Guaranteed discovery of the NmSuGra model

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Abstract.

We analyze the discovery potential of the next-to-minimal supergravity motivated model: NmSuGra. This model is an extension of mSuGra by a gauge singlet, and contains only one additional parameter: $\lambda$, the Higgs-singlet-Higgs coupling. NmSuGra solves the $\mu$-problem and reduces the fine tuning of mSuGra. After identifying parameter space regions preferred by present experimental data, we show that these regions of NmSuGra are amenable to detection by the combination of the Large Hadron Collider and an upgraded Cryogenic Dark Matter Search. This conclusion holds strictly provided that the more than three sigma discrepancy in the difference of the experimental and the standard theoretical values of the anomalous magnetic moment of the muon prevails in the future.

Keywords: Supersymmetry phenomenology, Supersymmetric standard model, Dark matter, Rare decays

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INTRODUCTION

Supersymmetry is very successful in solving outstanding problems of the standard model (SM) of elementary particles, including the hierarchy of fundamental energy scales, the existence and properties of dark matter and the unification of gauge forces. However, the minimal supersymmetric standard model (MSSM) suffers from several problems. For example, the $\mu$ term is not protected from radiative corrections, and its viable parameter regions are now quite fine tuned [1]. Gauge-singlet extensions of the MSSM offer solutions to these problems. In the next-to-minimal MSSM (NMSSM), the $\mu$ term is dynamically generated and no dimensionful parameters are introduced in the superpotential (other than the vacuum expectation values that are all naturally weak-scale), making the NMSSM a truly natural model (see references in [2]). We define the next-to-minimal supergravity motivated (NmSuGra) model, imposing universality of sparticle masses, gaugino masses, and trilinear couplings at the grand unification theory (GUT) scale.

Using a simple likelihood analysis, we first identify the parameter regions of the NmSuGra model that are preferred by present experimental data. We combine theoretical exclusions with limits from the CERN Large Electron-Positron (LEP) collider, the Fermilab Tevatron, NASA’s Wilkinson Microwave Anisotropy Probe (WMAP) satellite, the Soudan Cryogenic Dark Matter Search (CDMS), the Brookhaven Muon g–2 Experiment, and various $b$-physics measurements including $b \to s\gamma$ and $B_s \to l^+l^-$. We then show that, assuming recent results on the muon $g-2$ are accurate, the favored parameter space can be detected by the combination of the LHC and an upgraded CDMS. (See Ref.s [3, 4] on the theoretical uncertainty of $\Delta a_{\mu}$.)

THE NMSUGRA MODEL

In this work, we adopt the superpotential

$$ W = W_Y + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3, \quad (1) $$

where $W_Y$ is the MSSM Yukawa superpotential, $\hat{S} (\hat{H}_{u,d})$ is a standard gauge singlet ($SU(2)_L$ doublet) chiral superfield, $\lambda$ and $\kappa$ are dimensionless couplings, and $\hat{H}_u \cdot \hat{H}_d = \epsilon_{a\beta} \hat{H}_u^a \hat{H}_d^\beta$ with $\epsilon_{11} = 1$. The corresponding soft supersymmetry breaking terms are

$$ \mathcal{L}^{soft} = \mathcal{L}^{soft}_{\text{MSSM}} + m_3^2 |S|^2 + (\lambda A_\lambda S \hat{H}_u \cdot \hat{H}_d + \frac{\kappa A_{\lambda}}{3} |S|^3 + h.c.), \quad (2) $$

where $\mathcal{L}^{soft}_{\text{MSSM}}$ contains no $B\mu$ term.$^1$

We assume that the soft masses of the gauginos unify to $M_{1/2}$, those of the sfermions and Higgses to $M_0$, and all the trilinear couplings (including $A_K$ and $A_{\lambda}$) to $A_0$ at the GUT scale. Defining $\mu = \lambda \langle S \rangle$, and $\tan \beta = \langle H_u \rangle / \langle H_d \rangle$ (the ratio of Higgs vevs), our free parameters are [2]:

$$ M_0, M_{1/2}, A_0, \tan \beta, \lambda, \text{sign}(\mu). \quad (3) $$

To keep all the attractive features of the CMSSM/mSuGra, we adhere to universality and use only $\lambda$ to parametrize the singlet sector. This minimal extension alleviates problems of CMSSM/mSuGra rooted in the MSSM. Other constrained versions of the NMSSM have

