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Viable models with non-universal gaugino mediated supersymmetry breaking

Howard Baer, Csaba Balázs and Alexander Belyaev*

Department of Physics, Florida State University, Tallahassee, FL 32306 USA
E-mail: baer@hep.fsu.edu, balazs@hep.fsu.edu, belyaev@hep.fsu.edu

Radovan Dermíšek

Department of Physics, The Ohio State University, Columbus, OH 43210, USA
E-mail: dermisek@pacific.mps.ohio-state.edu

Arash Mafi

Department of Physics, University of Arizona, Tucson, AZ 85712, USA
E-mail: mafi@physics.arizona.edu

Azar Mustafayev

Department of Physics, Florida State University, Tallahassee, FL 32306, USA
E-mail: mazar@hep.fsu.edu

Abstract: Recently, extra dimensional SUSY GUT models have been proposed in which compactification of the extra dimension(s) leads to a breakdown of the gauge symmetry and/or supersymmetry. We examine a particular class of higher-dimensional models exhibiting supersymmetry and SU(5) or SO(10) GUT symmetry. SUSY breaking occurs on a hidden brane, and is communicated to the visible brane via gaugino mediation. Non-universal gaugino masses are developed at the compactification scale as a consequence of a restricted gauge symmetry on the hidden brane. In this case, the compactification scale is at or slightly below the GUT scale. We examine the parameter space of such models where gaugino masses are related due to a Pati-Salam symmetry on the hidden brane. We find limited but significant regions of model parameter space where a viable spectra of SUSY matter is generated. Our results are extended to the more general case of three independent gaugino masses; here we find that large parameter space regions open up for large values of the U(1) gaugino mass M_1. We also find the relic density of neutralinos for these models to be generally below expectations from cosmological observations, thus leaving room for hidden sector states to make up the bulk of cold dark matter. Finally, we evaluate the branching fraction $BF(b \to s\gamma)$ and muon anomalous magnetic moment a_μ.

Keywords: Supersymmetry Breaking, Supersymmetry Phenomenology, GUT.

*On leave of absence from Nuclear Physics Institute, Moscow State University.

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Contents

1. Introduction

Introducing supersymmetry (SUSY) to solve the hierarchy problem gives rise to a puzzle of identifying the way it is broken. Several mechanisms for SUSY breaking have been invented. Although at present there is no compelling reason to prefer one to the other, we know that the soft SUSY breaking terms in the minimal supersymmetric standard model (MSSM) must have a very special form. In order to avoid unacceptably large flavor violation, the masses of squarks and sleptons must be degenerate to a high precision.[1] Similarly the trilinear couplings must be proportional to the Yukawa matrices. Therefore it is intriguing to explore scenarios which naturally produce soft SUSY breaking parameters with these desired properties. Examples of such scenarios are gauge mediation [1], anomaly mediation [2, 3], and gaugino mediation [4, 5].

In the gaugino mediation scenario, the MSSM matter fields are localized on a 3-brane — the "matter" brane embedded in higher dimensional spacetime — while gauge fields can propagate in the bulk of the extra dimensions. Supersymmetry is broken on a separate "hidden sector" brane which is separated from the matter brane in extra dimensions. Gauginos can directly couple to the source of SUSY breaking to obtain nonzero masses, while masses of squarks and sleptons and trilinear couplings are suppressed due to the spatial separation of the branes. Thus, just below the compactification scale M_c,[2] the effective 4-dimensional theory is the MSSM and in the minimal version gaugino masses are the only non-negligible soft SUSY breaking parameters.[3] Scalar masses and trilinear couplings receive large contributions from gaugino masses through the renormalization

[1] Other solutions to the SUSY flavor problem such as decoupling or alignment are generally more awkward to implement in models.

[2] $M_c \sim 1/R$, R represents the size of extra dimension(s).

[3] Soft SUSY breaking Higgs masses can also be generated if Higgs fields propagate in the bulk.

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group (RG) running between M_c and the electroweak (EW) scale. These contributions are flavor blind and therefore the resulting soft SUSY breaking terms at the EW scale cause only a modest flavor violation coming from the Yukawa couplings.

In earlier works on gaugino mediation [4, 5], the compactification scale was assumed to be at or above the GUT scale, in order to preserve the success of gauge coupling unification. Therefore all gaugino masses are equal at M_c. For $M_c = M_{\rm GUT}$, however, this scenario predicts the lightest stau $\tilde{\tau}_1$ to be the lightest supersymmetric particle (LSP), which violates cosmological bounds on the existence of stable charged or colored relics from the Big Bang in models which conserve R-parity. The situation is different for $M_c > M_{\rm GUT}$. In this case the additional RG running between M_c and $M_{\rm GUT}$ has to be considered [5]. This generates non-zero scalar masses and trilinear couplings at the GUT scale; most importantly the stau mass gets a positive contribution which eventually can make the $\tilde{\tau}_1$ heavier than the lightest neutralino $\widetilde{Z}_1$. This removes the unpleasant charged LSP feature of the scenario with $M_c = M_{\rm GUT}$ [5, 6]. In models which assume a simple GUT beyond $M_{\rm GUT}$, the values of $\tan\beta$ ($\sim 35 - 50$) consistent with Yukawa coupling unification do not match the $\tan\beta$ values ($\sim 10 - 25$) predicted by the presence of a small bilinear soft SUSY breaking parameter B_0 [6].

There has been recent interest in constructing GUT models in higher dimensional spacetimes [7]–[11]. Orbifold compactification of the extra dimensions is an elegant way of achieving GUT symmetry breaking and the doublet triplet splitting of Higgs fields. Proton decay due to dimension 5 operators that is a serious problem in 4-dimensional GUT models [12], can be naturally suppressed in these models. The common feature of these models is the existence of a brane or several branes at orbifold fixed points on which the gauge symmetry is restricted to be a subgroup of the GUT symmetry. This results in an effective 4-dimensional theory with gauge symmetry given by an intersection of gauge symmetries on orbifold fixed points.

Positive features of GUTs, like charge quantization or gauge coupling unification, can be preserved. If matter multiplets live in the bulk or are localized on a brane which respects the GUT symmetry, then they come in complete GUT multiplets. Furthermore, if the compactification scale is not far from $M_{\rm GUT}$, the gauge couplings still unify. The gauge couplings run from the EW scale to the compactification scale with the ordinary MSSM β functions. They almost unify at M_c which is below but very close to the conventional GUT scale. Beyond M_c, the gauge couplings run according to the power-law rule [13] due to the heavy KK modes that do not fill degenerate GUT multiplets; they ultimately unify at a scale M_*, the cutoff scale of the model.

The existence of a brane with restricted gauge symmetry can play an important role for gaugino mediation. If SUSY is broken on a brane with restricted gauge symmetry, non-universal gaugino masses are generated. For example, if using proper boundary conditions SU(5) is broken on a brane down to the standard model (SM), non-universal gaugino masses M_1, M_2, M_3 can be generated on this brane [8].

Even more interesting is the situation for SO(10) models in higher dimensions [10, 11] which can contain branes with gauge symmetries being different subgroups of SO(10). Using proper boundary conditions, fixed branes with Pati-Salam $\mathrm{SU}(4)\times\mathrm{SU}(2)_L\times\mathrm{SU}(2)_R$,

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Georgi-Glashow $\mathrm{SU}(5)\times\mathrm{U}(1)$, or flipped $\mathrm{SU}(5)'\times\mathrm{U}(1)'$ gauge symmetries can be obtained. If gauginos get masses on these branes, the gauge symmetry relates gaugino masses of the MSSM at the compactification scale. In the case of Pati-Salam gauge symmetry, gaugino masses M_2 and M_3 are free parameters while the M_1 is given by a linear combination of M_2 and M_3 [10].

The compactification scale in these models is below the GUT scale and the boundary conditions with negligible squark and slepton masses and trilinear couplings are realized at this scale. Therefore the cure of ref. [5] to the stau LSP problem doesn't apply here. However, in this case the non-universal gaugino masses may help to obtain viable SUSY spectra with a neutralino LSP, at least in some restricted regions of model parameter space. Non-universal gaugino masses can also be very helpful in order to obtain Yukawa coupling unification for models with a positive μ term [14].

We emphasize that extra dimensional gauge theories are not the only way to get the MSSM at the GUT scale with the non-universal gaugino masses as the only sources of the soft SUSY breaking. For example, one may imagine deconstructing the 5-dimensional models with non-universal gaugino masses (for discussion of deconstructed universal gaugino mediation see [15]). In addition, models of no-scale supergravity can also provide us with the desired boundary conditions i.e. vanishing scalar masses and trilinear couplings and non-zero gaugino masses [16]. In a no-scale locally supersymmetric GUT, a non-trivial choice of the couplings between the vector supermultiplets and the chiral supermultiplet can easily result in non-universal gaugino masses at the GUT scale [17]. Similar results can also be obtained in type-I string constructions, see for example [18].

