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Journal

Physical Review D - Particles, Fields, Gravitation and Cosmology, 74(1)

ISSN

1550-7998

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Publication Date

2006-07-27

DOI

10.1103/PhysRevD.74.015013

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Minimal supergravity with $m_0^2 < 0$

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(Received 12 January 2006; published 21 July 2006)

We extend the parameter space of minimal supergravity to negative values of m_0^2 , the universal scalar mass parameter defined at the grand unified scale. After evolving to the weak scale, all scalars can be nontachyonic with masses consistent with collider constraints. This region of parameter space is typically considered excluded by searches for charged dark matter, since the lightest standard model superpartner is a charged slepton. However, if the gravitino is the lightest supersymmetric particle, the charged slepton decays, and this region is allowed. This region provides qualitatively new possibilities for minimal supergravity, including spectra with light sleptons and very heavy squarks, and models in which the lightest slepton is the selectron. We show that the $m_0^2 < 0$ region is consistent with low-energy precision data and discuss its implications for particle colliders. These models may provide signals of supersymmetry in even the first year of operation at the Large Hadron Collider.

DOI: [10.1103/PhysRevD.74.015013](https://doi.org/10.1103/PhysRevD.74.015013)

PACS numbers: 04.65.+e, 12.60.Jv, 13.85.-t

I. INTRODUCTION

Supersymmetric models are theoretically motivated extensions of the standard model (SM) of particle physics that predict both direct and indirect signals in particle physics experiments. Most analyses of supersymmetric models assume the minimal supersymmetric standard model (MSSM), the supersymmetric extension of the SM that contains the minimal number of superpartners. Supersymmetry (SUSY) must also be broken. To make phenomenological analyses tractable, a moderately simple model for soft supersymmetry-breaking terms must be chosen.

By far the most studied supersymmetric model is minimal supergravity (mSUGRA) [1], which is specified by 6 parameters:

$$m_0^2, \quad M_{1/2}, \quad A_0, \quad \tan\beta, \quad (1)$$

$$\text{sign}(\mu), \quad \text{and} \quad m_{3/2}.$$

Here m_0^2 is the universal soft scalar mass squared, $M_{1/2}$ is the universal soft gaugino mass, A_0 is the universal soft trilinear term, $\tan\beta$ is the ratio of the vacuum expectation values of the up and down type Higgs bosons, μ is the supersymmetric Higgs mass parameter, and $m_{3/2}$ is the gravitino mass. The first three terms are defined at the grand unified theory (GUT) scale $M_{\text{GUT}} \simeq 2.4 \times 10^{16}$ GeV, where the gauge couplings unify. All superpartner masses and couplings are determined by these 6 parameters and renormalization group equations (RGEs). The lightest SM superpartner is typically either the lighter stau or the lightest neutralino.

Note that mSUGRA is typically thought to be determined by the first 5 parameters. When the gravitino is not the lightest supersymmetric particle (LSP), much of cosmology and all of particle phenomenology is insensitive to $m_{3/2}$. However, if the gravitino is the LSP, both cosmology

and particle phenomenology are sensitive to the gravitino mass, and $m_{3/2}$ is an essential parameter of mSUGRA.

When R -parity is conserved, as we assume throughout this study, the LSP is stable. Commonly it is (implicitly) assumed that the gravitino is not the LSP. In this case, the region of parameter space in which the stau is the lightest SM superpartner is strongly disfavored, as it predicts an absolutely stable charged massive particle (CHAMP), which has not been found [2,3]. Results of mSUGRA analyses are often displayed in the $(m_0^2, M_{1/2})$ plane. Null results from CHAMP searches then exclude from consideration a thin triangular wedge in this plane with small $m_0^2 > 0$ and, *a fortiori*, the entire half plane with $m_0^2 < 0$.

As emphasized above, however, this line of reasoning relies on the assumption that the gravitino is not the LSP. There are no theoretical motivations for this assumption—the gravitino mass is a free parameter in mSUGRA. In this, as well as in other scenarios with high-scale supersymmetry breaking, it is naturally of the same order of magnitude as other superpartner masses, but it is not necessarily larger. In addition, recent work has established that there are also no phenomenological or cosmological reasons to exclude the gravitino LSP scenario [4–11]. In fact, high-scale supersymmetry breaking with a gravitino LSP has a number of novel implications and virtues. For example, if the gravitino is the LSP and the next-lightest supersymmetric particle (NLSP) is charged, the signal of SUSY at colliders will be metastable charged particles. Such particles have spectacular signatures [12–15]. They also make possible the investigation of gravitational interactions and the quantitative verification of supergravity in high energy physics experiments [16–20]. Cosmologically, gravitinos produced through decays naturally have the correct relic density to be superweakly-interacting massive particle (superWIMP) dark matter. For some parameters, gravitino dark matter produced in this way has features usually associated with warm dark matter and may resolve controversial discrepancies in halo profiles and the formation

of small scale structure [21–25]. Last, the late decays that produce gravitino dark matter also release electromagnetic and hadronic energy, with (possibly felicitous) implications for Big Bang nucleosynthesis [4,6,9,11,26–29] and the cosmic microwave background [4,6,30].

In this paper we consider the possibility of mSUGRA with a gravitino LSP and $m_0^2 < 0$. We define

$$m_0 \equiv \text{sign}(m_0^2) \sqrt{|m_0^2|}. \quad (2)$$

We show that the region with $m_0 < 0$ contains models consistent with all collider limits. We also consider precision measurements, analyzing the anomalous magnetic moment of the muon a_μ , $B(b \rightarrow s\gamma)$, and $B_s^0 \rightarrow \mu^+ \mu^-$. We find that the current discrepancy in a_μ between experiment and the SM prediction may be resolved for $m_0 < 0$ without disrupting the agreement for $B(b \rightarrow s\gamma)$, and near future probes of $B_s^0 \rightarrow \mu^+ \mu^-$ will have significant reach in $m_0 < 0$ model space. Precision data do not currently favor one sign of m_0 over the other.

The simple modification of taking $m_0 < 0$ therefore “doubles” the viable mSUGRA parameter space and leads to qualitatively new possibilities. For example, in some regions of parameter space, the NLSP is not the stau, but the selectron. This overturns the common lore that Yukawa couplings in RGEs lower soft masses; when some scalars are tachyonic in part of the RG evolution, Yukawa terms may *increase* scalar masses. We also find that light charged sleptons can be produced for any value of $M_{1/2}$. This produces spectra where the charged sleptons have masses around 100 GeV, but all other superpartner masses are above 1 TeV, with squark and gluino masses around 3–4 TeV. Such spectra are not found for $m_0 > 0$ and have novel implications for the Large Hadron Collider (LHC) and International Linear Collider (ILC). Although all of these features may be found in general MSSM models, it is striking that we find them here in a framework with universal scalar and gaugino masses, motivated as these features are by simplicity, the SUSY flavor and CP problems, and gauge coupling unification.

Cosmologically, these models differ from conventional models with $m_0 > 0$ in several ways. As noted above, the $m_0 < 0$ models have superWIMP dark matter, as opposed to the conventional neutralino WIMP dark matter, with the implications mentioned above for Big Bang nucleosynthesis, the cosmic microwave background, and structure formation. In addition, models with $m_0 < 0$ contain potentials with charge breaking minima and also directions in field space where the potential is unbounded from below at tree level [31]. These models are potentially unstable [11], and there are also possibly novel implications for gauge symmetry breaking at high temperatures. We comment briefly in the conclusions on the vacuum stability of these models. Primarily, however, we focus here on implications for particle physics and defer detailed discussions of cosmological issues to a future work [32].

