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Natural dark matter in SUSY GUTs with non-universal gaugino masses

Stephen F. King

School of Physics and Astronomy, University of Southampton,
Highfield, Southampton, SO17 1BJ, U.K.
E-mail: sfk@hep.phys.soton.ac.uk

Jonathan P. Roberts

Institute of Theoretical Physics, Warsaw University,
00-681 Warsaw, Poland
E-mail: roberts@fuw.edu.pl

Durga Prasad Roy

Homi Bhabha Centre for Science Education, Tata Institute of Fundamental Research,
Mumbai 400088, India, and
Instituto de Fisica Corpuscular, CSIC-U.de Valencia, Correos,
E-46071 Valencia, Spain
E-mail: dproy1@gmail.com

Abstract: We consider neutralino dark matter within the framework of SUSY GUTs with non-universal gaugino masses. In particular we focus on the case of SU(5) with a SUSY breaking F-term in the 1, 24, 75 and 200 dimensional representations. We discuss the 24 case in some detail, and show that the bulk dark matter region cannot be accessed. We then go on to consider the admixture of the singlet SUSY breaking F-term with one of the 24, 75 or 200 dimensional F-terms, and show that in these cases it becomes possible to access the bulk regions corresponding to low fine-tuned dark matter. Our results are presented in the (M_1, M_2) plane for fixed M_3 and so are useful for considering general GUT models, as well as more general non-universal gaugino models.

Keywords: Cosmology of Theories beyond the SM, Supersymmetry Phenomenology.

JHEP10(2007)106

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Contents

1. Introduction

Supersymmetry (SUSY) at the TeV scale remains an attractive possibility for new physics beyond the Standard Model. SUSY helps in the unification of couplings in Grand Unified Theories (GUTs), and provides a resolution of some aspects of the hierarchy problem. In addition the lightest SUSY particle (LSP) may be a neutralino consisting of a linear combination of Bino, Wino and neutral Higgsinos, providing a consistent WIMP dark matter candidate [1]. For example the minimal supersymmetric standard model (MSSM) with conserved R-parity provides such an LSP with a mass of order the electroweak scale. Although general arguments suggest that such a particle should provide a good dark matter candidate [2], the successful regions of parameter space allowed by WMAP and collider constraints are now tightly restricted [3]–[30].

Such a restricted parameter space has lead to recent claims that supersymmetry must be fine-tuned to fit the observed dark matter relic density [31]. This is a serious concern for supersymmetry, especially as much of the motivation for supersymmetry arises from fine-tuning arguments in the form of its solution to the hierarchy problem. In previous work [32]–[34] we quantitatively studied the fine-tuning cost of the primary dark matter regions within the MSSM. It was found that the majority of dark matter regions did indeed require some degree of fine-tuning, and that this fine-tuning could be directly related to

JHEP10(2007)106

the mechanism responsible for the annihilation of SUSY matter in the early universe that defined each region. The one region that exhibited no fine-tuning at all was the 'bulk region' in which the dominant annihilation mechanism is via t-channel slepton exchange. This region can be accessed in models in which the gauginos have non-universal soft masses at the GUT scale [4]–[20].

These results motivate a more careful study of models that give rise to non-universal gaugino masses. In our previous work such a region was accessed by allowing all the gaugino masses to vary independently. Such an approach is very unconstrained. We would expect the gaugino masses to arise from a deeper theory such as string constructions, as studied in [5, 33, 34] or in GUT models [35]–[38]. Both approaches generally impose specific relations between the gaugino masses at the GUT scale. In this paper we shall discuss non-universal gaugino masses in a more general way than previously, allowing for different relative signs of gaugino masses, focusing on SU(5) GUTs as an example, although it is clear that similar effects can be achieved in other GUTs such as SO(10) or Pati-Salam. We shall show how the bulk region may be readily accessed in such models providing that the SUSY breaking sector arises from a combination of an SU(5) singlet 1, together with an admixture of one of the 24, 75 or 200 representations of SU(5). We will also show that in all cases the fine-tuning required to access such a region remains small.

The rest of the paper is set out as follows. First we review our methodology in section 2. In section 3 we review the structure of gaugino non-universality in $SU(5)$. In section 4 we consider the specific case where all of the gaugino masses arise from a 24 of SU(5). In section 5 we generalise this to the case where the masses arise from an admixture of the singlet representation and one of the 24, 75 or 200. In section 6 we present our conclusions.

2. Methodology

2.1 Codes

The GUT structure of the theory is a structure that is imposed on the soft SUSY breaking masses at the GUT scale, $m_{\mathrm{GUT}} \approx 2 \times 10^{16}$ GeV. To study the low energy phenomenology of such a model we need to run the mass spectrum down to the electroweak scale. To do this we use the RGE code `SoftSusy` [39]. This interfaces with the MSSM package within `micrOMEGAs` [40]. We use this to calculate the dark matter relic density $\Omega_{\mathrm{CDM}} h^2$, as well as $BR(b \to s\gamma)$ and δa_μ.

