PROCEEDINGS OF SCIENCE

Sub-GUT mSUGRA

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In this talk we consider the phenomenology of minimal supergravity (mSUGRA) models in which the supersymmetry-breaking parameters are universal at a scale below the scale at which the Standard Model gauge couplings unify, known as the GUT scale. We find that these so-called sub-GUT mSUGRA models can accommodate a $\sim$125 GeV Standard Model-like Higgs boson while at the same time providing a viable explanation for the observed dark matter in the universe. Here, we present a brief exploration of the sub-GUT mSUGRA parameter space, focusing on cosmologically-favored regions where the dark matter abundance is in agreement with the measured value.

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1. Introduction

Supersymmetry is a well-studied and elegant extension of the Standard Model (SM) of particle physics with many virtues, such as gauge coupling unification and the prediction of a light SM-like Higgs boson, achieved through the implementation of a beautiful but broken symmetry. Furthermore, supersymmetric theories provide a host of natural particle candidates for dark matter, including the lightest neutralino and the gravitino, which may constitute some or all of the observed cold dark matter in the universe.

The recent discovery of a new particle with properties consistent with those expected of a SM-like Higgs boson with a mass of ~ 125 GeV [1] and ongoing searches of supersymmetric particles at the LHC [2] have put some pressure on low-mass regions of the Minimal Supersymmetric Standard Model (MSSM), and especially in cases where there is a high degree of universality, such as the Constrained MSSM (CMSSM) [3]. In addition to the discovery of what appears to be a Higgs boson and null results of sparticle searches, there have been very significant improvements in the measurement of the branching ratio of $B_s \to \mu^+\mu^-$ [4], constraining models with large $\tan\beta$. In Ref. [5] we explore a variety of models related to the CMSSM in light of these developments.

Here we restrict our attention to the lowest-dimensional class of supersymmetric models in which supersymmetry breaking is gravity-mediated, known as minimal supergravity (mSUGRA) [6]. These models are defined by three parameters, specified at the universality scale, an a sign: $m_{1/2}$, the universal gaugino mass; m_0, the universal scalar mass; A_0, the universal value of the trilinear couplings; and the sign of the Higgs mixing parameter, μ. If the gaugino and scalar masses and the trilinear couplings are universal at the GUT scale, $M_{GUT} \approx 2\times 10^{16}$ GeV, there is little to speak of in terms of phenomenologically-favored parameter space, however we find that for lower universality scales, as studied for the CMSSM in [7], there are large regions of parameter space that are compatible with a ~ 125 GeV Higgs boson and at the same time account for the dark matter in the universe.

2. mSUGRA

Minimal supergravity (mSUGRA) models possess a flat Kähler potential that leads to minimal kinetic terms in the supergravity Lagrangian[1] [9]. There are several relevant phenomenological consequences of choosing such a minimal Kähler potential for the following discussion: First, scalar masses are universal with $m_0 = m_{3/2}$, where $m_{3/2}$ is the gravitino mass. As a result of this relation, we see that for small enough $m_{3/2}$ the gravitino would be the lightest supersymmetric particle (LSP), and therefore the dark matter candidate. Second, a flat Kähler potential leads to universality of the trilinear couplings. It also implies to a relationship between bilinear (B_0) and trilinear couplings of $B_0 = A_0 - m_0$. It is therefore possible to calculate the ratio of the Higgs vacuum expectation values, $\tan\beta$, from the electroweak vacuum conditions (though the sign of the Higgs mixing parameter, μ, is not determined). And finally, choosing a minimal gauge kinetic function will yield gaugino mass universality. Here we focus on models with $A_0 = (3-\sqrt{3})m_0$, as in the original Polonyi model [10], and refer the reader to [5] for discussion of other values of A_0/m_0.