This study is organized as follows. In Sec. II we show that, even given $m_0 < 0$ at the GUT scale, all superpartner masses, when evolved to the weak scale, can have values consistent with current experimental bounds. We delineate the allowed regions and determine which regions of parameter space have stau and selectron NLSPs. The resulting superpartner masses in the $m_0 < 0$ region are discussed in Sec. III. Low-energy observables are analyzed in Sec. IV. In Sec. V, we show two representative superpartner spectra and briefly discuss the implications for the LHC and ILC. In Sec. VI, we conclude and indicate interesting avenues for further investigation.

II. REGIONS OF MSUGRA PARAMETER SPACE FOR $m_0 < 0$

In this section, we determine the allowed regions of mSUGRA parameter space with $m_0 < 0$, and further classify the allowed parameter space according to what particles are the LSP and NLSP, since these play a large role in determining experimental signatures.

For $m_0 < 0$, an immediate worry is that scalar masses will remain tachyonic even after RG evolution to the weak scale. As usual, gauge interactions raise the soft masses, and so the most problematic scalars are the right-handed sleptons, since these have only hypercharge interactions. The RGEs for conventional mSUGRA have been studied in great detail. A well-known approximate relation for the weak-scale right-handed selectron mass in terms of GUT-scale parameters is [33]

$$m_{\tilde{e}_R}^2 = m_0^2 + 0.15M_{1/2}^2. \quad (3)$$

This remains valid for $m_0 < 0$. From this, we see that negative m_0^2 can always be compensated by large $M_{1/2}$ to make the right-handed sleptons, and with them the entire superpartner spectrum, nontachyonic.

Allowed regions of the $(m_0, M_{1/2})$ plane are shown for two values of $\tan\beta$ in Fig. 1. The SUSY spectra have been calculated with the software package ISAJET v7.71 [34], modified to accommodate $m_0 < 0$. ISAJET includes 2-loop RGEs and 1-loop corrections to superpartner masses, and we choose a top quark mass of 175 GeV. The green (medium shaded) region is excluded. For $m_0 > 0$ the boundary is determined by the LEP chargino mass limit $m_{\tilde{\chi}^\pm} > 103.5$ GeV [35]. For $m_0 < 0$, it is essentially determined by null searches for long-lived charged sleptons at LEP, leading to limits $m_{\tilde{l}_R} > 99$ GeV [36]. For $\tan\beta = 10$, the border for $m_0 < 0$ follows to a reasonable approximation the tachyonic slepton line $m_0 = -2.6M_{1/2}$ one can derive from Eq. (3). For $\tan\beta = 60$, the excluded region has a more complicated shape because large 1-loop corrections play an important role, as discussed below.

The allowed regions may be further divided according to what particles are the LSP and NLSP. The unshaded regions of Fig. 1 are the conventional regions in which the

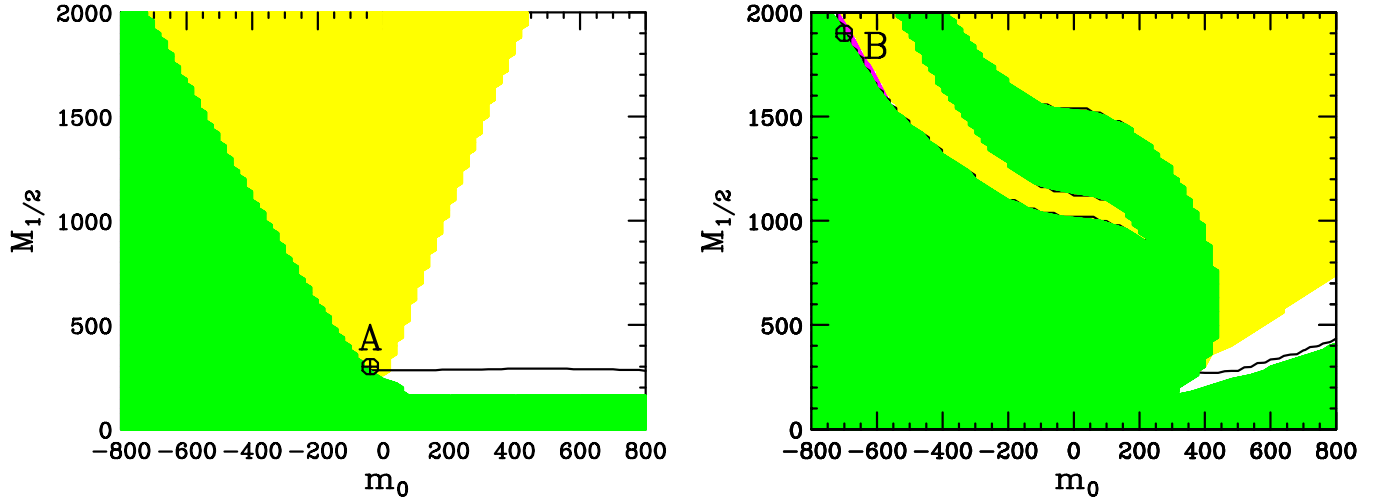


FIG. 1 (color online). Regions of the $(m_0, M_{1/2})$ plane, extended to $m_0 < 0$, for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 10$ (left) and $\tan\beta = 60$ (right). The green (medium shaded) region is experimentally excluded, and the unshaded region is the conventional neutralino (N)LSP region. In the remaining regions, the gravitino is the LSP: in the yellow (light shaded) region, the stau is the NLSP, and in the thin magenta (dark shaded) region of the $\tan\beta = 60$ plot, the selectron is the NLSP. The present Higgs mass bound $m_h > 114.1$ GeV excludes regions below the solid contours. The symbols \oplus mark the location of benchmark Models A and B; their RG evolution is shown in Fig. 2.

lightest SM superpartner is the lightest neutralino. It is either the LSP or, if the gravitino is the LSP, the NLSP.

In the rest of the allowed regions shown, the gravitino must be the LSP to avoid having charged dark matter, and the NLSP is a charged slepton. To determine which charged slepton is the NLSP, consider the RGEs for their soft mass parameters. At 1-loop, these are

$$\frac{dm_{\tilde{e}_R}^2}{dt} = \frac{2}{16\pi^2} \left[-\frac{12}{5} g_1^2 M_1^2 \right] \quad (4)$$

$$\frac{dm_{\tilde{\tau}_R}^2}{dt} = \frac{2}{16\pi^2} \left[-\frac{12}{5} g_1^2 M_1^2 + 2\lambda_\tau^2 (m_{\tilde{\tau}_L}^2 + m_{\tilde{\tau}_R}^2 + m_{H_d}^2 + A_\tau^2) \right], \quad (5)$$

where $t = \ln(Q^2/M_{\text{GUT}}^2)$. As is well-known, when all mass parameters are nontachyonic, Yukawa interactions lower soft masses, leading to the common lore that, given universal scalar boundary conditions, the lightest slepton is always the stau. In the present case, however, $m_0 < 0$, and so in evolving from the GUT scale, selectron masses initially rise slower than stau masses. Of course, for the spectrum to be viable, all physical scalar masses must eventually become nontachyonic, and so will exert the conventional effect of Yukawa couplings as one approaches the weak scale. (The Higgs scalar mass parameters may remain negative.) The competition between the new and the conventional effects determines whether the NLSP is the selectron or the stau.

