at least some of the Higgs scalars and sparticles will be detected in the near future at the LHC.

The next-to-minimal supersymmetric standard model (NMSSM) [1–3], in which the spectrum of the minimal extension (MSSM) is extended by one singlet superfield, was among the first SUSY models based on supergravity-induced SUSY-breaking terms. It has gained a renewed interest in the last decade, since it solves in a natural and elegant way the so-called μ problem [4] of the MSSM; in the NMSSM μ is linked to the vacuum expectation value (vev) of the singlet Higgs field, generating a value close to the SUSY-breaking scale. Furthermore, it leads to an interesting phenomenology as the MSSM spectrum is extended to include an additional CP-even and CP-odd Higgs state as well as a fifth neutralino, the singlino.

In contrast to the non- or partially constrained versions of the NMSSM that have been intensively studied in the recent years [5] and which involve many free parameters, the constrained model (cNMSSM) has soft SUSY-breaking parameters that are universal at a high scale. This is motivated by schemes for SUSY-breaking that are mediated by (flavor blind) gravitational interactions, and leads to a more predictive model as the number of unknown parameters is reduced to a handful.

In the present Letter we investigate which regions of the parameter space of the cNMSSM satisfy simultaneously constraints from colliders (essentially lower bounds on the lightest Higgs scalar from LEP [6]), B-physics, and which give rise to a dark matter relic density consistent with the latest Wilkinson Microwave Anisotropy Probe (WMAP) constraints [7]. We find, remarkably, that essentially only *one single parameter* is sufficient to describe the features (the Higgs and sparticle spectrum) of the phenomenologically acceptable cNMSSM. This makes the model much more predictive than the celebrated constrained version of the MSSM (cMSSM). In addition, as will be shown, the phenomenology differs considerably in the two scenarios.

In the following, we consider the NMSSM with a scale invariant superpotential given by [1–3] $\mathcal{W} = \lambda S H_u H_d + \frac{\kappa}{3} S^3 + \ldots$, where the two terms shown substitute the $\mu H_u H_d$ term in the MSSM superpotential and we have omitted the usual generalization of the Yukawa interactions. The soft SUSY-breaking terms consist of mass parameters for the gauginos $M_{1,2,3}$, sfermions $m_{\tilde{F}_{L,R}}$ and Higgs fields $m_{H_{u,d}}$ and trilinear interactions A_f as in the MSSM, supplemented by an additional scalar mass m_S and two trilinear couplings A_κ and A_λ for the singlet field. Once the unification of the soft SUSY-breaking masses ($M_{1,2,3} \equiv M_{1/2}$, $m_{\tilde{F}_{L,R}} = m_{H_{u,d}} = m_S \equiv m_0$) and trilinear couplings ($A_f = A_\kappa = A_\lambda \equiv A_0$) at the scale M_{GUT} is imposed, the Higgs and sparticle sectors of the cNMSSM depend on the five parameters $M_{1/2}$, m_0, A_0, λ, and κ. The correct value for M_Z reduces the dimension of the parameter space from five to four; e.g., κ can be determined in terms of the other parameters. (Hence, the number of continuous free parameters in the cNMSSM is the same as in the cMSSM [8].)

General features of the cNMSSM parameter space as well as its phenomenology have been discussed earlier in [2,3]. Since the early studies, bounds on the Higgs and SUSY particle spectrum from high-energy collider data and low-energy measurements have become more severe, while important inputs such as the top quark mass are more accurately measured [9]. In addition, tools for a more precise determination of the mass spectrum and couplings

[10], and the cosmological dark matter relic density [11] have become available. In this Letter, we reinvestigate the parameter space of the cNMSSM in the light of these recent constraints, using the updated tools.

In agreement with the earlier studies, our results reveal that the allowed range for the parameters $M_{1/2}$, m_0, and A_0 is different from that of the cMSSM. In the cMSSM, small values for m_0 are disfavored as they lead to charged sleptons that are lighter than the neutralino χ_1^0 (the preferred LSP, which should be neutral). On the other hand, small m_0 is needed in the cNMSSM: To generate a nonvanishing vev of the singlet, the inequality $m_0 \lesssim \frac{1}{3}|A_0|$ has to hold [2]. The slepton LSP problem can be evaded in the cNMSSM owing to the presence of the additional singlinolike neutralino which, in large regions of the parameter space, is the true LSP [12].