$^1$ Radiative breaking the $Z_1$ symmetry may destabilize the hierarchy of vevs in the NMSSM, however by imposing a $Z_2$ R-symmetry these problems can be alleviated without affecting the phenomenology [5].
be studied in the recent literature \[6, 7, 8, 9, 10\] (see also the contributions by U. Ellwanger in these proceedings).

Our goal is to show that the NmSuGra model can be discovered by nascent experiments in the near future. To this end, for each set of the model parameters, we quantify the experimental preference in terms of:

\[
\sqrt{\chi^2} = \left( \sum_{i=1}^{7} \left( \frac{m_i^\text{experiment} - m_i^\text{NmSuGra}}{\sigma_i} \right)^2 \right)^{1/2}
\]

where \(m_i\) is the central value of a physical quantity measured by an experiment or calculated in the NmSuGra model, and \(\sigma_i\) is the combined experimental and theoretical uncertainty. We include experimental upper limits for \(\Omega h^2 = 0.1143 \pm 0.0034\) [11], \(Br(B_s \rightarrow \mu^+\mu^-) = 5.8 \times 10^{-8} (95 \% \text{ CL})\) [12] and \(\sigma_{SI}\) by CDMS [13]. We also include the LEP lower limits of the lightest scalar Higgs and chargino masses (which can be approximately stated as) [14]: \(m_h > 114.4\) GeV for \(\tan \beta \leq 10\), \(m_h > 91\) GeV for \(\tan \beta > 10\), \(m_{\tilde{W}} > 104\) GeV. Finally, we consider the central values of \(\Delta m^2 = 29.5 \pm 8.8 \times 10^{10} \) [3], and \(Br(b \rightarrow s\gamma) = 3.55 \pm 0.26 \times 10^{-4}\) [12]. The related uncertainties are given above at 68 \% CL, unless stated otherwise. Theoretical uncertainties are calculated using NMSSMTools [15] for the b-physics related quantities.

A glance at the likelihood reveals a significant statistical preference for relatively narrow intervals of \(M_0, M_{1/2}\) and \(A_0\), as shown in figure 1 for a randomly selected set of models with sign(\(\mu\)) > 0. At high values of \(M_0, M_{1/2}\) and \(|A_0|\), \(\chi^2\) is dominated by \(\Delta a_\mu\), similar to the CMSSM. Based on this, we limit our study to the following ranges of the continuous parameters: \(0 < M_0 < 4\) TeV, \(0 < M_{1/2} < 2\) TeV, \(0 < |A_0| < 5\) TeV, \(1 < \tan \beta < 60, and 0.01 < \lambda < 0.7\).

**DETECTABILITY OF NMSUGRA**

Having defined the NmSuGra model and the range of its parameters, we set out to show that this parameter region will be detectable by the LHC and an upgraded CDMS detector. Two million theoretically allowed representative model points (from an initial sample of 20 million) are projected in figure 2 to the plane of \(\Omega h^2\) vs. the gaugino admixture of the lightest neutralino. From figure 2 it is evident that the WMAP upper limit (green horizontal line) favors models with mostly bino-red circles) and higgsino-like (magenta squares) lightest neutralino, while the fraction of allowed models with singlino-like (blue pluses) dark matter is negligible. By checking mass relations and couplings, we can easily establish that branch 4 contains only models with dominant neutralino-stop coannihilation, while branch 3 corresponds to neutralino-stau coannihilation. Branch 2 represents the Higgs resonance corridors, and branch 1 is the equivalent of the CMSSM/mSuGra focus point region.