These effects are shown in Fig. 2 for the two benchmark models highlighted in Fig. 1. In the left panel, all scalar

masses of Model A quickly become positive as they evolve from the GUT scale, and so the stau becomes the NLSP, as usual. In the right panel, however, the scalar masses of Model B are negative for much of the RG evolution, and $m_{H_d}^2$ becomes negative, leading to an inverted flavor spectrum with a selectron NLSP.

In Fig. 1, the $\tilde{\tau}_1$ is the NLSP in the yellow (light shaded) region, and \tilde{e}_R is the NLSP in the magenta (dark shaded) region. The current experimental limits force sleptons to be not just nontachyonic, but significantly so, and so the viable selectron NLSP region is reduced to a thin sliver near the upper, left-hand corner in the $\tan\beta = 60$ plot. Its exact location is therefore rather sensitive to small corrections and depends on the implementation of RG evolution and loop-level corrections to the superpartner mass spectrum. The mere possibility that universal slepton masses can lead to selectrons lighter than staus, however, is a robust physics effect; it is novel and never realized in conventional mSUGRA. The selectron NLSP region may be much larger in even slightly more general models where the Higgs soft mass terms are not unified to $m_0^2 < 0$, but some other negative value at the GUT-scale. Some models have been considered with $m_H^2 < 0 < m_0^2$ [37,38]. Ferrandis considered a supersymmetric SU(5) fixed-point model where the Higgs soft mass terms are negative at the GUT-scale [37]. Baer *et al.* systematically studied the phenomenology and cosmology of nonuniversal Higgs models with one and two additional GUT-scale parameters, including those with negative Higgs soft masses and $m_0^2 > 0$ [38]. In models when $m_H^2 < m_0^2 < 0$ the stau mass will receive large positive contributions for the $m_{H_d}^2$ that are absent for the selectron, as can be seen from Eq. (5), and

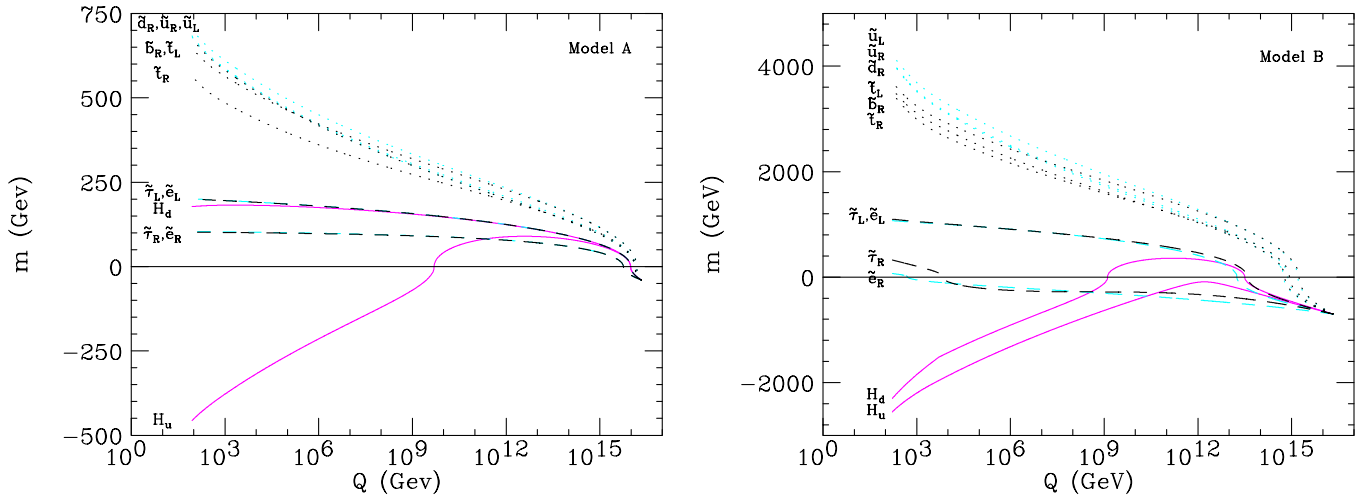


FIG. 2 (color online). The RG evolution of soft scalar masses in Model A, the stau NLSP point with $m_0 = -40$ GeV, $M_{1/2} = 300$ GeV, $\tan\beta = 10$ (left) and in Model B, the selectron NLSP point with $m_0 = -700$ GeV, $M_{1/2} = 1900$ GeV, $\tan\beta = 60$ (right). In both cases, $A_0 = 0$ and $\mu > 0$.

the selectron NLSP region with be extended. Last, we note that in the mSUGRA models considered here, the possibility of a nontachyonic sneutrino (N)LSP also exists at low $M_{1/2}$, but this lies entirely in the excluded region.

As noted above, the excluded region can have a rather complicated shape. For $\tan\beta = 60$, for example, as can be seen in the right-hand panel of Fig. 1, the excluded region has an interesting shape. This results from the remarkable fact that the light charged slepton masses do not increase monotonically as one increases $M_{1/2}$ for constant m_0 . In fact, this is not peculiar to $m_0 < 0$, as it occurs even for positive constant m_0 .

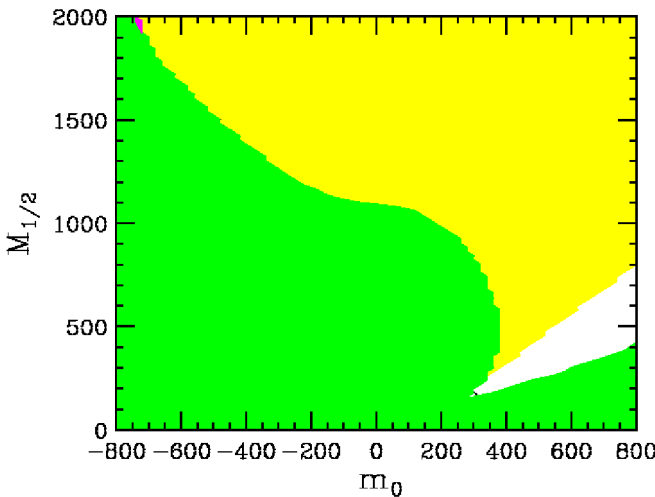


FIG. 3 (color online). Regions of the $(m_0, M_{1/2})$ plane, extended to $m_0 < 0$, for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 60$ as in the right-hand panel of Fig. 1, but with 1-loop corrections to sparticle masses neglected.

This behavior results from 1-loop corrections present in the slepton mass matrix

$$\begin{pmatrix} M_{LL}^2 + \delta M_{LL}^2 & M_{LR}^2 + \delta M_{LR}^2 \\ M_{RL}^2 + \delta M_{RL}^2 & M_{RR}^2 + \delta M_{RR}^2 \end{pmatrix}, \quad (6)$$

where M^2 are tree-level contributions and δM^2 are 1-loop corrections. If 1-loop corrections are neglected, the slepton mass monotonically increases for increasing m_0 and fixed $M_{1/2}$ (or vice versa), as illustrated in Fig. 3. However, for large $\tan\beta$ the loop corrections have the proper sign and magnitude to lower the mass eigenvalues of the stau below the experimental bounds in part of the parameter space. Of course, the 1-loop corrections are physical, and we include them in all plots and results below.