[1] More general forms of the Kähler potential lead to the CMSSM [3, 8]

In Fig. 1, we show the $(m_{1/2}, m_0)$ plane for an mSUGRA model with universality (or "input") scale $M_{in} = M_{GUT}$. At very small $m_{1/2}$, the region to the left of the green contour is excluded by the branching ratio of $b \to s\gamma$ [11], and left of the black dot-dashed contour is excluded by the LEP chargino mass bound [12].Yellow contours represent constant $\tan\beta$ as specified by the values listed. We see that $\tan\beta$ is moderate over this plane. Red dashed contours indicate the mass of the SM-like Higgs boson of 114, 119, 122.5, 124, 125 GeV, from the lower left outward (the final contour just visible at the top right of the plane). Below the solid brown contour, the mass of the gravitino, $m_{\tilde{G}}$ is less than that of the lightest neutralino, $m_{\tilde{\chi}^0_1}$. Below the brown dotted contour, the lighter stau, $\tilde{\tau}_1$ appears in the hierarchy $m_{\tilde{G}} < m_{\tilde{\tau}_1} < m_{\tilde{\chi}^0_1}$. Finally, turquoise shaded regions have a relic density of $\tilde{\chi}^0_1$ or $\tilde{G}$ compatible with the value measured by WMAP [13]. We note that the relic density of $\tilde{G}$ is calculated assuming only thermal production, i.e. from the decay of the next-to-LSP. With the exception of a very thin strip stretching from $\sim (2100, 1200)$ GeV to $(3400, 2600)$ GeV, the relic abundance of neutralino dark matter is too large. Furthermore, the mass of the SM-like Higgs boson is typically well below 125 GeV, even where gravitino dark matter might be a possibility.

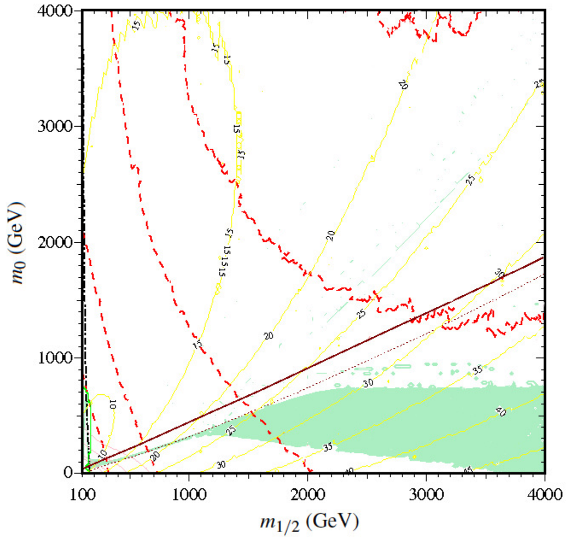
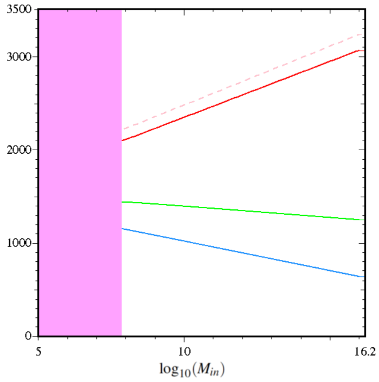


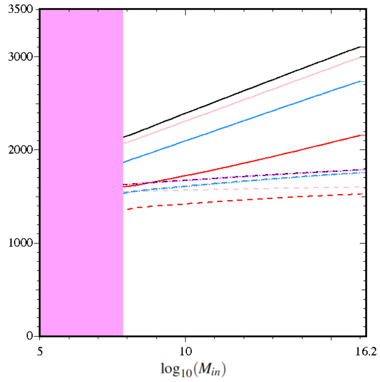
Figure 1: Polonyi-type model with GUT-scale universality. Contours are described in the text.