In this paper, we present the allowed region of SUSY parameter space and study the supersymmetric particle spectrum for the case where the bino mass M_1 is related to M_2 and M_3 by the Pati-Salam symmetry. In this case we *do* find regions of parameter space leading to a viable SUSY particle spectrum although the allowed regions turn out to be rather tightly restricted. We also evaluate the relic density of neutralinos for these models; we find it in general to be somewhat below expectations from cosmological measurements due to the presence of a non-negligible higgsino component to the LSP. This is a positive feature of such models, since one may expect additional cold dark matter (CDM) states associated for instance with the hidden brane. We evaluate as well the branching fraction $BF(b\to s\gamma)$ and muon anomalous magnetic moment $a_\mu=\frac{(g-2)_\mu}{2}$. We also study the effect of adding non-zero soft SUSY breaking Higgs masses on the allowed regions of parameter space; typically, these Higgs masses do not ameliorate the situation. Finally, we examine the case of completely independent non-universal gaugino masses at the compactification scale. In this case, we find that regions of parameter space leading to viable spectra open up for large values of the bino mass M_1. We show sample spectra for these models; they typically lead to spectra with nearly degenerate $\widetilde{W}_1$ and $\widetilde{Z}_1$, since the LSP turns out to be either wino-like (as in AMSB models) or higgsino-like.

This paper is organized as follow. In section 2, we review some details of extra dimensional SUSY GUT models with gaugino mediated SUSY breaking, and their associated parameter space. In section 3, we examine models where M_1 is determined in terms of M_2 and M_3 by the Pati-Salam gauge symmetry, and show that there exists parameter space

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leading to viable models, although its extent is somewhat limited. In section 4, we present our results for completely independent gaugino masses. These models emphasize regions of parameter space with large $\mathrm{U}(1)_Y$ gaugino mass M_1, and can frequently lead to spectra with a wino-like LSP. Our conclusions are presented in section 5.

2. Non-universal gaugino mediation

In this section, we will review the basic features of GUT models in higher dimensional spacetimes. We start with the simple example of an SU(5) GUT in five dimensions (for more detailed discussion, see [8]). The fifth dimension is compactified on an $S^1/(Z_2 \times Z_2')$ orbifold where S^1 is a circle of radius R defined with a periodic coordinate $0 \leq y < 2\pi R$. Z_2 identifies opposite points on the circle $y \to -y$ and Z_2' identifies opposite points with respect to $y' = y - \pi R/2$, i.e. $y' \to -y'$. The resulting orbifold has two inequivalent fixed points O at $y = 0$ and O' at $y = \pi R/2$ ($y' = 0$). There are fixed branes (4-dimensional Minkowski spaces) at these points. Let's assume that the gauge supermultiplet and two Higgs hypermultiplets in $\mathbf{5}$ and $\bar{\mathbf{5}}$ representations propagate in the bulk. In five dimensions, $\mathcal{N} = 1$ supersymmetry is generated by 8 supercharges and is equivalent to $\mathcal{N} = 2$ supersymmetry in four dimensions. Using 4 dimensional superfield notation, the 5-dimensional gauge supermultiplet can be written as (V, Σ) where V is a 4-dimensional gauge supermultiplet and Σ is a chiral supermultiplet, both in the adjoint (24-dimensional) representations of SU(5). Similarly Higgs hypermultiplets that transform as $\mathbf{5}$ and $\bar{\mathbf{5}}$ can be written as (H_5, H_5^c) and $(H_{\bar{5}}, H_{\bar{5}}^c)$ where H_5 and H_5^c ($H_{\bar{5}}$ and $H_{\bar{5}}^c$) are 4-dimensional chiral supermultiplets in the $\mathbf{5}$ and $\bar{\mathbf{5}}$ ($\bar{\mathbf{5}}$ and $\mathbf{5}$) representations of SU(5).

A generic field $\phi(x_\mu, y)$ in the 5-dimensional bulk is identified by its transformations under the Z_2 and Z_2' parities $P = \pm$ and $P' = \pm$, respectively; $\phi(-y) = P\phi(y)$ and $\phi(-y') = P'\phi(y')$. Only those fields with parity $(+,+)$ under $Z_2 \times Z_2'$ have massless Kaluza-Klein modes in the resulting 4-dimensional effective theory. Invariance of the 5-dimensional gauge interactions under Z_2 requires a relative minus sign between the parity transformations of V and Σ and similarly between H and H^c (in both $\mathbf{5}$ and $\bar{\mathbf{5}}$). Z_2 parities of V, H_5 and $H_{\bar{5}}$ are taken to be $+$ and those of Σ, H_5^c and $H_{\bar{5}}^c$ are taken to be $-$. Therefore the orbifold compactification breaks $\mathcal{N} = 2$ supersymmetry in four dimensions down to $\mathcal{N} = 1$.

Using a non-trivial assignment of Z_2' parities $P' = \mathrm{diag}(-1, -1, -1, +1, +1)$ acting on $\mathbf{5}$, the SU(5) gauge symmetry is restricted to the standard model gauge symmetry $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \equiv G_{\mathrm{SM}}$ on the O' brane. At the same time P' splits Higgs doublets from their color triplet partners. As a result only gauge fields of the minimal supersymmetric standard model and two Higgs doublets H_u and H_d (those contained in H_5 and $H_{\bar{5}}$) are (+,+) fields and therefore will be present at the massless level in the resulting 4-dimensional effective theory.

The third generation matter fields can be localized on the O brane. Since the gauge symmetry on the O brane is SU(5), matter fields must come in complete SU(5) multiplets. Therefore we can have usual SU(5) $b - \tau$ Yukawa unification although the 4-dimensional theory is just the MSSM.

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This setup with two separated fixed branes is very suitable for gaugino mediation. Let's assume that SUSY is broken by the vacuum expectation value of a gauge singlet chiral superfield X that is localized on the O' brane,

$$\langle X \rangle = \theta^2 F_X \,. \tag{2.1}$$

X can couple directly to the gauge fields on the O' brane through the ultraviolet scale suppressed terms

$$\mathcal{L}_{O'} \supset \int d^2\theta \left(\lambda_3 \frac{X}{M_*^2} W^{i\alpha} W^i_\alpha + \lambda_2 \frac{X}{M_*^2} W^{j\alpha} W^j_\alpha + \lambda_1 \frac{X}{M_*^2} W^\alpha_Y W_{Y\alpha} + H.c. \right), \tag{2.2}$$

where index $i(j)$ runs over the gauge fields of the SU(3)(SU(2)) gauge group. This will give masses to gauginos of SU(3), $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ separately,

$$M_i = \frac{\lambda_i F_X M_c}{M_*^2}\,, \qquad i = 1, 2, 3 \tag{2.3}$$

which corresponds to the fact that the gauge symmetry on the O' brane is restricted to G_{SM}. The factor M_c (the compactification scale, $M_c \sim 1/R$) comes from the wave function normalization of the 4-dimensional gaugino fields. Similarly the μ and B_μ terms ($B_\mu = B\mu$) can be generated:

$$\mathcal{L}_{O'} \supset \int d^4\theta \left(\frac{X^\dagger}{M_*^2} H_u H_d + \frac{X X^\dagger}{M_*^3} H_u H_d + H.c. \right), \tag{2.4}$$

leading to

$$\mu \sim \frac{F_X M_c}{M_*^2}\,, \qquad B_\mu \sim \frac{F_X^2 M_c}{M_*^3}\,. \tag{2.5}$$

Finally soft SUSY breaking masses for Higgs scalars can be generated:

$$\mathcal{L}_{O'} \supset \int d^4\theta \left(\frac{X X^\dagger}{M_*^3} H_u H_u^\dagger + \frac{X X^\dagger}{M_*^3} H_d H_d^\dagger \right), \tag{2.6}$$

giving

$$m^2_{H_u} \sim m^2_{H_d} \sim \frac{F_X^2 M_c}{M_*^3}\,. \tag{2.7}$$

To summarize the results of this model, in the effective 4-dimensional theory at the massless level we have MSSM gauge fields and two Higgs doublets. At the compactification scale non-universal gaugino masses and the μ term are generated together with B_μ term and soft SUSY breaking Higgs masses. Soft SUSY breaking masses of squarks and sleptons and trilinear couplings are negligible at M_c. Furthermore, Yukawa couplings of b and τ unify at M_c.

The fact that in some sectors of the theory there are GUT relations between parameters and in others there are no relations is clearly a consequence of having branes with grand unified gauge symmetry and with restricted gauge symmetry. The results of the above model can also be easily modified by different arrangements of fields living in the bulk and those localized on branes. For example if the third generation matter fields are not localized

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on the brane with GUT symmetry (they can be localized on the brane with restricted gauge symmetry or can come from different multiplets living in the bulk), the Yukawa unification is not predicted.[4] Similarly if the Higgs fields do not live in the bulk and are not localized on the brane where SUSY is broken, the soft SUSY breaking Higgs masses are not generated. In this case the μ term is not generated either; however, it can be generated within the effective 4-dimensional theory [19]. Therefore, generating gaugino masses is not necessarily connected with either generating Higgs masses or Yukawa unification.