To conclude this section, the impression that neutralinos are the lightest SM superpartners in most of mSUGRA parameter space is artificial: it follows only if one requires $m_0 > 0$. Allowing $m_0 < 0$ extends the viable region of mSUGRA parameter space significantly and shows that staus are the lightest SM superpartners in much of mSUGRA parameter space. In addition, allowing $m_0 < 0$ leads to other new phenomena, such as the possibility that the selectron is the lightest SM superpartner. In the next section, we explore the implications of $m_0 < 0$ for the sparticle spectrum more fully.

III. SUSY MASS SPECTRA FOR $m_0 < 0$

The squark and gluino masses are presented in the $(m_0, M_{1/2})$ plane in Fig. 4. In the allowed region with $m_0 < 0$, they are relatively insensitive to m_0 , since they are dominated by the RG contributions of the gaugino masses. The left-handed down and up squarks are approximately degenerate, as are the right-handed up and down squarks.

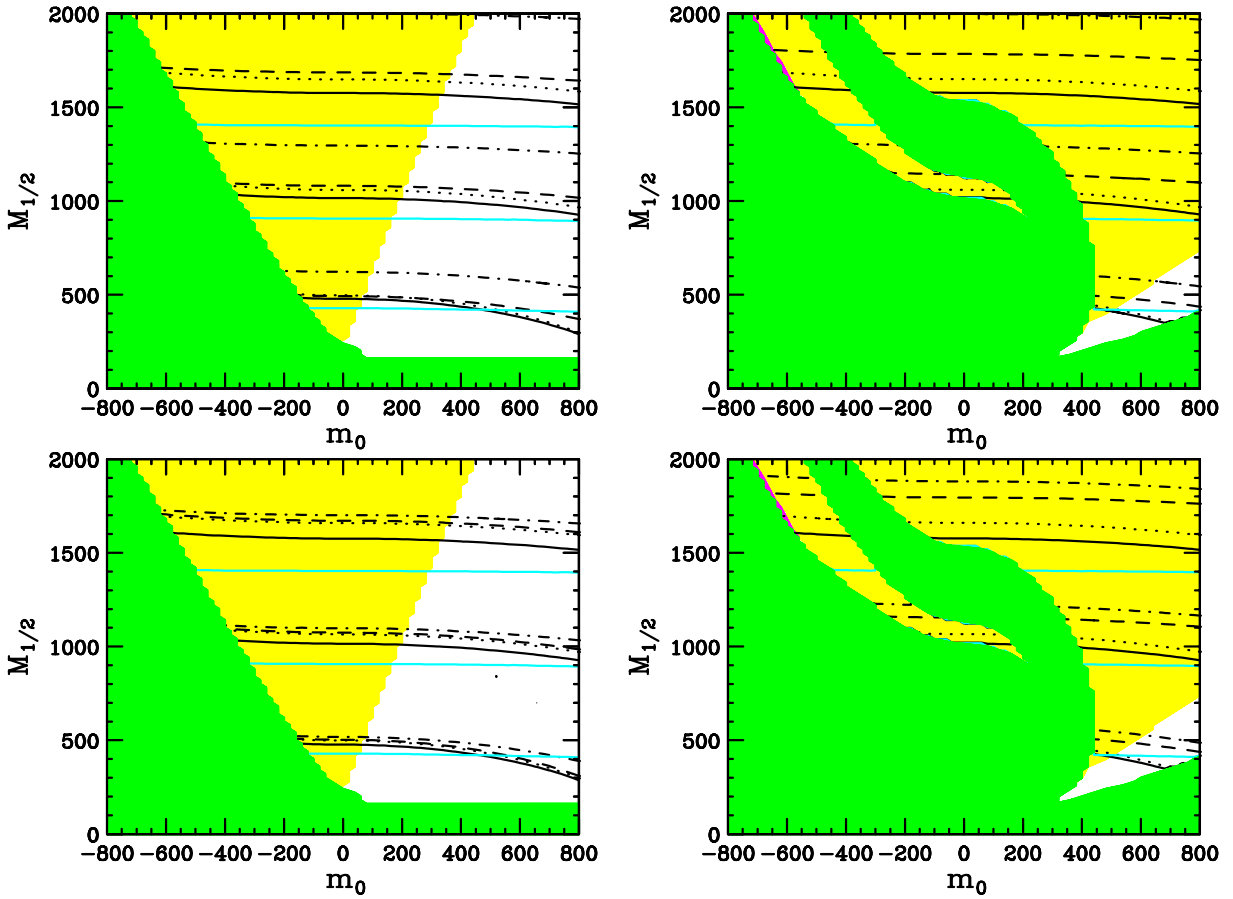


FIG. 4 (color online). Squark masses for mSUGRA extended to $m_0 < 0$ for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 10$ (left) and $\tan\beta = 60$ (right). The up-type squarks (top) are \tilde{u}_L (solid black), \tilde{u}_R (dotted black), \tilde{t}_1 (dot dashed black), and \tilde{t}_2 (dashed black). Similarly the down-type squarks (bottom) are \tilde{d}_L (solid black), \tilde{d}_R (dotted black), \tilde{b}_1 (dot dashed black), and \tilde{b}_2 (dashed black). The gluino mass (cyan, solid light) is presented on all 4 plots. The contours are for masses 1 TeV, 2 TeV, and 3 TeV from bottom to top.

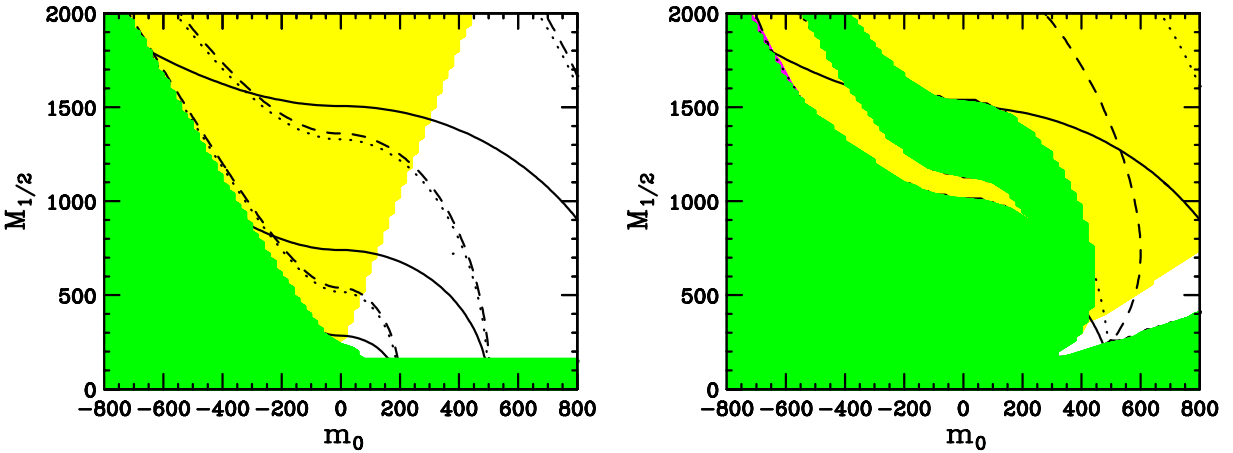


FIG. 5 (color online). Slepton masses for mSUGRA extended to $m_0 < 0$ for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 10$ (left) and $\tan\beta = 60$ (right). The contours are for $\tilde{\tau}_1$ (dashed), \tilde{e}_L (solid) and \tilde{e}_R (dotted). The contours are for masses 200 GeV, 500 GeV, and 1 TeV from bottom left to top right, with the exception that in the right panel, because the slepton masses drop and then rise again for fixed $M_{1/2}$ and increasing m_0 , there are two sets of 200 GeV contours for both \tilde{e}_R and $\tilde{\tau}_1$. For both of these particles, the leftmost 200 GeV contour is barely visible in the selectron NLSP region. Throughout the parameter space, the sneutrinos and $\tilde{\tau}_2$ are almost degenerate with the \tilde{e}_L .