However, two conditions have to be satisfied in order that the relic density of the singlinolike neutralino is not too large. First, its mass has to be close to (but below) the mass of the next-to-LSP, which is always the lighter (mostly right-handed) $\tilde{\tau}_1 \sim \tilde{\tau}_R$ in the present case: only then the singlino can coannihilate sufficiently rapidly with the next-to-LSP [13]. This first condition allows us to understand qualitatively which region of the cNMSSM remains viable: Replacing the analytic approximation for $\langle S\rangle$ (for $\langle S\rangle$ large) [2] into the expression for the mass squared of the singlinolike neutralino χ_S and using $A_\kappa \sim A_0$, $m_s^2 \sim m_0^2$, one obtains $m_{\chi_S}^2 \simeq \frac{1}{2}(A_0^2 + |A_0|\sqrt{A_0^2 - 8m_0^2}) - 2m_0^2$. An analytic approximation for the right-handed stau mass at the weak scale is [2] $m_{\tilde{\tau}_R}^2 \lesssim m_0^2 + 0.1M_{1/2}^2$. From $m_{\chi_S}^2 \sim m_{\tilde{\tau}_R}^2$ and $m_0 \lesssim \frac{1}{3}|A_0|$ one would then obtain $m_0^2 \lesssim \frac{1}{30}M_{1/2}^2$. In practice, however, all approximations above tend to overestimate m_0, and the stronger bound $m_0 \lesssim \frac{1}{12}M_{1/2}$ holds. Within this remaining allowed domain, m_0 has a small effect on the Higgs and sparticle spectrum, and the WMAP constraint determines A_0 as a function of $M_{1/2}$.

Secondly, $M_{1/2}$ must not be too large (similar to the cMSSM [14]): The dominant annihilation of R-odd sparticles is via $\tilde{\tau}_1\tilde{\tau}_1 \to$ SM particles. The rate decreases with $M_{1/2}$, becoming too small for $M_{1/2} \gtrsim$ 2–3 TeV.

As will be discussed below, LEP constraints on the Higgs sector imply $\lambda \lesssim 10^{-2}$. Then, also this parameter has practically no effect on the remaining particle spectrum: For $m_0 \lesssim \frac{1}{12}M_{1/2}$, $\lambda \lesssim 10^{-2}$ and A_0 fixed in terms of $M_{1/2}$, the complete Higgs and sparticle spectrum depends essentially only on $M_{1/2}$, as claimed above.

For our analysis of the phenomenologically acceptable region in the parameter space $M_{1/2}$, m_0, A_0, λ we employ the routine NMSPEC within NMSSMTOOLS [10], which calculates the spectra of the Higgs and SUSY particles in the NMSSM in terms of the soft SUSY-breaking terms at M_{GUT}. In practice, the following procedure is adopted: In addition to M_Z, one allows for five input parameters

$$M_{1/2},\ m_0,\ A_0,\ \lambda,\ \text{and}\ \tan\beta. \tag{1}$$

The parameters κ and the soft singlet mass squared m_S^2 are both determined at M_{SUSY} via the minimization equations of the scalar potential. [The vev $\langle S\rangle$ or $\mu_{\mathrm{eff}} \equiv \lambda\langle S\rangle$ is also fixed through the third independent minimization equation, leaving sign (μ_{eff}) undetermined.]

Clearly, at M_{GUT}, m_S^2 will in general not coincide with m_0^2. However, one can choose $\tan\beta$ such that the difference between m_S^2 and m_0^2 is negligibly small, which leaves us with the original four-dimensional parameter space.