3. Sub-GUT Universality

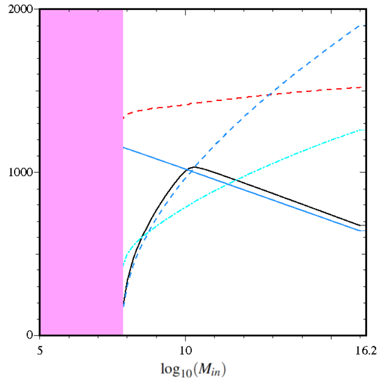
While the choice of $M_{in} = M_{GUT}$ is standard, it may not be the best description of the universe with which we are faced [7]. If supersymmetry breaking appears below the GUT scale, i.e. $M_{in} < M_{GUT}$, the spectrum of sparticles will be more compressed than that expected for $M_{in} = M_{GUT}$. This is demonstrated in Fig. 2, where, from left to right, we show the gaugino masses, scalar masses, and assorted masses/parameters as functions of M_{in}. In each panel, the pink shaded region indicates that electroweak symmetry breaking (EWSB) is not obtained. Increasingly compressed spectra at lower M_{in} are evident in panels (a) and (b). In panel (c), one can see that μ decreases at low M_{in} and eventually becomes less than the bino mass parameter, M_1, at which point the neutralino LSP becomes higgsino-like. The pseudoscalar Higgs mass, m_A, also decreases with M_{in}. Here there are two values of M_{in} for which $2m_{\tilde{\chi}^0_1} = m_A$, where efficient annihilation through s-channel A exchange decreases the relic abundance of neutralinos. This scenario is known as a rapid annihilation funnel. At low M_{in}, due to both the possibility of pole annihilations and the higgsino-like character of the LSP (and therefore multiple significant coannihilation channels), a lower relic abundance of neutralinos, relative to $M_{in} = M_{GUT}$, is typical.



(a) Gauginos



(b) Scalars



(c) Assorted

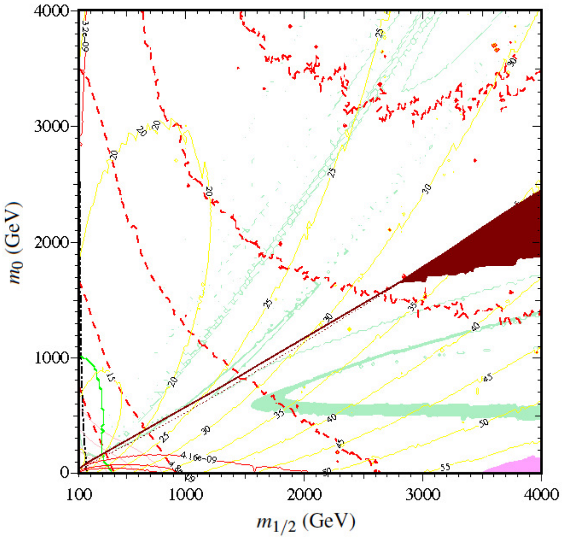
Figure 2: Sparticle masses in GeV as functions of M_{in} for (1500 GeV, 1500 GeV). (a) Gaugino masses: M_1 (blue), M_2 (green), M_3 (red), $m_{\tilde{g}}$ (pink dashed). (b) Scalar masses: $m_{\tilde{t}_{1,2}}$ (red, blue), $m_{\tilde{q}_{L,R}}$ (black, pink), $m_{\tilde{e}_{L,R}}$ (black, pink dashed), $m_{\tilde{\nu}_{e,\tau}}$ (red, blue dotted), $m_{\tilde{\tau}_{1,2}}$ (red, blue dashed). (c) Assorted: $m_{\tilde{\chi}_1^0}$ (black), M_1 (blue), μ (blue dashed), $m_A/2$ (cyan dot-dashed), $m_{\tilde{\tau}_1}$ (red dashed).