The gluino is always heavier than all squarks in the $m_0 < 0$ allowed region.

Slepton masses are shown in Fig. 5. In contrast to squark masses, slepton masses are extremely sensitive to m_0 in the allowed $m_0 < 0$ region. Contours of constant slepton mass switch from concave down for $m_0 > 0$ to concave up for $m_0 < 0$. As a result, light sleptons near their experimental limit may be found for any value of $M_{1/2}$. This is true even though the masses of all other superpartners becomes large for large $M_{1/2}$, as may be seen in Model B, the selectron NLSP model shown in the right panel of Fig. 2.

In Fig. 6, we present contours for neutralino and chargino masses and for the Higgsino mass parameter μ . In the $m_0 < 0$ region, $|\mu|$ is always much larger than the electroweak gaugino masses M_1 and M_2 . As a result, the lighter chargino and lighter two neutralinos are nearly pure gauginos, with $\tilde{\chi}_1^0 \approx \tilde{B}$, $\tilde{\chi}_2^0 \approx \tilde{W}^0$, $\tilde{\chi}_1^\pm \approx \tilde{W}^\pm$, and $m_{\tilde{\chi}_1^0} \approx M_1$ and $m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx M_2 \approx 2M_1$.

Last, Higgs boson masses are given in Fig. 7. The masses of the Higgs bosons, h^0 , A^0 , H^0 , and H^\pm are all insensitive to m_0 for $m_0 < 0$. The predicted value of m_{h^0} is above 114 GeV throughout the allowed $m_0 < 0$ region, and so

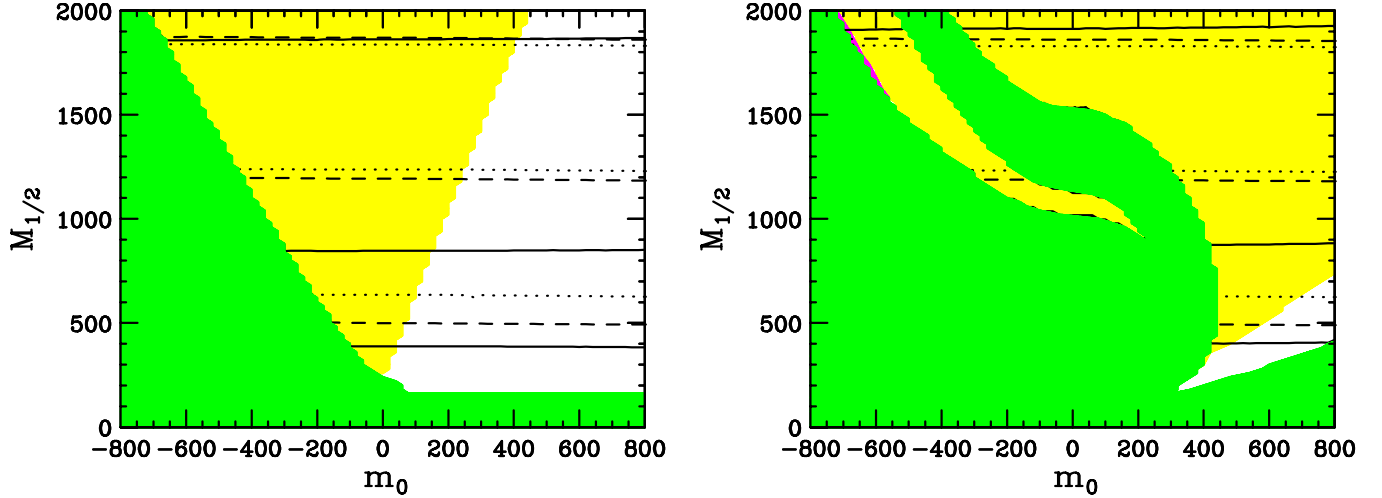


FIG. 6 (color online). Neutralino and chargino masses for mSUGRA extended to $m_0 < 0$ for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 10$ (left) and $\tan\beta = 60$ (right). The lightest neutralino $\tilde{\chi}_1^0$ (dashed) has values from bottom to top of 200 GeV, 500 GeV, and 800 GeV. The lightest chargino $\tilde{\chi}_1^\pm$ (dotted) has values from bottom to top of 500 GeV, 1 TeV, and 1.5 TeV, while μ (solid) has values 500 GeV, 1 TeV, and 2 TeV from bottom to top.

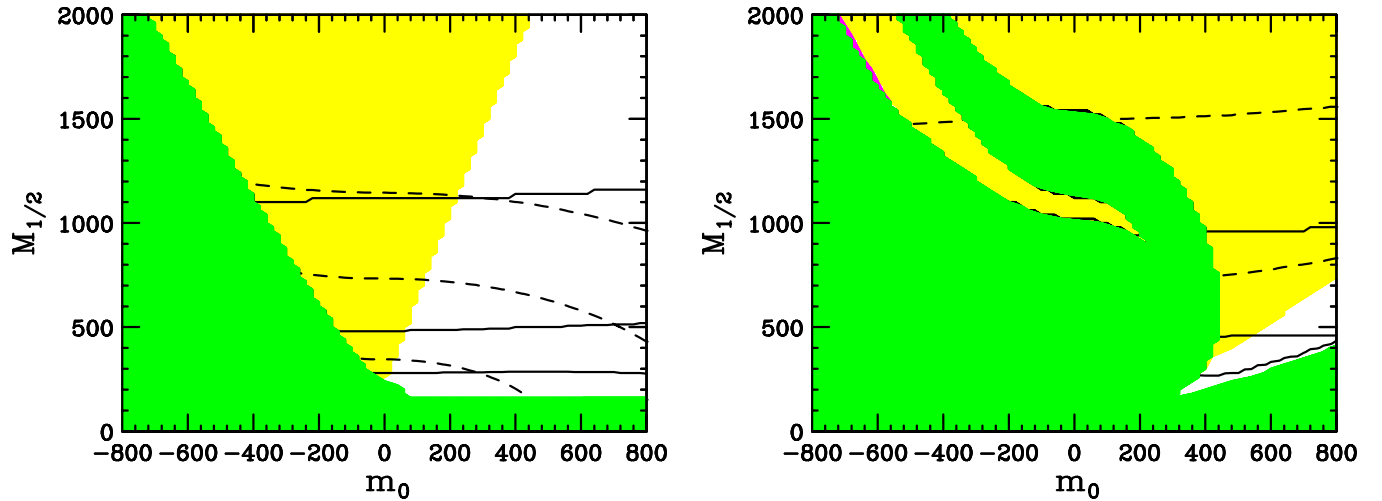


FIG. 7 (color online). Higgs boson masses for mSUGRA extended to $m_0 < 0$ for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 10$ (left) and $\tan\beta = 60$ (right). The SM-like Higgs boson h^0 mass contours (solid) have values 114 GeV, 118 GeV, and 122 GeV from bottom to top. The A^0 mass contours (dashed) have values 500 GeV, 1 TeV, and 1.5 TeV from bottom to top. The heavy CP -even and charged Higgs scalars are approximately degenerate with the A^0 .

consistent with current bounds. It increases with increasing $M_{1/2}$, rising to approximately 122 GeV for $M_{1/2} = 1$ TeV. A^0 , H^0 , and H^\pm are all approximately degenerate for $m_0 < 0$.