A very interesting situation can happen in models with SO(10) GUT symmetry in higher dimensional spacetimes [10, 11]. There are more ways to break SO(10) symmetry down to $G_{\rm SM}$ and therefore branes on which the gauge symmetry is restricted to different subgroups of SO(10) can appear in a model. Splitting of Higgs doublets and triplets can be achieved if the gauge symmetry on a brane is restricted to SO(6) $\times$ SO(4) which is isomorphic to the Pati-Salam gauge symmetry SU(4) $\times$ SU(2)$_L$ $\times$ SU(2)$_R$. In a similar way as in eqs. (2.1), (2.3), masses of gauginos of SO(6) and SO(4) gauge groups can be generated on this brane separately [10],

$$M_6 = \frac{\lambda'_6 F_X M_c}{M_*^2}, \qquad M_4 = \frac{\lambda'_4 F_X M_c}{M_*^2}. \tag{2.8}$$

The masses of gauginos of the MSSM (M_1, M_2, M_3) are then given as

$$M_1 = \frac{2}{5} M_6 + \frac{3}{5} M_4\,, \qquad M_2 = M_4\,, \qquad M_3 = M_6\,. \tag{2.9}$$

The special form of M_1 is related to the way in which the generator of hypercharge is expressed as a linear combination of the generator of $B-L$ from SO(6) and the generator of t_{3R} from SO(4), namely $Y = \sqrt{\frac{2}{5}}(B-L) - \sqrt{\frac{3}{5}} t_{3R}$ (for detailed discussion see [10]).[5]

As in the case of SU(5), Yukawa unification may or may not be present, depending on the way matter fields are introduced in the model. If the third generation matter fields are localized on a brane with SO(10) symmetry, $t-b-\tau$ Yukawa unification is predicted. However, matter fields can be localized on a brane with SU(5) $\times$ U(1) gauge symmetry in which case only $b-\tau$ Yukawa unification should be expected at M_c. And of course models can be built without having any kind of Yukawa unification. Similarly soft SUSY breaking Higgs masses can be generated. If they are generated on the same brane as gaugino masses, SO(6) $\times$ SO(4) symmetry guarantees that $m^2_{H_u} = m^2_{H_d}$ at the compactification scale.

3. Pati-Salam scenario

In this section, we investigate the parameter space of gaugino mediated SUSY breaking models where gaugino masses are constrained by the Pati-Salam (PS) symmetry to

[4] This can be actually very useful for treating first two generation, since the unification of Yukawa couplings of first two generation fermions is excluded by experimental observations.

[5] Similarly, if gaugino masses are generated on a brane with flipped SU(5)$'$ $\times$ U(1)$'$ symmetry, we have relation $M_2 = M_3 = M_{5'}$ and M_1 is a linear combination of $M_{5'}$ and $M_{1'}$. Therefore gaugino masses are given by two independent parameters M_1 and $M_2 = M_3$.

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obey

$$M_1 = \frac{3}{5}M_2 + \frac{2}{5}M_3 \tag{3.1}$$

at the compactification scale. Scalar masses and trilinear soft SUSY breaking terms are restricted to be $m_0 \simeq A_0 \simeq 0$. In minimal gaugino mediation the bilinear B_0 parameter is also $\simeq 0$, which leads to a predicted value of $\tan\beta$. Here, we will work with a somewhat more general format, taking $\tan\beta$ as an independent parameter and determining the value of B at the weak scale by imposing minimization conditions on the scalar potential, so that radiative EW symmetry breaking occurs (REWSB). Note that this procedure also determines the magnitude, but not the sign, of the superpotential Higgs mass term μ.

Our goal is to delineate the allowed regions of the parameter space in this scenario, and to find the regions that can be explored by near future experiments. The parameter space of the model is then given by

$$M_2(M_c)\,, \quad M_3(M_c)\,, \quad \tan\beta\,, \quad \mathrm{sign}(\mu)\,, \quad M_c \tag{3.2}$$

as the independent parameters. The sparticle spectrum will depend only logarithmically on the value of M_c, which nonetheless must be near the GUT scale. Hence, we adopt the choice $M_c = 1 \times 10^{16}$ GeV, i.e. just below the usual unification scale of $M_{\mathrm{GUT}} \simeq 2 \times 10^{16}$ GeV.

We employ an updated version of ISAJET version 7.58 [20] which allows for sparticle spectra predictions for negative values of the gaugino mass M_3 (as well as M_2 and M_1 as in earlier versions). Briefly, the subprogram ISASUGRA (which is a part of ISAJET) begins with weak scale values of gauge and Yukawa couplings, and evolves up in energy until the unification scale where $g_1 = g_2$ is identified. At M_{GUT} (or other intermediate scales), the soft SUSY breaking boundary conditions can be imposed, and evolution of the set of 26 coupled RGEs of the MSSM is calculated down to the weak scale, where the 1-loop effective potential is minimized at an optimized scale choice which reproduces to within $1-2$ GeV the light scalar Higgs mass m_h as predicted by the FeynHiggsFast program [21]. Yukawa couplings are updated via their SUSY loop corrections, and the process of up-down RGE evolution is iterated until a stable solution is obtained, using the complete set of two-loop RGEs. A variety of non-universal soft SUSY breaking mass inputs are allowed, including for this study independent gaugino masses.

Our first results are presented in figure 1, where we show regions of the M_2 vs. M_3 parameter plane for $\mu < 0$ and $\tan\beta =5$, 10, 15, 20, 25 and 30. The regions with low values of $|M_i|$ denoted by red crosses give rise to tachyonic sparticle masses. In these cases, the Yukawa coupling contribution to the RGEs for top and bottom squarks is dominant, and quickly drives these squared masses to negative values. The red shaded regions do not give rise to an appropriate radiative breakdown of EW symmetry. The magenta regions give rise to a charged LSP, the lightest stau. This is the well-known problem associated with models of minimal gaugino mediation. The light and dark blue shaded regions give rise to spectra in violation of LEP and LEP2 limits from sparticle searches. In the case of LEP bounds, the Z boson has non-negligible decays to sparticles, while in the LEP2 case we require

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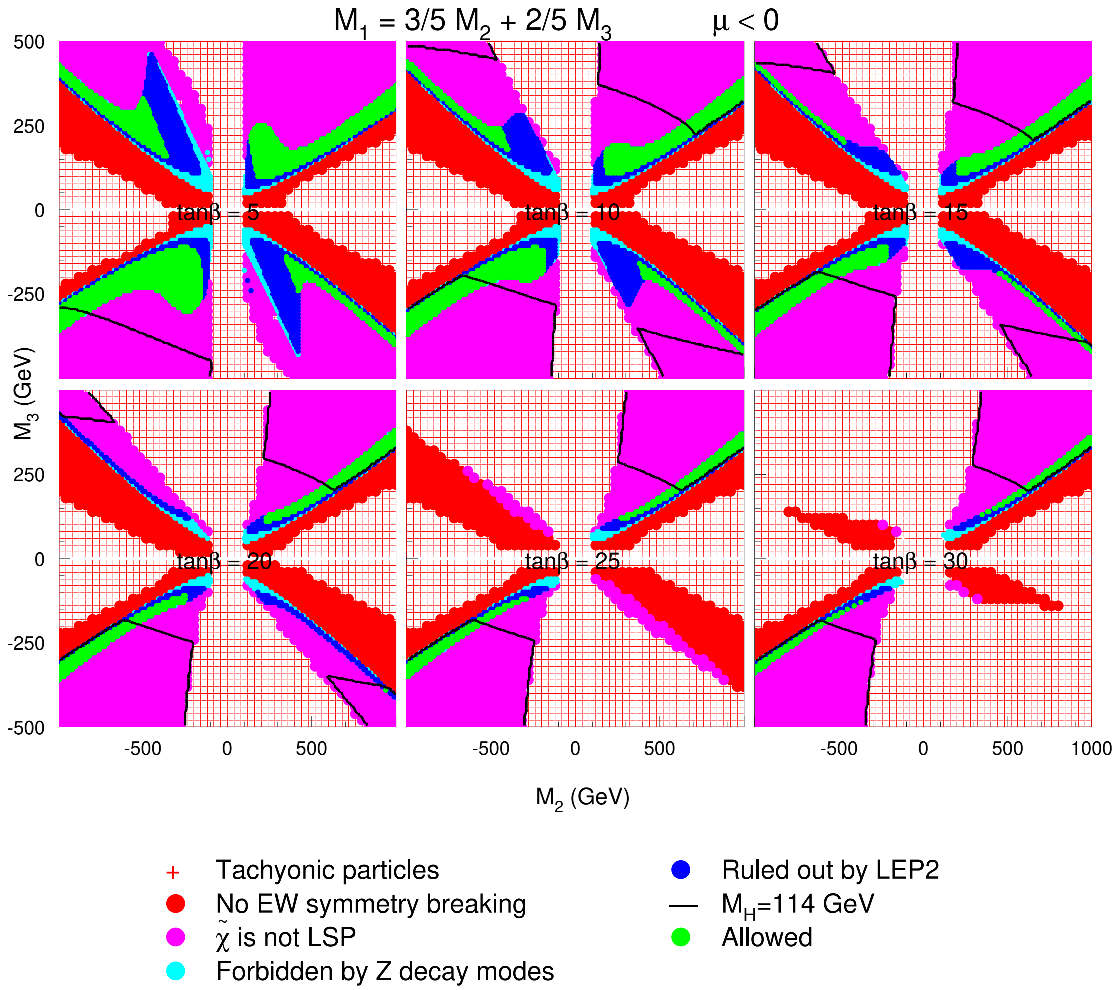

Figure 1: Allowed and excluded regions of the $M_2(M_c)$ vs. $M_3(M_c)$ parameter plane in the Pati-Salam scenario for various $\tan\beta$ values with $\mu < 0$. Most of the parameter space is excluded by the lack of REWSB (red shaded), tachyonic particles in the spectrum (red crosses) or the stau being the LSP (magenta). Regions with viable spectra but in violation of limits from LEP (LEP2) are denoted by light blue (dark blue) shading. The black contour denotes regions where the light Higgs mass $m_h > 114\,\mathrm{GeV}$. Finally, the green shaded region is allowed by all constraints (except possibly those from LEP2 Higgs searches).