Since we always obtain m_0 much smaller than $M_{1/2}$, we first explore the cNMSSM parameter space defined by arbitrary values of $M_{1/2}$, A_0, and λ, assuming μ_{eff} positive and $m_0 = 0$. (Note that vanishing values for m_0 are naturally obtained in supergravity models with Kähler potentials of the no-scale type [15]; however, the additional no-scale prediction $A_0 = 0$ is difficult to realize in the cNMSSM.) $\tan\beta$ is determined by the requirement that $m_S(M_{\mathrm{GUT}}) < 5$ GeV, which typically requires that we tune the fourth decimal of $\tan\beta$ (this should not be interpreted as a fine tuning, since m_S^2 should be considered as an input parameter, whereas $\tan\beta$ is determined by the minimization of the effective potential).

For this set of parameters, we select the cNMSSM space which survives once one imposes theoretical requirements such as correct electroweak symmetry breaking, perturbative couplings at the high scale, the absence of tachyonic masses, a neutralino LSP, etc., and phenomenological constraints such as the LEP bounds on Higgs boson masses and couplings, collider bounds on the SUSY particle masses [9], experimental data from B-meson physics [16] and from the anomalous magnetic moment of the muon [17], and a relic density compatible with cosmological data [7]. For $\lambda \lesssim 10^{-2}$, as discussed below, the phenomenologically allowed region is nearly independent of the input λ.

Leaving aside, for the time being, the WMAP constraints on the LSP relic density Ωh^2, but including all the other constraints above, the phenomenologically allowed region in the $[M_{1/2}, A_0]$ plane is shown in Fig. 1.

This allowed region is bounded from below, i.e., for large absolute values of $|A_0|$, by the absence of a charged (generally tau slepton) LSP as in the cMSSM for $m_0 = 0$; inside the allowed region, the LSP is a singlinolike state. The upper bound at $A_0 \sim 0$ follows from the positivity of the mass squared of the singletlike CP-odd Higgs boson, which is given to a good approximation by $-3\kappa A_\kappa\langle S\rangle$, $\kappa\langle S\rangle$ being positive, and $A_\kappa \sim A_0$. To the left, i.e., towards smaller values of $M_{1/2}$, the allowed region is bounded simultaneously by the condition that the lightest tau slepton mass must be above $\sim$100 GeV from its nonobservation at LEP, and the mass of the lightest SM-like CP-even Higgs boson above $\sim$114 GeV.

To the right, i.e., towards larger values of $M_{1/2}$, it becomes impossible to satisfy the WMAP constraints on the dark matter relic density (see the discussion above). For $m_0 = 0$, this upper bound on $M_{1/2}$ is $M_{1/2} \lesssim 2$ TeV. Inside this allowed region, $\tan\beta$ turns out to be quite large (see

Ref. [18] for earlier work on the cNMSSM at large $\tan\beta$). In Fig. 1, we have indicated lines corresponding to constant $\tan\beta = 25$, 30, 33, and 35.

As a next step, we require that the WMAP constraint on the relic density of the χ_1^0 dark matter (DM) candidate, calculated using the program MICROMEGAS [11], is satisfied. Given the actual small error bars, $0.094 \lesssim \Omega_{\chi_1^0} h^2 \lesssim 0.136$ at the 2σ level [7], this constraint (if satisfied at all) reduces the parameter space of any model to a lower dimensional hypersurface. Within the allowed region in Fig. 1, the correct relic density for χ_1^0 is obtained along the line close to the lower boundary (DM line), where the mass of the singlinolike LSP is close to the mass of the next-to-LSP which is the lightest tau slepton $\tilde{\tau}_1$, $M_{\tilde{\tau}_1} - M_{\chi_1^0} \sim 3$ to 5 GeV (the mass difference being smaller for larger $M_{1/2}$). From the analytic approximations above, one then obtains $A_0 \sim -\frac{1}{4} M_{1/2}$. Near the upper boundary, the mass of the LSP becomes very small, implying a far too large relic density.

As mentioned previously, we have checked that constraints from B physics [16], such as the branching ratio for the radiative decays $b \to s\gamma$, are satisfied. Moreover, we find that the supersymmetric contribution $\delta a_\mu^{\mathrm{SUSY}}$ to the anomalous magnetic moment of the muon accounts for the $\sim 3\sigma$ deviation from the SM expectation [17]: along the DM line, $\delta a_\mu^{\mathrm{SUSY}}$ decreases from $\sim 4.2 \times 10^{-9}$ for $M_{1/2} \sim 400$ GeV to $\sim 0.2 \times 10^{-9}$ for $M_{1/2} \sim 1.5$ TeV. In view of a desired value $\delta a_\mu^{\mathrm{SUSY}} \sim (2.7 \pm 2) \times 10^{-9}$, the region $M_{1/2} \lesssim 1$ TeV is thus preferred by this observable.