IV. PRECISION EXPERIMENTAL CONSTRAINTS

We now consider constraints on these models from precision experimental data. We focus on three processes that are well-known to have significant sensitivity to supersymmetric contributions: the anomalous magnetic moment of the muon a_μ and the rare decays $b \rightarrow s\gamma$ and $B_s^0 \rightarrow \mu^+ \mu^-$. These contributions have been calculated using the software package micrOMEGAs, v1.3.6 [39].

A. Anomalous magnetic moment of the muon

Determining the SM value of the anomalous magnetic moment of the muon is not straightforward because of hadronic contributions to higher order loop processes. These hadronic loop contributions are usually estimated from measurements of $e^+e^- \rightarrow$ hadrons or $\tau \rightarrow$ hadrons. The resulting SM predictions for a_μ are $a_\mu = 116592018(63) \times 10^{-11}$ if the τ data are used, and $a_\mu = 116591835(69) \times 10^{-11}$ if the e^+e^- data are used [40,41].

Given theoretical assumptions required to use the τ data, the e^+e^- value is generally judged to be more reliable [42]. These should be compared to the measured value $a_\mu = 116592080(60) \times 10^{-11}$ from the Muon ($g-2$) Collaboration [43,44]. Taking the SM value for a_μ using the e^+e^- data, there is a discrepancy between theory and experiment of $\delta a_\mu = 245 \times 10^{-11}$, a deviation of approximately 3σ .

The SUSY contribution to a_μ in mSUGRA with $m_0 < 0$ is shown in Fig. 8. A deviation consistent with the discrepancy between experiment and the e^+e^- SM prediction may be obtained for $\mu > 0$ and light neutralinos and sleptons or light charginos and sneutrinos. As noted in Sec. III, sleptons are light along the entire $m_0 < 0$ experimentally excluded border, but the gauginos increase in mass as $M_{1/2}$ increases. A large SUSY contribution to a_μ is therefore found only for relatively small $M_{1/2}$. The 3σ deviation mentioned above may be explained, for example, for $\tan\beta = 10$ and $M_{1/2} \sim 300$ GeV.

B. $B(b \rightarrow s\gamma)$

The flavor changing neutral current transition $b \rightarrow s\gamma$ has a branching fraction measured to be

$$B(b \rightarrow s\gamma) = \begin{cases} 3.21 \pm 0.43 \pm 0.27^{+0.18}_{-0.10} \times 10^{-4} & \text{(CLEO)} \\ 3.88 \pm 0.36 \pm 0.37^{+0.43}_{-0.23} \times 10^{-4} & \text{(BABAR)} \\ 3.55 \pm 0.32 \pm 0.30^{+0.11}_{-0.07} \times 10^{-4} & \text{(BELLE)} \end{cases} \quad (7)$$

[45–47], respectively. The SM prediction is $3.79^{+0.36}_{-0.53} \times 10^{-4}$ [48]. The $m_0 < 0$ mSUGRA predictions for $B(b \rightarrow s\gamma)$ are shown in Fig. 9. The experimental and SM theory values agree within errors, and so $b \rightarrow s\gamma$ may, in principle, eliminate models with light squarks and gauginos. As

can be seen in Fig. 9, however, supersymmetric effects in the plotted $m_0 < 0$ region are never large enough to create a discrepancy between these mSUGRA models and experiment.

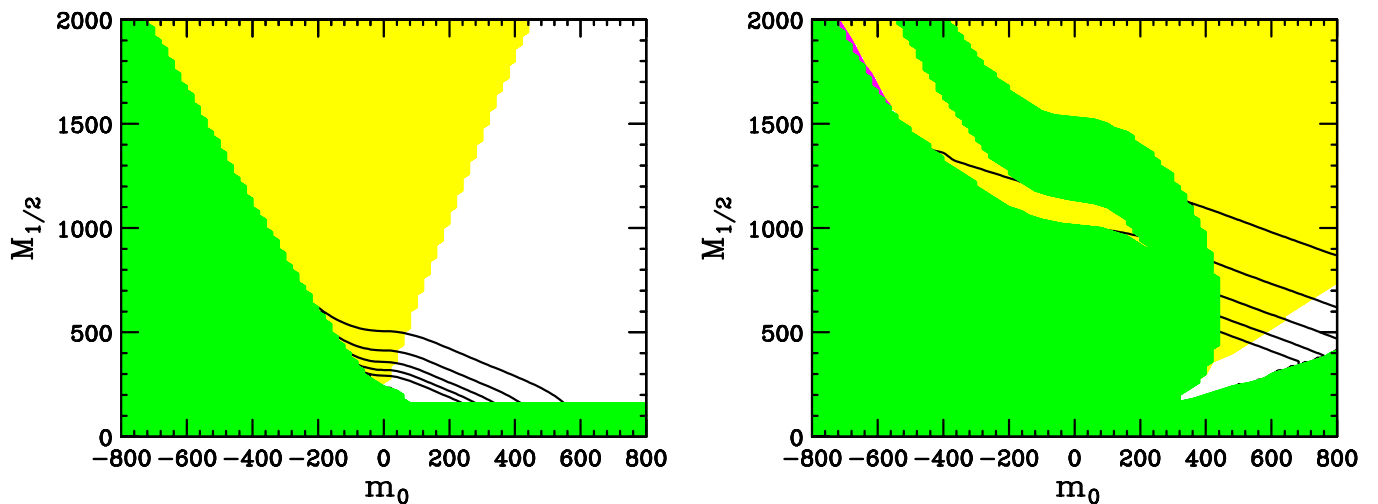


FIG. 8 (color online). The SUSY contribution to a_μ for mSUGRA extended to $m_0 < 0$ for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 10$ (left) and $\tan\beta = 60$ (right). From bottom to top the contour values are 300, 250, 200, 150, and 100 in units of 10^{-11} .