$m_{\widetilde{W}_1} > 100\,\mathrm{GeV}$, $m_{\tilde{\ell}_1} > 92\,\mathrm{GeV}$, $m_{\tilde{\mu}_1} > 85\,\mathrm{GeV}$, $m_{\tilde{\tau}_1} > 68\,\mathrm{GeV}$ and $m_{\widetilde{Z}_1} > 37\,\mathrm{GeV}$ [22]. The green shaded region obeys all constraints with the possible exception of LEP2 Higgs searches. These range from $m_h > 114$ GeV for low $\tan\beta$ to $m_h > 91$ GeV for $\tan\beta > 10$ [23]. We show instead the black contour where $m_h = 114\,\mathrm{GeV}$, and where $m_h > 114\,\mathrm{GeV}$ occurs for larger values of M_2 and M_3.

For $\tan\beta = 5$, a significant green region survives all constraints with the exception being that the light Higgs scalar has mass $m_h < 114\,\mathrm{GeV}$ except for a tiny region in the lower left. As $\tan\beta$ increases, the green allowed region gradually shrinks, while the tachyonic and stau LSP regions increase. This is reasonable in that as $\tan\beta$ increases, the b and τ Yukawa couplings increase, and they contribute more strongly to driving scalar squared masses to small or tachyonic values. As $\tan\beta$ increases, however, the light Higgs mass

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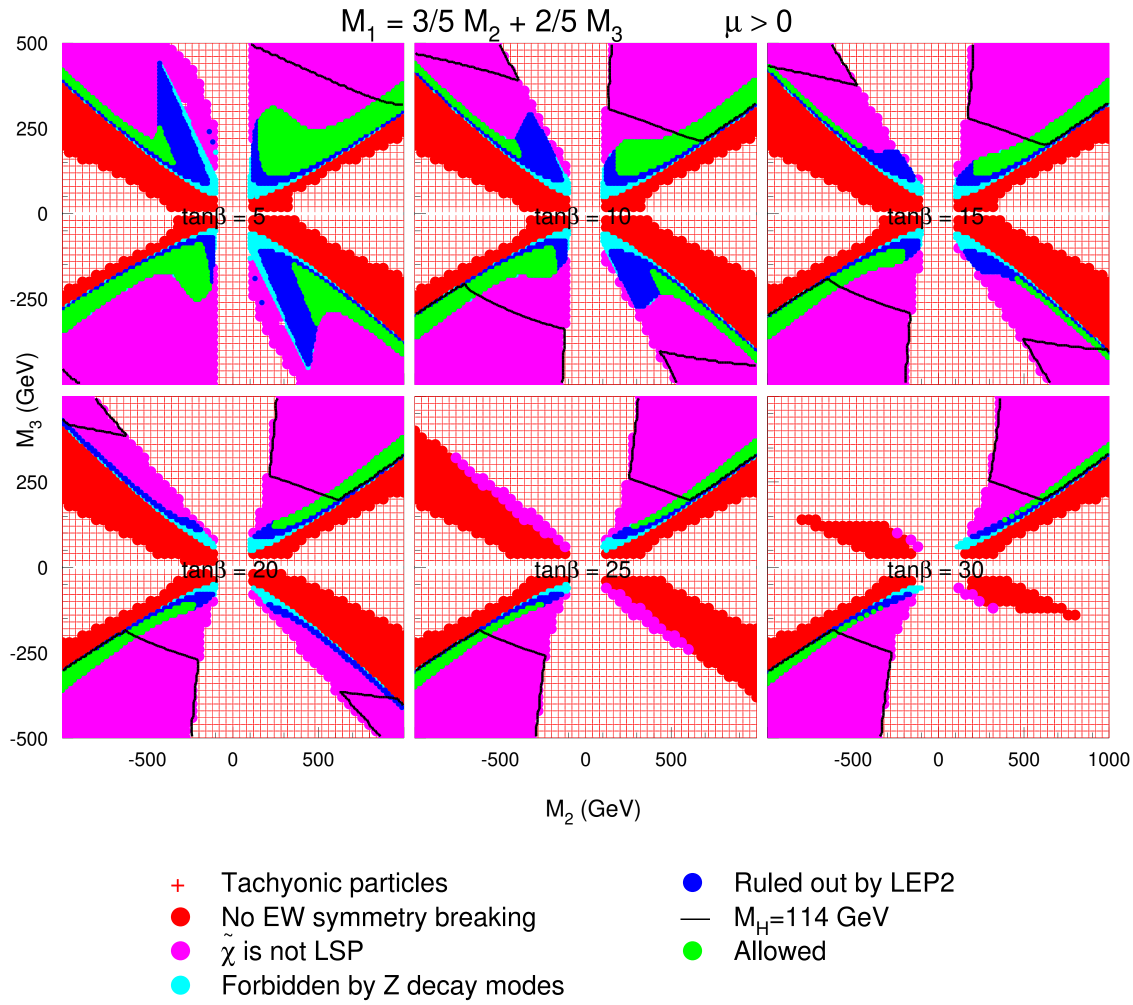

Figure 2: Same as in figure 1, but with $\mu > 0$.

m_h also increases, giving rise to regions with viable supersymmetric spectra. This verifies the conjecture in ref. [10] that the increased flexibility in the non-universal gaugino masses can cure the stau LSP problem inherent in models of minimal gaugino mediation without beyond the GUT scale running. However, we must note that the region of viable parameter space is rather limited, and in fact disappears for both high and low values of $\tan\beta$.

In our plots, both positive as well as negative gaugino mass parameters are allowed. In fact, we observe a near symmetry of parameter space when $M_2 \to -M_2$ and $M_3 \to -M_3$. In this case, $M_1 \to -M_1$ as well, and all gaugino masses flip sign, but remain with the same absolute value. The MSSM lagrangian is in fact invariant under the simultaneous sign change of the gaugino masses, the A and B parameters and μ,[6] so the near symmetry under sign flip of all gaugino masses may not be surprising. If instead we flip the sign of

[6]We thank X. Tata for emphasizing this point.

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just one of M_2 or M_3, then of course there is much less symmetry, since a different absolute value of the bino mass M_1 is generated. Toward larger values of $\tan\beta$, this asymmetry increases because for $(M_2 \cdot M_3) < 0$, $|M_1|$ becomes smaller than in the $(M_2 \cdot M_3) > 0$ case, and the tau Yukawa coupling can more easily drive the right handed stau squared mass to negative values.

To illustrate the sort of spectra that can occur in the PS scenario, we show three cases in table 1 for low, moderate and high $\tan\beta$. In the first case, *universal* gaugino masses are actually taken along the line where $M_2 = M_3$. Along this line, however, the light Higgs mass m_h is always below the limit from LEP2, and so is excluded. In addition, for the first case, the $\tilde{\tau}_1$ and $\widetilde{Z}_1$ are nearly mass degenerate. The spectra for the other two cases are taken from the upper right branches of allowable parameter space in figures 1 and 2.

parameter	value		
$M_1(M_c)$	250	590	666
$M_2(M_c)$	250	800	900
$M_3(M_c)$	250	275	315
$\tan\beta$	5	10	30
μ	>0	<0	>0
$\mu(M_{\rm weak})$	337.6	-153.5	147.0
$B(M_{\rm weak})$	81.7	-186.3	62.5
$m_{\tilde{g}}$	583.9	652.3	738.9
$m_{\tilde{u}_L}$	519.5	729.1	823.6
$m_{\tilde{d}_R}$	502.8	541.6	614.0
$m_{\tilde{t}_1}$	376.7	344.3	398.0
$m_{\tilde{b}_1}$	485.2	536.3	565.5
$m_{\tilde{e}_L}$	174.0	531.4	596.6
$m_{\tilde{e}_R}$	101.4	222.1	249.6
$m_{\tilde{\nu}_e}$	156.1	525.5	591.3
$m_{\tilde{\tau}_1}$	98.4	215.4	162.6
$m_{\tilde{\nu}_\tau}$	156.0	524.2	577.7
$m_{\widetilde{Z}_2}$	172.6	161.2	152.6
$m_{\widetilde{W}_1}$	171.3	153.2	144.7
$m_{\widetilde{Z}_1}$	98.2	141.9	134.7
m_h	109.3	115.2	118.0
m_A	377.3	541.0	511.4
m_{H^+}	385.6	547.2	519.1

Table 1: Representative weak scale (physical) sparticle masses (in GeV units) and parameters for three Pati-Salam scenarios. We take $M_c = 1 \times 10^{16}$ GeV.