The Higgs, neutralino, and stau masses are shown in Fig. 2 where we also indicate the corresponding values of A_0. The essential features of the Higgs spectrum are as follows. For $M_{1/2} \lesssim 660$ GeV, the lightest CP-even Higgs boson has a dominant singlet component, hence a very small coupling to the Z boson, which allows it to escape LEP constraints. The next-to-lightest CP-even scalar is SM-like, with a mass slightly above 114 GeV. The lightest CP-odd scalar is again singletlike, with a mass above ~ 120 GeV. The heaviest CP-even and CP-odd scalars are practically degenerate with the charged Higgs boson, with masses above ~ 520 GeV. For $M_{1/2} \gtrsim 660$ GeV, the lightest CP-even scalar is SM-like with a mass increasing slightly with $M_{1/2}$ up to ~ 120 GeV, while the next-to-lightest CP-even scalar is now singletlike.

The right-hand side of Fig. 2 displays the neutralino and stau spectrum, the lighter stau $\tilde{\tau}_1$ being the next-to-LSP with a mass ~ 3 to 5 GeV above the one of the χ_1^0 singlino-like LSP. χ_2^0 and χ_3^0 are, respectively, B-ino- and W-ino-like while the nearly degenerate $\chi_{4,5}^0$ states are Higgsino-like. The charginos $\chi_1^\pm$ and $\chi_2^\pm$ are nearly degenerate in mass with, respectively, χ_3^0 and $\chi_{4,5}^0$. The remaining sparticle spectrum is very "cMSSM"-like and can be obtained by running the program NMSPEC [10] with input parameters as in Fig. 3 below (and $m_0 \approx 0$) and also by using any cMSSM-based code, since the singlet sector practically decouples from the SUSY spectrum. One approximately obtains $m_{\tilde{g}} \approx m_{\tilde{q}} \approx 2M_{1/2}$ for the gluino and (first or second generation) squark masses.

Let us now discuss the impact of other values of the parameters m_0 and λ. As already stated above, the Higgs and sparticle spectra change very little with λ provided that it remains small enough. Upper bounds on λ result from LEP constraints on Higgs scalars with masses below the SM limit of ~ 114 GeV. For $M_{1/2} \lesssim 660$ GeV, increasing λ increases the mixing of the singletlike CP-even scalar with doubletlike CP-even scalars and hence its couplings to the Z boson, which must not be too large. For $M_{1/2} \gtrsim 660$ GeV, a stronger mixing among the CP-even scalars can lower the mass of the lighter Higgs boson which is now SM-like, until it violates the LEP bound.

Figure 3 shows the corresponding upper limits on the parameter λ, which are particularly strong in the "crossover" region near $M_{1/2} \sim 660$ GeV, where relatively small values of λ can generate a large mixing angle; in all cases, one has $\lambda \lesssim 0.02$. For completeness, we also show the values of $\tan\beta$ along the DM line.

We have also investigated the cNMSSM parameter space for nonzero m_0. However, for $M_{1/2} \approx 400$ GeV only $m_0 \lesssim 20$ GeV is viable. For large values of $M_{1/2} \gtrsim 2$ TeV,

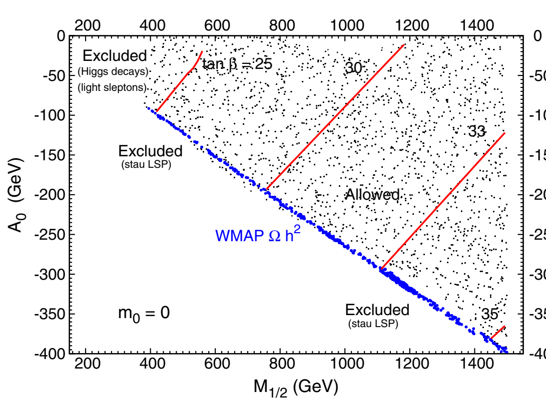

FIG. 1 (color online). The viable cNMSSM region in the $[M_{1/2}, A_0]$ plane for $m_0 \sim 0$ and $\lambda = 2 \times 10^{-3}$, once theoretical, collider and cosmological constraints have been imposed.