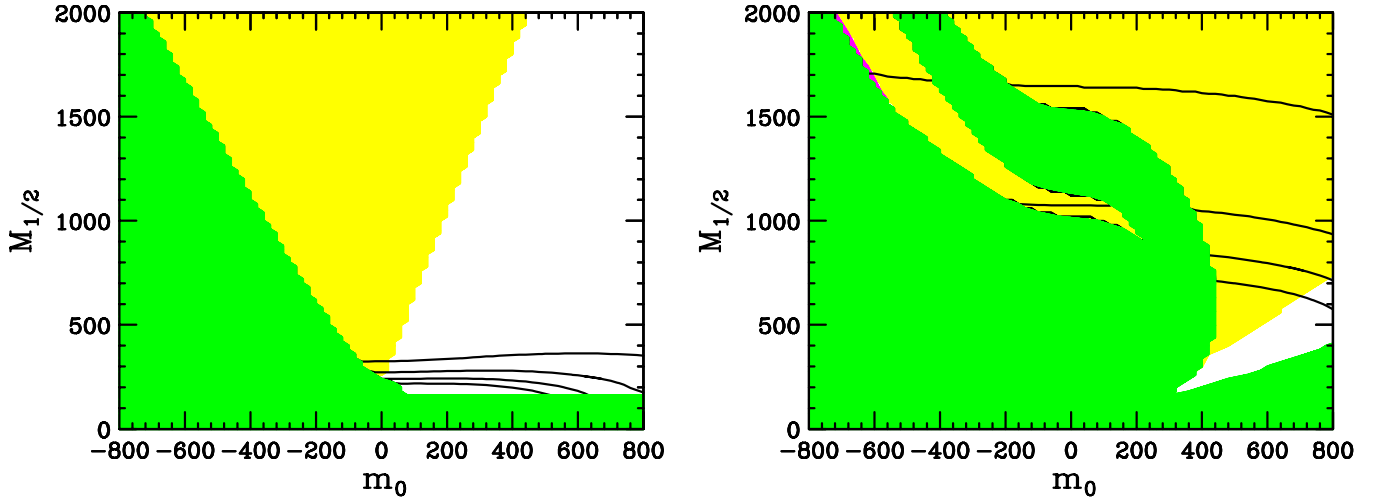


FIG. 9 (color online). $B(b \rightarrow s\gamma)$ for mSUGRA extended to $m_0 < 0$ for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 10$ (left) and $\tan\beta = 60$ (right). The values from bottom to top are 3.10, 3.25, 3.40, and 3.55 in units of 10^{-4} . In the $\tan\beta = 10$ panel, $B(b \rightarrow s\gamma)$ does not exceed 3.59×10^{-4} .

C. $B(B_s^0 \rightarrow \mu^+ \mu^-)$

The branching fraction for B_s^0 decaying to two leptons is an important measurement for constraining supersymmetric models with large $\tan\beta$ [49–53]. The decay is enhanced by $(\tan\beta)^6$ for large $\tan\beta$. The current experimental bound is $B(B_s^0 \rightarrow \mu^+ \mu^-) < 1.5 \times 10^{-7}$ from CDF II, based on 364 pb^{-1} of data [54], while the SM prediction is $3.42(54) \times 10^{-9}$ [55]. For small $\tan\beta$, mSUGRA with $m_0 < 0$, along with other SUSY models, predicts deviations far below current experimental bounds. These deviations will not be probed until the LHC. However, for large $\tan\beta$, observable deviations are predicted even in Tevatron data. As shown in Fig. 10, the current Tevatron data do not exclude additional parameter space. Nevertheless, future

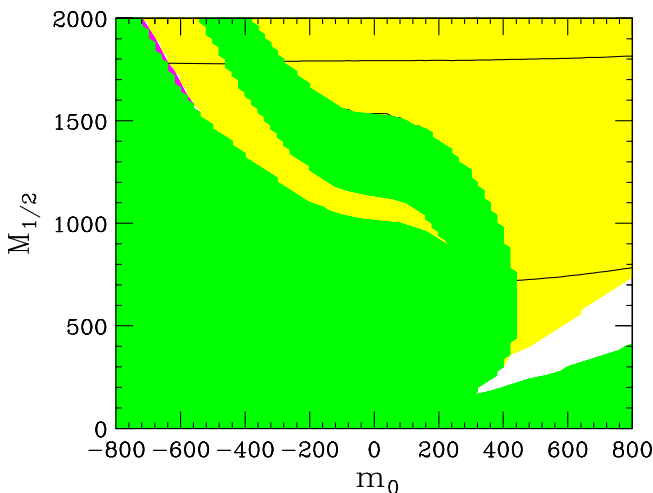


FIG. 10 (color online). $B(B_s^0 \rightarrow \mu^+ \mu^-)$ for mSUGRA extended to $m_0 < 0$ for $A_0 = 0$, $\mu > 0$, and $\tan\beta = 60$. The lower contour is CDF II's experimental upper bound 1.5×10^{-7} , and the upper contour is for $B(B_s^0 \rightarrow \mu^+ \mu^-) = 1.0 \times 10^{-8}$.

improvements to sensitivities of $\sim 10^{-8}$ will probe the $m_0 < 0$ region all the way up to $M_{1/2} \sim 1.8 \text{ TeV}$ for $\tan\beta = 60$, and will also be sensitive to models with more moderate values of $\tan\beta$.

V. COLLIDER SIGNALS

As is well-known, the LHC will provide an extremely powerful probe of weak-scale supersymmetry in the next few years. Here we discuss the implications of $m_0 < 0$ mSUGRA for the LHC and the proposed ILC.

The prototypical signature of (R -parity conserving) supersymmetry at hadron colliders is missing transverse energy. In the case of mSUGRA with $m_0 < 0$, however, all SUSY events result in the production of two metastable charged sleptons. These have lifetimes of seconds to months, and so pass through collider detectors without decaying. These models therefore provide a conventional setting for what might otherwise be considered to be rather exotic signals, such as highly-ionizing tracks and time-of-flight signatures [12–15]. Even a few events will provide unmistakable signals.

As examples, let us consider the benchmark models indicated in Fig. 1. The RGEs for scalars in these models were shown in Fig. 2. In Fig. 11, we display the full superpartner spectrum for each of these models, and in Table I we list all mass parameters, which define these models at the electroweak scale.

In Model A, the stau NLSP model of the right panel in Fig. 11, all superpartners have masses under 1 TeV. This model is an excellent benchmark model. It explains the 3σ deviation in a_μ , and preserves the agreement between the SM and experimental values of $B(b \rightarrow s\gamma)$. In addition, electroweak symmetry is broken radiatively and naturally, with $\mu \sim 400 \text{ GeV}$.

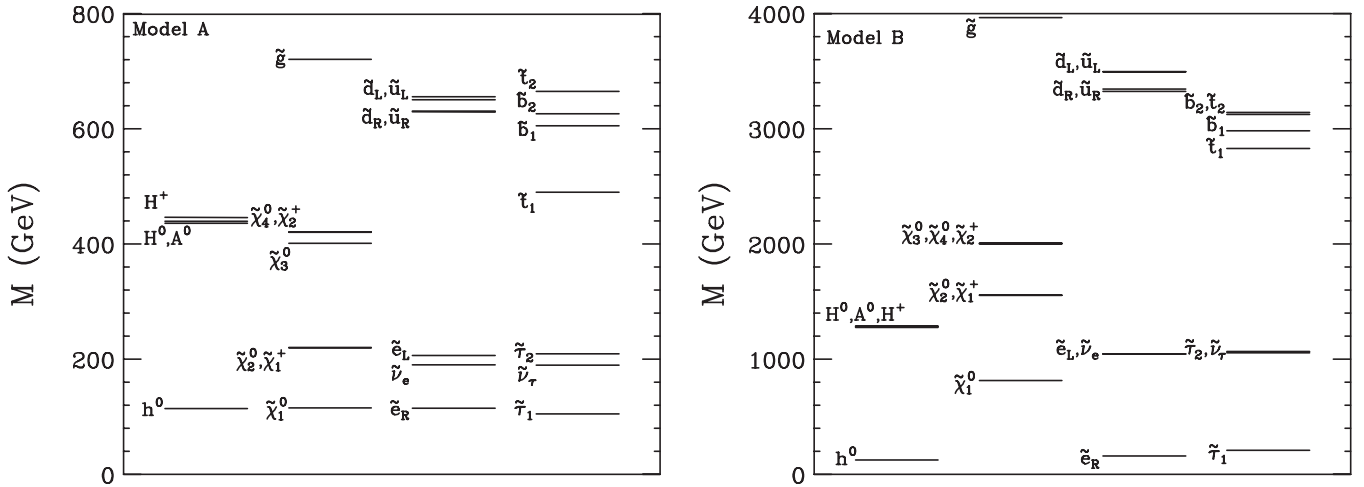


FIG. 11. Superpartner spectra for Model A, the stau NLSP point $m_0 = -40$ GeV, $M_{1/2} = 300$ GeV, $\tan\beta = 10$ (left) and for Model B, the selectron NLSP point $m_0 = -700$ GeV, $M_{1/2} = 1900$ GeV, $\tan\beta = 60$ (right). In both cases, $A_0 = 0$ and $\mu > 0$. These models correspond to the parameter points highlighted with \oplus symbols in Fig. 1; the RGEs of their scalars are displayed in Fig. 2, and their weak-scale parameters are given in Table I.