Moving to regions beyond the black $m_h = 114$ GeV contour, we find the allowed parameter space is bounded from below by regions where $\mu^2 < 0$ (no REWSB) and from above by where the $\tilde{\tau}_1$ becomes the LSP. These cases typically have small values of $|\mu|$, and hence a higgsino-like LSP. The $\widetilde{W}_1$ ($\widetilde{Z}_2$) will decay into three body modes dominated by virtual W (Z) exchange. There is a very small mass gap between $\widetilde{W}_1$ and $\widetilde{Z}_1$, so that $\widetilde{W}_1$ and $\widetilde{Z}_2$ decay products will be quite soft, making collider searches challenging. One can expect that the search for lightest sleptons – selectron, smuon or stau – will be a better choice to hunt for SUSY particles.

In figure 3, we show in addition the relic density of neutralinos and the region excluded by $BF(b \to s\gamma)$ constraints in the allowed parameter space regions from figure 2. For $BF(b \to s\gamma)$, we use the program of ref. [24], upgraded to include running b-quark mass effects which are important at large $\tan\beta$. The red regions give too high a value of $BF(b \to s\gamma) > 5 \times 10^{-4}$, while pink regions give too low a value: $< 2 \times 10^{-4}$. We also evaluate the muon anomalous magnetic moment a_μ following the program of ref. [25]. All of the allowed region not excluded by $BF(b \to s\gamma)$ falls within the range $-10 \times 10^{-10} < a_\mu < 60 \times 10^{-10}$. We caution the reader that the excluded regions we present here and later on due to the $BF(b \to s\gamma)$ and a_μ criteria should be interpreted as illustrative. The first reason for this is the theoretical uncertainty and the

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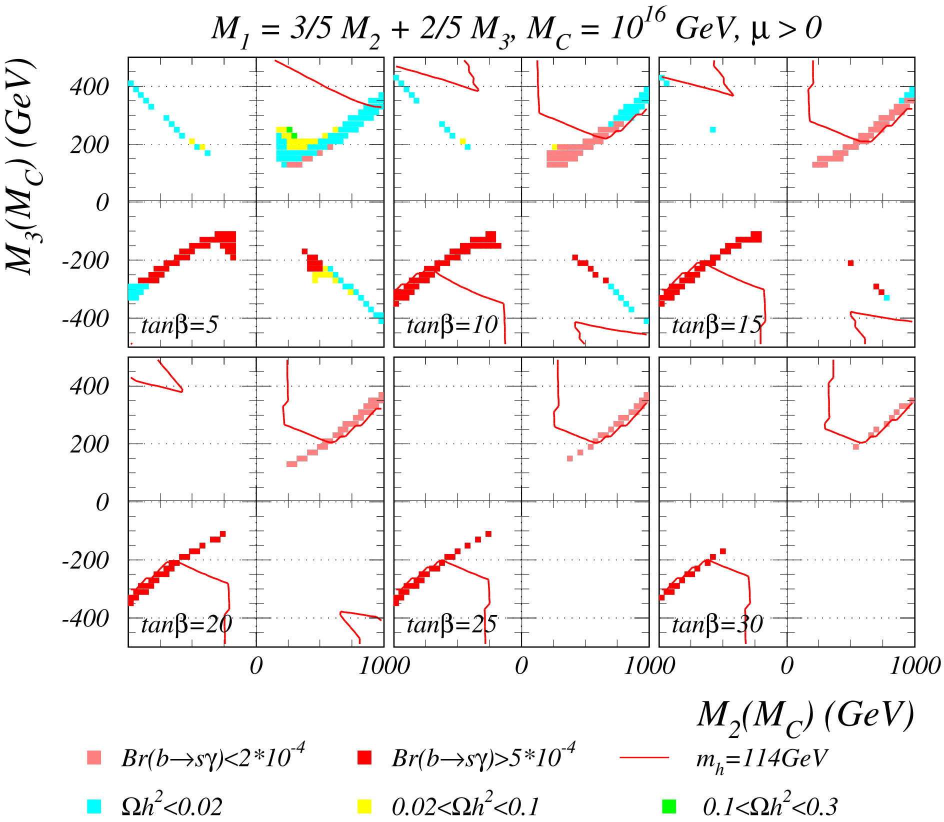

Figure 3: Same parameter space as in figure 2, but showing the neutralino relic density Ωh^2 in the viable regions of parameter space.

imminent new experimental analysis for a_μ. Secondly, the results on $BF(b \to s\gamma)$ are quite model-dependent — the potential contributions from small off-diagonal SSB masses to $BF(b \to s\gamma)$ can easily work in both ways — they can easily increase or decrease the deviations of $BF(b \to s\gamma)$ from the SM value.

For the neutralino relic density, we use the recent calculation of ref. [26], which includes all relevant co-annihilation channels as well as relativistic thermal averaging of annihilation cross sections times neutralino velocity. The blue regions have $\Omega h^2 < 0.02$, while yellow regions have $0.02 < \Omega h^2 < 0.1$. The current cosmologically favored amount of CDM is $0.1 < \Omega h^2 < 0.3$ (green). Thus, the neutralino relic density in the PS scenario is typically quite low compared with the cosmologically favored values of the CDM density. This is easy to understand, since the allowed parameter space of the PS scenarios have an LSP with a large higgsino component. In this case, there is a large annihilation rate into WW, ZZ and Zh pairs, which results in a general reduction of the expected CDM density. Since our scenario is a higher dimensional model, the low neutralino relic density can easily be augmented by other forms of CDM related to extra dimensions. Thus, the predicted low neutralino relic density does not restrict the allowed parameter space in the PS case, and leaves room for other forms of CDM inherent in extra-dimensional models.

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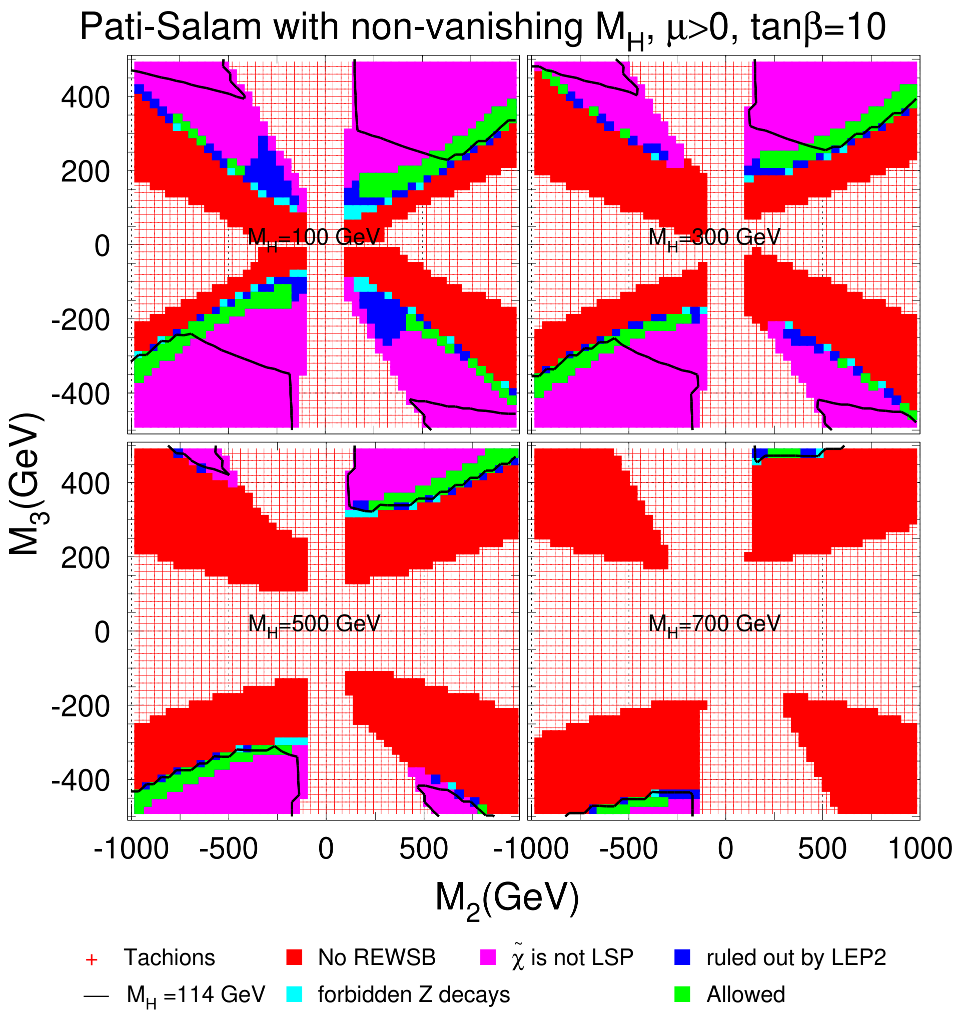

Figure 4: Allowed and excluded regions of the $M_2(M_c)$ vs. $M_3(M_c)$ parameter plane for the Pati-Salam scenario with $\mu > 0$ and $\tan\beta = 10$, but with $m_{H_u}(M_c) = m_{H_d}(M_c) = 100$, 300 500 and 700 GeV. For $\mu < 0$ the result is qualitatively the same.