4. Results

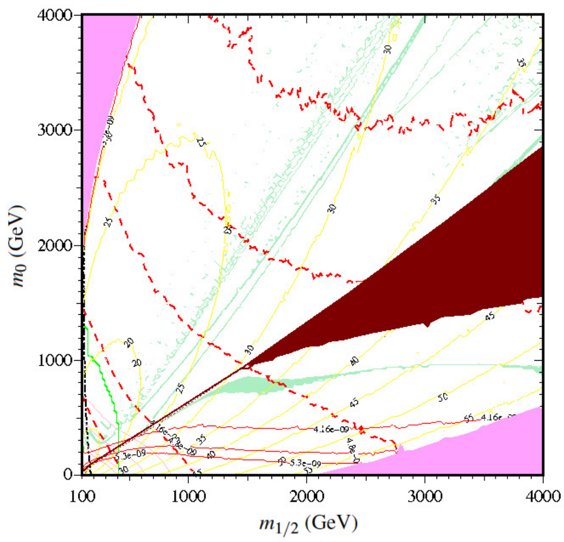
In Figs. 3 and 4 we present the $(m_{1/2}, m_0)$ planes for mSUGRA with $A_0 = (3-\sqrt{3})m_0$ and $M_{in} < M_{GUT}$. In Fig. 3a we see one clear funnel rising above the solid brown contour at $m_{1/2} \approx 1200$ GeV. Inside this funnel, $\Omega_{\tilde{\chi}_1^0} < \Omega_{CDM}$. Additional diagonal turquoise regions indicate neutralino and/or chargino annihilations/coannihilations at a pole. As the LSP becomes higgsino-like at lower M_{in} more poles are possible, and therefore more rapid annihilation funnel-type structures. This is evident in Fig. 3b where the funnels move up into the plane. We also see that in the upper right and lower left corners, EWSB is not obtained. Furthermore, $m_{\tilde{\tau}_1}$ decreases with M_{in}, so there is now a brown shaded region where the lighter stau is the LSP. Below this excluded region, the gravitino is the LSP. In Fig. 3c, a cosmologically-favored focus point strip appears in the upper left corner, as does a $\tilde{\tau}_1$-$\tilde{\chi}_1^0$ coannihilation strip above the $\tilde{\tau}_1$-LSP region. For lower $M_{in} = 10^{10.5}$ GeV, the focus point moves to merge with the upper funnel wall creating an hourglass shape, while a "V" remains of the lower funnel wall and the coannihilation strip.

Also appearing in Fig. 3 are contours of the branching ratio of $B_s \to \mu^+\mu^-$. The contours, from top to bottom, are 4.16, 4.8, and 5.3×10^{-9}, which creep into the plane as M_{in} is decreased. Finally, comparison with Fig. 1 reveals that as M_{in} decreases, the Higgs mass contours move to slightly lower $m_{1/2}$ and m_0. More importantly, though, regions compatible with the measured abundance of dark matter are now possible for a large range of $m_{1/2}$ and m_0.

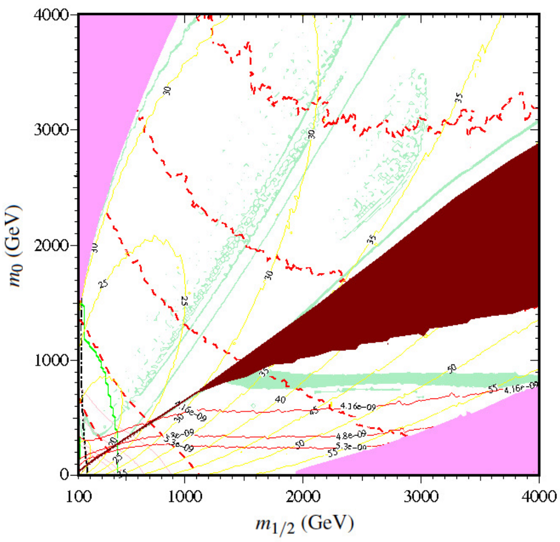
Fig. 4 tells the rest of the story. In Fig. 4a, the hourglass separates into an oval and a large-m_0 V. And the lower funnel wall merges with the coannihilation strip to become a fat wishbone. By $M_{in} = 10^9$ GeV, the neutralino LSP is higgsino-like over most of the plane, and the relic abundance of neutralinos has fallen below the cosmologically-viable range, allowing for the possibility of a secondary source of cold dark matter. The large C-shaped turquoise region shows that much of the plane has $\Omega_{\tilde{\chi}_1^0} \approx \Omega_{CDM}$, especially where the Higgs mass is 124-125 GeV. It is only to the right