This stau NLSP model has a total SUSY cross section at the LHC of $\sigma_{\text{LHC}}(14 \text{ TeV}) = 13.6 \text{ pb}$, as determined by ISAJET [34]. Even with an integrated luminosity of 100 pb^{-1} , this implies over 1000 SUSY events, each with two metastable sleptons. In many of these, the sleptons will be slow enough to be seen as highly-ionizing tracks, providing a spectacular signal of new physics in even the first year of LHC operation. With more luminosity, large numbers of sleptons may be collected and their decays studied, making possible a variety of measurements with implications for cosmology, astrophysics and supergravity [4,6,9,11,16–28,30].

Model B, the selectron NLSP model indicated in Fig. 1, is a complementary benchmark model. As seen in Fig. 11, the model has squarks and gluinos around 3–4 TeV, neutralinos, sneutrinos, non-SM type Higgs bosons, and left-

handed sleptons around 1–2 TeV, a 210 GeV stau, 160 GeV selectron and smuon, and finally a 124 GeV Higgs boson. The squarks and gluinos are too heavy to be produced with large cross section at the LHC. The biggest sources of SUSY particles at the LHC are direct Drell-Yan production of NLSP pairs, leading to 2 metastable charged sleptons, and Drell-Yan production of the heavier sleptons, leading to even more unusual events with 2 taus, 2 muons/electrons, and 2 metastable charged sleptons. The total SUSY production cross section for this model is $\sigma_{\text{LHC}}(14 \text{ TeV}) = 41 \text{ fb}$. This signal will be challenging to find in the first year of LHC running, but at the target luminosity of $100 \text{ fb}^{-1}/\text{yr}$, the LHC will produce 4100 SUSY events per year.

At the ILC, the total SUSY production cross sections are $\sigma_{\text{ILC}}(500 \text{ GeV}) = 1.35 \text{ pb}$ for the stau NLSP Model A and

TABLE I. Mass parameters in GeV and the predicted values for precision observables for benchmark Models A and B. The masses in category MSSMA are physical masses; all other masses listed are soft SUSY-breaking parameters specified at the electroweak scale.

ISAJET Specification	Parameter	Model A	Model B
MSSMA	$m_{\tilde{g}} \mu$	720.70 395.95	3964.95 1994.33
	$m_{A^0} \tan\beta$	436.09 10.00	1274.81 60.00
MSSMB	$m_{\tilde{q}_1} m_{\tilde{d}_R} m_{\tilde{u}_R}$	652.21 601.12 603.80	3352.61 3178.77 3198.46
	$m_{\tilde{l}_1} m_{\tilde{e}_R}$	199.04 103.81	1027.84 67.57
MSSMC	$m_{\tilde{q}_3} m_{\tilde{b}_R} m_{\tilde{t}_R}$	578.76 598.21 502.38	2987.96 2860.45 2727.32
	$m_{\tilde{l}_3} m_{\tilde{\tau}_R}$	198.49 101.56	1040.40 255.73
	$A_t A_b A_\tau$	548.08 805.29 186.50	2788.73 3147.17 14.15
MSSMD	$m_{\tilde{q}_2} m_{\tilde{s}_R} m_{\tilde{c}_R}$	Same as MSSMB (default)	Same as MSSMB (default)
	$m_{\tilde{l}_2} m_{\tilde{\mu}_R}$		
MSSME	$M_1 M_2$	120.17 231.47	831.43 1527.66
	δa_μ	296×10^{-11}	78.1×10^{-11}
	$B(b \rightarrow s\gamma)$	3.49×10^{-4}	3.57×10^{-4}
	$B(B_s^0 \rightarrow \mu^+ \mu^-)$	3.21×10^{-9}	8.84×10^{-9}

$\sigma_{\text{ILC}}(500 \text{ GeV}) = 137 \text{ fb}$ for the selectron NLSP Model B. Although squarks and gluinos are out of reach, the ILC will produce large numbers of sleptons. All the usual advantages of the ILC will allow detailed studies of the SUSY parameter space. In addition, the ability to produce sleptons at low velocities implies that they may be more easily trapped and studied than at the LHC.

VI. CONCLUSIONS

In this study, we have extended the well-known framework of mSUGRA to $m_0 < 0$. To our knowledge, this part of parameter space has not been considered previously, perhaps because it contains a charged slepton as the lightest SM superpartner. If the gravitino is the LSP, however, cosmological difficulties with CHAMPs are avoided, and this extended parameter space is allowed. We have noted that it is consistent with all limits from direct searches and constraints from low-energy precision measurements. In addition, we find models with qualitatively novel mSUGRA superpartner spectra, which predict spectacular signals with metastable charged sleptons at future colliders.

Vacuum stability is inherently an issue in models with $m_0 < 0$. The lightness of charged sleptons in these models implies that the electroweak breaking vacuum is not the true vacuum. The fact that the scalar mass terms run negative as they approach the GUT scale also suggests the development of minima lower than the electroweak breaking vacuum in which we live. Ref. [31] has characterized the charge and color breaking minima (CCB) and unbounded from below (UFB) directions in the SUSY field space. The most dangerous direction for our models is the UFB-3 direction. We have estimated the lifetimes of the

metastable electroweak breaking vacua for Models A and B in the thin wall approximation. After finding the minima of the UFB-3 direction with the scale-dependent potential, we find lifetimes of roughly $e^{10^{11}} t_{\text{Universe}}$ and $e^{10^{15}} t_{\text{Universe}}$ for Models A and B, respectively, suggesting that these models are not excluded by this consideration. A more reliable evaluation of the lifetime can only be done numerically, with a prescription similar to that of Ref. [56]. Such an analysis is beyond the scope of this paper, but we note that in other cases, numerical analysis have implied larger lifetimes than those given by the thin wall approximation [57,58]. A more detailed discussion of vacuum stability and other cosmological concerns will be considered in a future work [32].

It would be interesting to extend this work to more general models. For example, as argued above, we expect that the selectron may emerge as the NLSP generically in models with nonunified Higgs masses, and there may well be other interesting phenomena. It would also be worthwhile to determine the reach of the LHC for various luminosities in the $m_0 < 0$ parameter space; given how spectacular the signal of metastable charged particles will be, these models provide a welcome example in which supersymmetry may be discovered and studied in even the first year of LHC running.

ACKNOWLEDGMENTS

The work of J.L.F. is supported in part by NSF CAREER grant No. PHY-0239817, NASA Grant No. NNG05GG44G, and the Alfred P. Sloan Foundation. A. R. is supported in part by NSF Grant No. PHY-0354993.

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