If the Higgs fields of an extra dimensional SUSY GUT propagate in the bulk, then they may gain non-negligible soft SUSY breaking masses as well. This additional freedom of non-zero Higgs squared masses at the compactification scale may allow additional parameter space to open up in the PS scenario. In figure 4, we plot the allowed parameter space in the M_2 vs. M_3 plane for $\tan\beta = 10$, but this time allowing for non-zero soft SUSY breaking Higgs masses $m_{H_u} = m_{H_d} = 100$, 300, 500 and 700 GeV. In fact as the Higgs masses increase, the allowed parameter space moves to higher absolute M_3 values, but also diminishes in area. The general diminution of parameter space occurs because in the RGEs for squared slepton masses, there exist terms where Higgs masses multiply Yukawa couplings. These contributions drive the soft SUSY breaking slepton masses to lower values than in the $m_{H_u} = m_{H_d} = 0$ case, giving larger regions of parameter space with a stau LSP.

Since the diminution of soft breaking sfermion masses is due to RGE terms involving Yukawa couplings, we expect the effect to be amplified for large $\tan\beta$, where the τ Yukawa

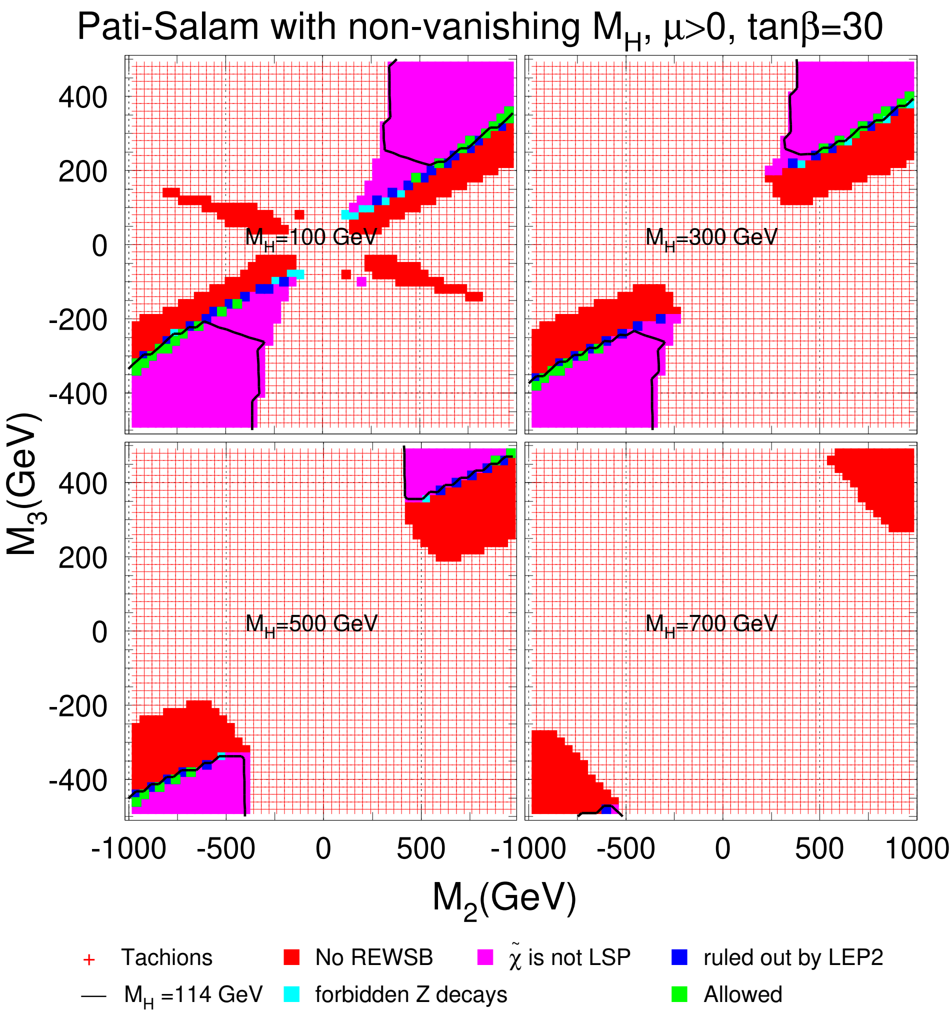

Figure 5: Allowed and excluded regions of the $M_2(M_c)$ vs. $M_3(M_c)$ parameter plane for the Pati-Salam scenario with $\mu > 0$ and $\tan\beta = 30$, but with $m_{H_u}(M_c) = m_{H_d}(M_c) = 100$, 300 500 and 700 GeV. For $\mu < 0$ the result is qualitatively the same.

coupling gets large. In fact this is shown in figure 5, where we show the same results, but for $\tan\beta = 30$. In this case, there is very little allowed parameter space for low values of Higgs masses, and no parameter space left on the frames shown for the very large values of m_{H_i} $(i = u,\ d)$.

4. Gaugino mediation with independent gaugino masses

A more general scenario occurs when all three gaugino masses are independent at the compactification scale, as in eq. (2.3). In this case, we again scan the M_2 vs. M_3 plane, but this time for different independent fixed values of gaugino mass M_1. In figure 6, we show the parameter space for $\tan\beta = 10$, $\mu > 0$ and fixed values of $M_1 = 500$, 1000, 1500 and 2000 GeV. The shading of the different forbidden and allowed regions is the same as in figures 1 and 2. We see that for $M_1 = 500$ GeV, for low values of M_3, the parameter space is forbidden

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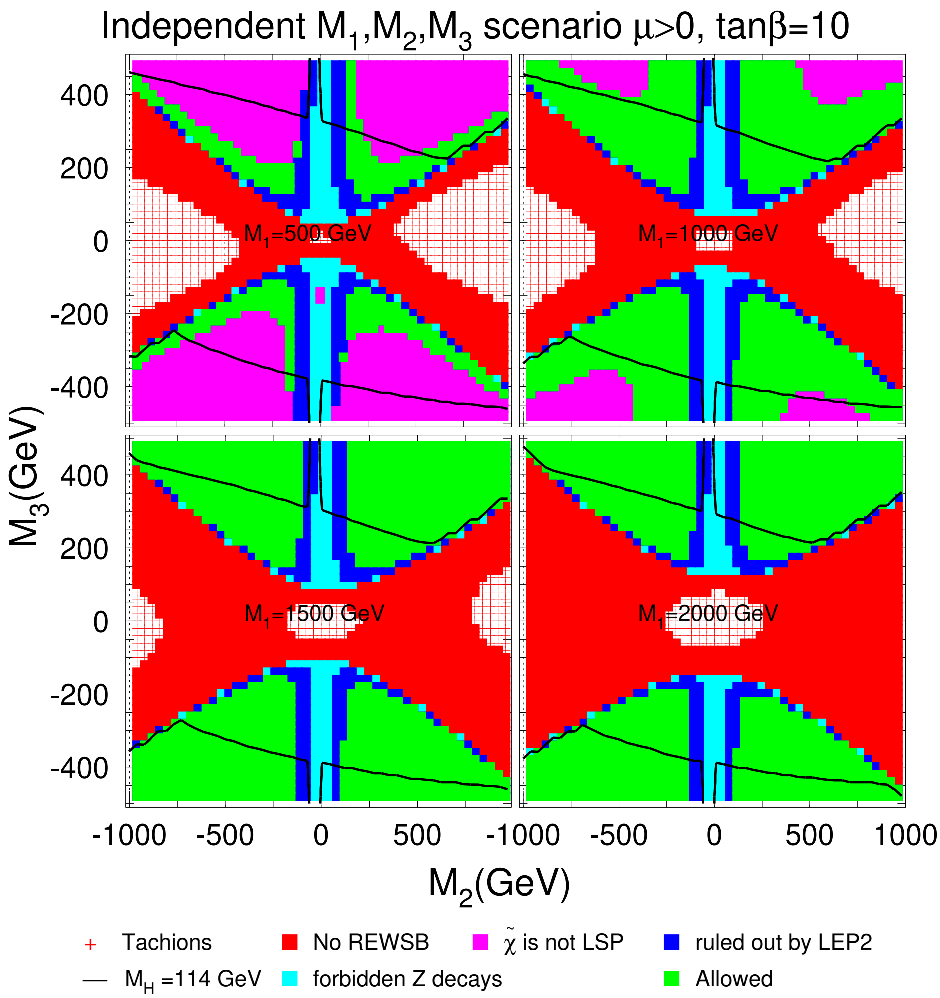

Figure 6: Allowed and excluded regions of the $M_2(M_c)$ vs. $M_3(M_c)$ parameter plane for independent gaugino masses at M_c, $\tan\beta = 10$ and $\mu > 0$. The four frames are shown for $M_1(M_c) = 500$ 1000, 1500 and 2000 GeV. For $\mu < 0$ the result is qualitatively the same.

either by tachyonic particles or no REWSB; for small values of M_2, additional parameter space is ruled out by constraints from LEP2 on the mass of the lightest chargino. As M_1 increases, the $\mathrm{U}(1)_Y$ contribution to the running of the soft SUSY breaking squared mass $m^2_{\tilde{\tau}_R}$ increases, so that the region of parameter space excluded by a $\tilde{\tau}_1$ LSP shrinks. The allowed region of parameter space grows to become a major fraction of the M_2 vs. M_3 plane.