2.2 Experimental bounds

Not all choices of parameters are equal. After running the mass spectrum of the model point from the GUT scale to the electroweak scale we perform a number of checks. A point is ruled out if it:

1. doesn't provide radiative electroweak symmetry breaking (REWSB).

JHEP10(2007)106

2. violates mass bounds on particles from the Tevatron and LEP2.[1]

3. results in a lightest supersymmetric particle (LSP) that is not the lightest neutralino.

In the remaining parameter space we plot regions that fit $BR(b \to s\gamma)$ and δa_μ at 1σ and 2σ.

2.2.1 δa_μ

Present measurements of the value of the anomalous magnetic moment of the muon a_μ deviate from the theoretical calculation of the SM value.[2] Taking the current experimental world average, and state of the art Standard Model value from [42] there is a discrepancy:

$$(a_\mu)_{\text{exp}} - (a_\mu)_{\text{SM}} = \delta a_\mu = (2.95 \pm 0.88) \times 10^{-9} \tag{2.1}$$

which amounts to a 3.4σ deviation from the Standard Model value.

We use micromegas to calculate the SUSY contribution to $(g-2)_\mu$. The dominant theoretical errors in this calculation are in the Standard Model contribution therefore we do not include the theoretical error in the calculation of the SUSY contribution in our results.

2.2.2 $BR(b \to s\gamma)$

The variation of $BR(b \to s\gamma)$ from the value predicted by the Standard Model is highly sensitive to SUSY contributions arising from charged Higgs-top loops and chargino-stop loops. To date no deviation from the Standard Model has been detected. We take the current world average from [43] of the BELLE [44], CLEO [45] and BaBar [46] experiments:

$$BR(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4} \tag{2.2}$$

We use micromegas to calculate both the SM value of $BR(b \to s\gamma)$ and the SUSY contributions. It is hard to estimate the theoretical uncertainty in the calculation of the SUSY contributions, but note that there is an uncertainty of 10% in the NLO SM prediction of $BR(b \to s\gamma)$[3] [48]. As with δa_μ we plot the 1σ and 2σ experimental limits and do not include a theoretical error in the calculation.

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[1] The current LEP2 bound on the lightest MSSM Higgs stands at 114.4 GeV. However there is a theoretical uncertainty of $3-5$ GeV in the determination of the mass of the light Higgs [41]. Therefore we take a hard cut at $m_h = 111$ GeV in our plots.

[2] There is a long running debate as to whether the calculation of the hadronic vacuum polarisation in the Standard Model should be done with the e^+e^- data, or the τ. The weight of evidence indicates the e^+e^- data is more reliable and we use this in our work.

[3] Micromegas calculates the SM contribution to $BR(b \to s\gamma)$ to NLO. A first estimate of the SM prediction of $BR(b \to s\gamma)$ to NNLO was presented in [47]. This showed a drop of around 0.4×10^{-4} in the central value of the SM prediction. The implementation of the NNLO contributions in the calculation is non-trivial and its implementation in micromegas is currently underway. As a result we do not account for this drop in the results we present but instead note that *positive* SUSY contributions to $BR(b \to s\gamma)$ look likely to be favoured in future. This will favour a negative sign of μ and thus cause tension with $(g-2)_\mu$.

JHEP10(2007)106

2.2.3 $\Omega_{\rm CDM}h^2$

Evidence from the CMB and rotation curves of galaxies both point to a large amount of cold non-baryonic dark matter in the universe. The present measurements [49] place the dark matter density at:

$$\Omega_{\rm CDM}h^2 = 0.106 \pm 0.008 \tag{2.3}$$

For any point that lies within the 2σ allowed region we calculate the fine-tuning and plot the resulting colour-coded point. We perform the calculation of the dark matter relic density using micromegas using the *fast* approximation. Given a low energy mass spectrum, this gives an estimated precision of 1% in the theoretical prediction of the relic density. The 2σ band plotted only takes into account the experimental error.[4]

2.3 Fine-tuning

As in [32] we follow Ellis and Olive [52] in quantifying the fine-tuning price of fitting dark matter with the measure:

$$\Delta_a^\Omega = \left| \frac{\partial \ln\left(\Omega_{\rm CDM}h^2\right)}{\partial \ln(a)} \right| \tag{2.4}$$

where the parameters a are the input parameters of the model. In this case we take them to be the soft masses and $\tan\beta$. We take the total fine-tuning of a point to be equal to the largest individual tuning, $\Delta = \max(\Delta_a)$.