To gauge the detectability of the NmSuGra model, first we identify model points that could have been seen at LEP [2]. The top left frame of figure 3 shows model points from figure 2 colored either green (plus) if the model would be accessible to LEP or red (cross) if it
passes the above LEP constraints and is therefore allowed. Just as in the CMSSM/mSuGra the neutralino-stop coannihilation region is mostly covered by LEP. For the LHC reach we use a conservative approximation relying on the similarity between the mSuGra and NmSuGra models. According to Ref. [16] the reach of the LHC for mSuGra can be well approximated by the combined reach for gluinos and squarks. Based on this, if either the gluino mass is below 1.75 TeV, or the geometric mean of the stop masses is below 2 TeV for a given model point, we consider it discoverable at the LHC.

The top right frame of figure 3 shows the model points that can be reached by LEP and the LHC using the above criteria. As in the CMSSM/mSuGra, most of the slepton coannihilation and the bulk of the Higgs resonance branches are covered by the LHC. A good part of the focus point is also within reach of the LHC, with the exception of models with high $M_0$ and/or $M_{1/2}$. The bottom left frame of figure 3 shows the reach of a one ton equivalent of CDMS (CDMS1T). As expected from the CMSSM/mSuGra, the rest of the focus point and most of the remaining Higgs resonances are in the reach of CDMS1T. The small number of models that remain inaccessible are all located in regions that have relatively low $M_0$ and high $M_{1/2}$, with dominant neutralino annihilation via s-channel Higgs resonances. The NmSuGra contribution to $\Delta a_\mu$ in these model points is outside the preferred 99% CL region as shown by the last frame.

Assuming that the NmSuGra contribution to the anomalous magnetic moment of the muon is larger than $3.1 \times 10^{-10}$ constrains slepton and chargino masses below 3 and 2.5 TeV, respectively. Since universality restricts the mass hierarchy within NmSuGra, the resulting mass spectrum is typically mSuGra-like. Thus, the cascade decays and their signatures at LHC are not expected to deviate significantly from that of the mSuGra case.

**CONCLUSIONS**

Analyzing the next-to-minimal supergravity motivated (NmSuGra) model, we found that the LHC and an upgraded CDMS experiment will be able to discover the experimentally favored regions of this model provided that the present deviation between the experimental and standard theoretical values of the muon anomalous magnetic moment prevails.

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**REFERENCES**

1. G. F. Giudice (2008), 0801.2562
2. C. Balazs, and D. Carter (2008), 0808.0770
3. D. Stockinger (2007), 0710.2429
4. M. Passera, W. J. Marciano, and A. Sirlin (2008), 0804.1142
5. C. Panagiotakopoulos, and K. Tamvakis, Phys. Lett. B446, 224–227 (1999), hep-ph/9809475
6. A. Djouadi, U. Ellwanger, and A. M. Teixeira (2008), 0803.0253
7. C. Hugonie, G. Belanger, and A. Pukhov, JCAP 0711, 009 (2007), 0707.0628
8. G. Belanger, F. Boudjemaa, C. Hugonie, A. Pukhov, and A. Semenov, JCAP 0509, 001 (2005), hep-ph/0505142
9. D. G. Cervero, E. Gabrielli, D. E. Lopez-Fogliani, C. Munoz, and A. M. Teixeira, JCAP 0706, 008 (2007), hep-ph/0701271
10. A. Djouadi, et al. (2008), 0801.4321
11. E. Komatsu, et al. (2008), 0803.0547
12. E. Barberio, et al. (2006), hep-ex/0603003
13. Z. Ahmed, et al. (2008), 0802.3530
14. G. Abbiendi, et al., Eur. Phys. J. C35, 1–20 (2004), hep-ex/0401025
15. U. Ellwanger, and C. Hugonie, Comput. Phys. Commun. 177, 399–407 (2007), hep-ph/0612134
16. H. Baer, C. Balazs, A. Belyaev, T. Krupovnickas, and X. Tata, JHEP 06, 054 (2003), hep-ph/0304303