We also show the same M_2 vs. M_3 parameter space for fixed values of M_1 for larger $\tan\beta$ values of 30 and 45 in figures 7 and 8, respectively. As $\tan\beta$ increases, the τ Yukawa coupling also increases, which suppresses the stau masses, so that more of parameter space is disallowed by either the $\tilde{\tau}_1$ LSP or tachyonic constraints. However, in all cases, if M_1 is taken to be sufficiently large, then the gauge contribution to $\tilde{\tau}_i$ running wins out, and much of the parameter space with large gaugino masses becomes again allowed.

In table 2, we show several representative cases from the allowed parameter space with independent gaugino masses. The first case has $M_1(M_c) = 500$ GeV, while $M_2(M_c) =$

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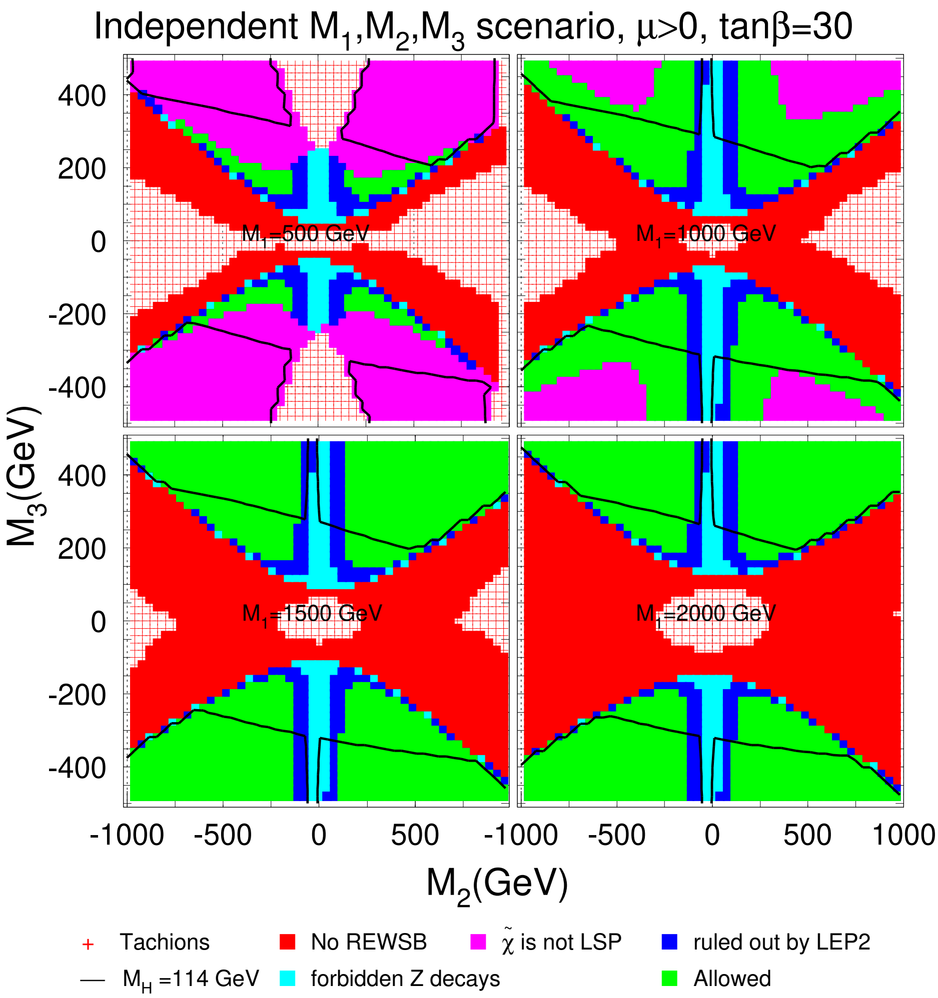

Figure 7: Allowed and excluded regions of the $M_2(M_c)$ vs. $M_3(M_c)$ parameter plane for independent gaugino masses at M_c, $\tan\beta = 30$ and $\mu > 0$. The four frames are shown for $M_1(M_c) = 500$, 1000, 1500 and 2000 GeV.

150 GeV and $M_3(M_c) = 300$ GeV. The most notable feature of this model is that $M_2(M_{\text{weak}}) = 111.9$ GeV, compared with a μ value of 392.4 GeV. This results in the LSP being wino-like, and the $\widetilde{W}_1$ and $\widetilde{Z}_1$ being nearly mass degenerate. In fact, in this case the $\widetilde{W}_1$ is just beyond the kinematic reach of LEP2. However, its dominant decay mode is $\widetilde{W}_1 \to \pi^+\widetilde{Z}_1$, and since the $\widetilde{W}_1 - \widetilde{Z}_1$ mass gap is very small, the pion will be soft and not easily detected. The chargino is sufficiently long-lived ($c\tau \simeq 0.1$ cm) that there may be a detectable track followed by kink in chargino production and decay. This is similar to the case from minimal anomaly-mediated SUSY breaking models (mAMSB) [2, 3], which also has a wino-like LSP. Other intriguing features of the spectra are that the light Higgs h is just near the LEP2 bound, and that the sneutrinos are the lightest of all the sleptons, and that the left sleptons are far lighter than right sleptons, in contrast to the case in the minimal supergravity (mSUGRA) model.

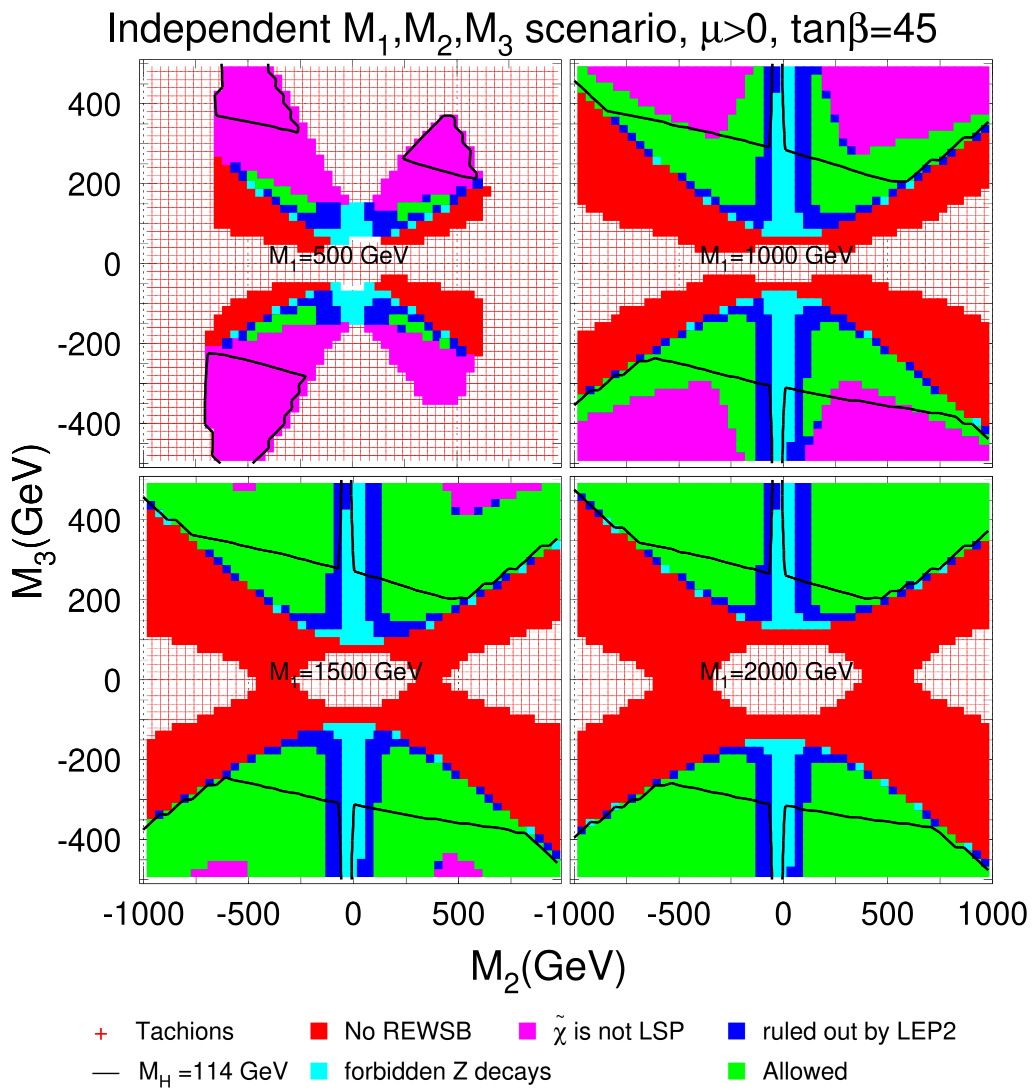

Figure 8: Allowed and excluded regions of the $M_2(M_c)$ vs. $M_3(M_c)$ parameter plane for independent gaugino masses at M_c, $\tan\beta = 45$ and $\mu > 0$. The four frames are shown for $M_1(M_c) = 500$, 1000, 1500 and 2000 GeV.