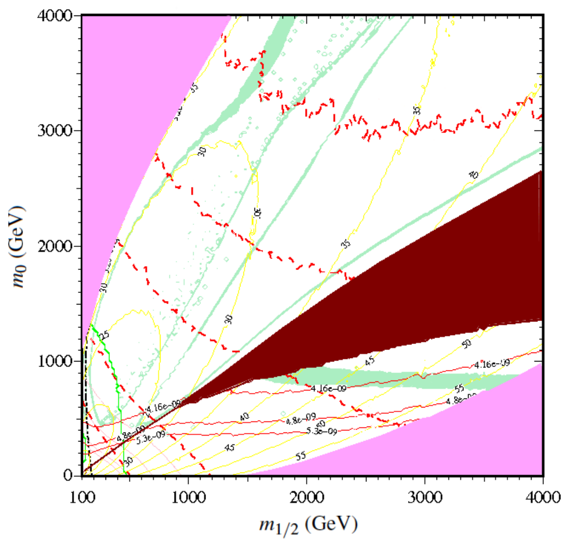
(a) $M_{in} = 10^{13}$ GeV



(b) $M_{in} = 10^{11.5}$ GeV



(c) $M_{in} = 10^{11}$ GeV



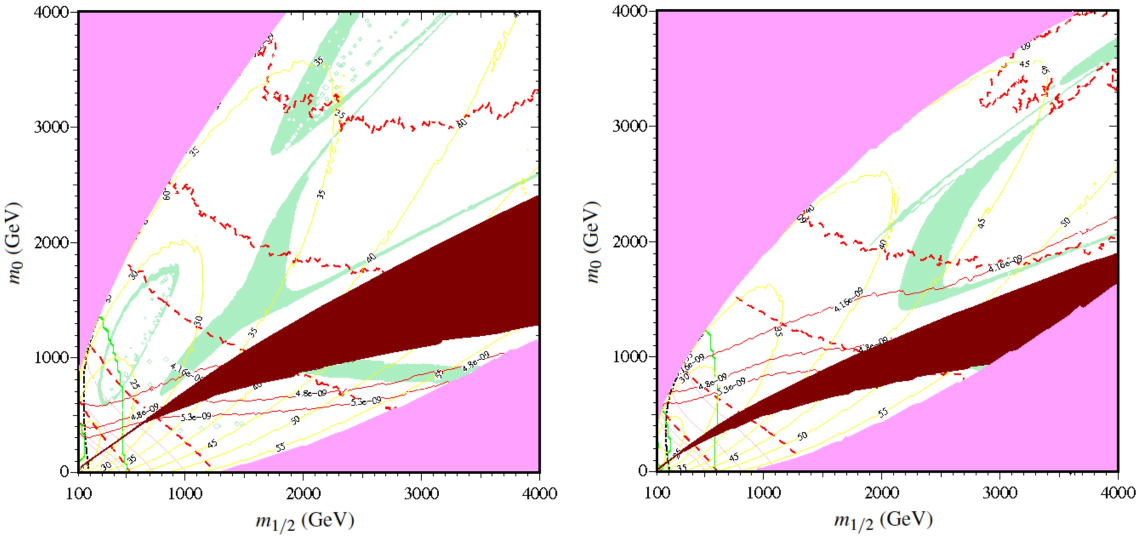
(d) $M_{in} = 10^{10.5}$ GeV

Figure 3: Polonyi-type models with sub-GUT universality. Contours are described in the text.

side of the turquoise C that the relic abundance of neutralinos is too large.

5. Summary

We have presented sub-GUT mSUGRA models with $A_0 = (3-\sqrt{3})m_0$ in which the abundance of neutralino LSPs is consistent with the measured abundance of dark matter while at the same time a SM-like Higgs boson with mass $m_h \approx 125$ GeV is predicted. These, as do other cases discussed in [5], illustrate that even within the most minimal supersymmetric frameworks, consistency with



(a) $M_{in} = 10^{10}$ GeV (b) $M_{in} = 10^{9}$ GeV

Figure 4: Polonyi-type models with sub-GUT universality. Contours are described in the text.

all current phenomenological constraints is not only possible, but appears to be, in a sense, natural, with sub-GUT universality.

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