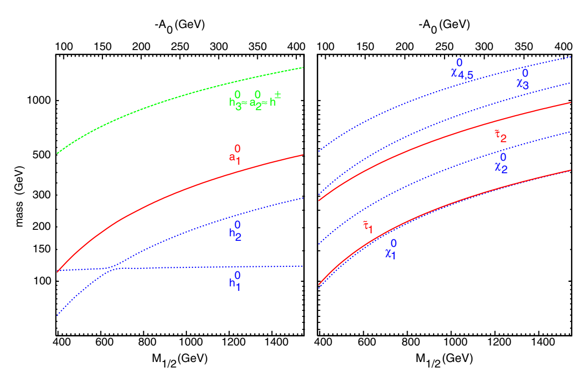

FIG. 2 (color online). The Higgs (left) and neutralino plus stau (right) mass spectra in GeV as a function of $M_{1/2}$ along the DM line; the values of A_0 are indicated in the upper axis.

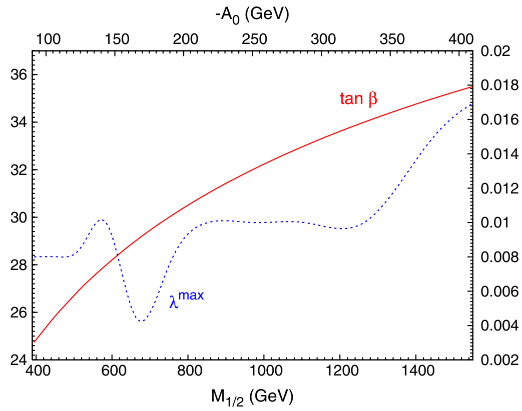

FIG. 3 (color online). $\tan\beta$ and the upper bound on λ as a function of $M_{1/2}$ along the DM line allowed by WMAP in Fig. 1.

m_0 up to $m_0 \sim \frac{1}{10} M_{1/2}$ is possible. Then the correct DM relic density (which requires $M_{1/2} < 2$ TeV for $m_0 = 0$) allows for $M_{1/2}$ up to 3 TeV (where $m_0 \sim 300$ GeV and $\tan\beta \sim 46$). Since $m_0 \ll M_{1/2}$ in all cases, we expect the phenomenology of the model to be similar to the one shown in the figures above. More details will be given in a forthcoming publication [19].

In conclusion, we have shown that the NMSSM with universal boundary conditions at the GUT scale is a very constrained scenario. For small values of the universal scalar mass m_0, which are theoretically interesting and excluded in the cMSSM, all present collider constraints on sparticle and Higgs masses are satisfied. Moreover, the requirement of a correct relic density for the dark matter candidate further constrains the parameter space to a one-dimensional $[M_{1/2}, A_0]$ line. Thus, only one single parameter, which can be taken as $M_{1/2}$, is required to describe the salient features of the model.

This model leads to an interesting phenomenology. For large $M_{1/2}$, the lightest *CP*-even Higgs boson is SM-like with a mass smaller than ~120 GeV, while for small $M_{1/2}$, it is a very light singletlike state which will be very difficult to detect, however, given the small value of λ. In the SUSY sector, the singlinolike LSP will considerably modify the decay chains of sparticles [20]: one expects that *all* sparticles decay via the lightest tau slepton which then decays into the singlinolike LSP, leading to missing energy. For very small λ, the lifetime of the tau slepton can become so large that its track can be visible [20]. In any case sparticle decays will differ in a spectacular way from the ones expected within MSSM-typical scenarios, hopefully allowing one to test the present scenario in the near future at the LHC.

A. D. is grateful to the Leverhulme Trust (U.K.) and to the A. von Humboldt Foundation (Germany). We acknowledge support from the ANR project PHYS@COL&COS and discussions with S. F. King and S. Moretti.

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