The second case shown in table 2 is quite different in that now M_1 and μ are comparable at the weak scale, and the LSP is a higgsino-bino mixture. There is a substantial mass gap between $\widetilde{W}_1$ and $\widetilde{Z}_1$, and the right- sleptons are lighter than left-sleptons. The $\tilde{\tau}_1$ is quite light, and in fact the decays of $\widetilde{W}_1$ and $\widetilde{Z}_2$ are dominantly into staus.

The third case in table 2 is at large M_1 and large $\tan\beta$, and the LSP is again wino-like, as in case 1. The lighter sleptons are dominantly left eigenstates.

In figure 9, we show the relic density of neutralinos, the $BF(b \to s\gamma)$ excluded region, and the region excluded by a_μ constraints, for two sample frames of the case with general gaugino masses. The first frame has $M_1 = 500$ GeV, $\tan\beta = 10$ and $\mu > 0$. The color coding is similar to figure 3, except that now regions excluded by a_μ are also shown as light and dark gray regions. When a region is excluded by both $BF(b \to s\gamma)$ and a_μ it is

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parameter	value		
$M_1(M_c)$	500	500	1500
$M_2(M_c)$	150	1000	500
$M_3(M_c)$	300	350	400
$\tan\beta$	10	10	30
μ	>0	>0	>0
$M_2(M_{\rm weak})$	112.0	796.1	393.2
$\mu(M_{\rm weak})$	392.4	181.6	466.4
$B(M_{\rm weak})$	42.1	244.4	22.1
$m_{\tilde g}$	688.9	815.2	903.6
$m_{\tilde u_L}$	595.0	909.6	824.2
$m_{\tilde d_R}$	596.3	672.9	787.4
$m_{\tilde t_1}$	471.6	424.5	645.7
$m_{\tilde b_1}$	556.4	666.6	729.4
$m_{\tilde e_L}$	139.1	653.2	425.2
$m_{\tilde e_R}$	189.8	189.1	555.0
$m_{\tilde\nu_e}$	114.4	648.4	417.7
$m_{\tilde\tau_1}$	128.4	176.7	398.7
$m_{\tilde\nu_\tau}$	113.6	646.9	398.2
$m_{\widetilde Z_2}$	206.6	186.3	470.7
$m_{\widetilde W_1}$	104.1	178.2	364.5
$m_{\widetilde Z_1}$	103.7	156.2	362.9
m_h	114.1	117.8	118.3
m_A	404.8	665.9	546.9
m_{H^+}	412.7	671.1	554.1

Table 2: Representative weak scale (physical) sparticle masses (in GeV units) and parameters for three independent gaugino mass scenarios. We take $M_c = 1\times 10^{16}$ GeV.

colored red or pink. We note that the excluded regions are *not* symmetric in $BF(b\to s\gamma)$ under $M_3\to -M_3$, since the A-parameters evolve quite differently, giving rise to different stop masses and also μ parameter.

Throughout almost all the allowed parameter space, the relic density Ωh^2 is less than 0.02 (blue), i.e. not enough to explain the CDM needed by cosmological observations. This is not surprising in that over much of parameter space, the LSP is either wino-like or higgsino-like. In the first case, there is a large co-annihilation rate between $\widetilde Z_1$ and $\widetilde W_1$ that leads to a small relic density. In the second case, there is a large annihilation rate into WW, ZZ and Zh pairs, which also suppresses the relic density. There are a few points for large positive M_2 and M_3 where $\Omega h^2 > 0.02$. In this region, μ and M_2 are comparable at the weak scale, and the mass gap between $\widetilde W_1$ and $\widetilde Z_1$ can reach up to 20 GeV, thus suppressing the $\widetilde W_1 - \widetilde Z_1$ coannihilation rate, and increasing the relic density. The second frame of figure 9 shows the relic density for $M_1 = 1500$ GeV, $\tan\beta = 30$ and $\mu > 0$. In this case, the relic density is low over all the parameter space shown, due

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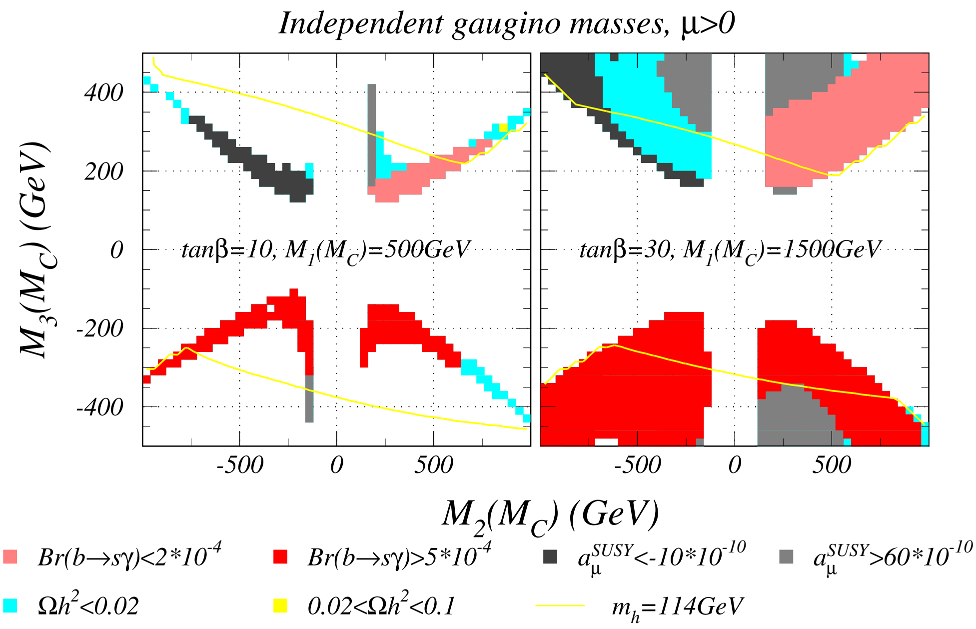

Figure 9: Regions of neutralino relic density in models with independent gaugino masses for $\tan\beta = 10$ and $M_1 = 500\,\mathrm{GeV}$, and for $\tan\beta = 30$ and $M_1 = 1500\,\mathrm{GeV}$. We take $\mu > 0$.

to the presence of a wino-like LSP. Again, a low neutralino relic density leaves room for other potential forms of CDM and does not restrict the allowed parameter space of the model.

5. Conclusions

Gaugino-mediated SUSY breaking is especially attractive in that it leads to a natural solution to the problem of flavor-changing and CP violating processes that are generic to the MSSM. If the soft SUSY breaking boundary conditions from gaugino mediation apply at the GUT scale, then models with universal gaugino masses lead to a charged (stau) LSP. Additional running of soft SUSY breaking parameters above the GUT scale can lift the stau mass to the level where a neutralino LSP is possible. However, if the running occurs in a simple GUT, then the values of $\tan\beta$ consistent with Yukawa unification may conflict with the predicted value of $\tan\beta$ from minimal gaugino mediation with a small B term.

In this paper we examined an alternative solution to the stau LSP problem, in that we allow non-universal gaugino masses. Extra dimensional GUT models can be easily constructed which include gaugino-mediated SUSY breaking, but non-universal gaugino masses. The additional freedom from the non-universal gaugino masses allows us to find viable regions of model parameter space where SUSY spectra are generated consistent with constraints on non-tachyonic sparticles, REWSB and constraints from LEP2. We examined the case of two independent gaugino masses, which occurs when SUSY breaking takes place on a hidden sector brane with Pati-Salam symmetry. In this case, limited regions of viable

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parameter space were found, usually with a higgsino-like LSP. Those regions vanish for the high values of $\tan\beta \sim 45 - 55$ where one could expect Yukawa coupling unification.

We also examined the case where all three gaugino masses were independent. In these models, choosing M_1 large enough opens up large regions of viable parameter space. In this case, the LSP might be either wino-like or higgsino-like. Regions with large $\tan\beta$ are allowed provided one chooses M_1 to be sufficiently large. We illustrated regions of parameter space constrained by muon $g-2$ and $BF(b \to s\gamma)$, although these constraints must be interpretted with caution. Due to the nature of the LSP, the relic density of neutralinos in these models is generally below expectations from cosmology; in this case, some other type of matter (axions or hidden sector states) would be needed to account for the bulk of CDM needed in the universe.

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