3. Gaugino non-universality in SU(5)

In the non-universal SU(5) model [10], in addition to the singlet F-term SUSY breaking, the gauge kinetic function can also depend on a non-singlet chiral superfield Φ, whose auxiliary F-component acquires a large vacuum expectation value (vev). In general the gaugino masses come from the following dimension five term in the Lagrangian:

$$L = \frac{< F_\Phi >_{ij}}{M_{\rm Planck}} \lambda_i \lambda_j \tag{3.1}$$

where $\lambda_{1,2,3}$ are the U(1), SU(2) and SU(3) gaugino fields i.e. the bino $\tilde{B}$, the wino $\tilde{W}$ and the gluino $\tilde{g}$ respectively. Since the gauginos belong to the adjoint representation of SU(5), Φ and F_Φ can belong to any of the irreducible representations appearing in their symmetric product, i.e.

$$(24 \times 24)_{\rm symm} = 1 + 24 + 75 + 200 \tag{3.2}$$

The minimal supergravity (mSUGRA) model assumes Φ to be a singlet, which implies equal gaugino masses at the GUT scale. On the other hand if Φ belongs to one of the

[4]Note that the quoted 1% accuracy is for a given low energy spectrum. The low energy spectrum is obtained via `softsusy` and there can be some small variation in the details of the mass spectrum between codes [50] for given high energy inputs. Different dark matter regions have different levels of sensitivity to these variations. For a detailed study see [51]. The result of the discrepancies between codes is to move the dark matter regions slightly in the GUT scale parameter space. As we are interested in the features of these regions, rather than their precise location, our results are reasonably insensitive to these uncertainties.

JHEP10(2007)106

n	M_3	M_2	M_1
1	1	1	1
24	1	$-3/2$	$-1/2$
75	1	3	-5
200	1	2	10

Table 1: Relative values of the SU(3), SU(2) and U(1) gaugino masses at GUT scale for different representations n of the chiral superfield Φ.

non-singlet representations of SU(5), then these gaugino masses are unequal but related to one another via the representation invariants. Thus the three gaugino masses at the GUT scale in a given representation n are determined in terms of a single SUSY breaking mass parameter $m_{1/2}$ by

$$M_{1,2,3} = C^n_{1,2,3} m_{1/2} \tag{3.3}$$

where $C^1_{1,2,3} = (1, 1, 1)$, $C^{24}_{1,2,3} = (-1, -3, 2)$, $C^{75}_{1,2,3} = (-5, 3, 1)$ and $C^{200}_{1,2,3} = (10, 2, 1)$. The resulting ratios of M_i's for each n are listed in table 1. Of course in general the gauge kinetic function can involve several chiral superfields belonging to different representations of SU(5) which gives us the freedom to vary mass ratios continuously. In this, more general, case we can parameterise the GUT scale gaugino masses as:

$$M_{1,2,3} = C^n_{1,2,3} m^n_{1/2} \tag{3.4}$$

where $m^n_{1/2}$ is the soft gaugino mass arising from the F-term vev in the representation n.

These non-universal gaugino mass models are known to be consistent with the observed universality of the gauge couplings at the GUT scale [35]–[38, 53]

$$\alpha_3 = \alpha_2 = \alpha_1 = \alpha (\simeq 1/25) \tag{3.5}$$

Since the gaugino masses evolve like the gauge couplings at one loop level of the renormalisation group equations (RGE), the three gaugino masses at the electroweak scale are proportional to the corresponding gauge couplings, i.e.

$$\begin{aligned} M_1^{\mathrm{EW}} &= (\alpha_1/\alpha_G) M_1 \simeq (25/60) C^n_1 m^n_{1/2} \\ M_2^{\mathrm{EW}} &= (\alpha_2/\alpha_G) M_2 \simeq (25/30) C^n_2 m^n_{1/2} \\ M_3^{\mathrm{EW}} &= (\alpha_3/\alpha_G) M_3 \simeq (25/9) C^n_3 m^n_{1/2} \end{aligned} \tag{3.6}$$

For simplicity we shall assume a universal SUSY breaking scalar mass m_0 at the GUT scale. Then the corresponding scalar masses at the EW scale are given by the renormalisation group evolution formulae [54].

4. The 24 model

We have previously seen [32] that a ratio $M_1 : M_2 : M_3 = 0.5 : 1 : 1$ allows us to access the bulk region without violating LEP bounds. The bulk region in the CMSSM is usually

JHEP10(2007)106

ruled out because of a light Higgs. By allowing M_3 to be large we can avoid a light Higgs while allowing M_1 to be light enough to give a light bino neutralino and light sleptons. This enhances neutralino decay via light t-channel slepton exchange and gives access to the bulk region.

From table 1 we observe that only the 24 model predicts a mass ratio $M_1 < M_3$. Therefore we shall explore the 24 model first. For the 24 model we have the input parameters:

$$a \in \left\{ m_0,\ m_{1/2}^{24},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu) \right\}.$$

where the masses are all set as in the CMSSM except for the gaugino masses which have the form:

$$\begin{aligned} M_1 &= -0.5\ m_{1/2}^{24} \\ M_2 &= -1.5\ m_{1/2}^{24} \\ M_3 &= m_{1/2}^{24} \end{aligned}$$

With this gaugino mass structure, the bino mass in the 24 for a given $m_{1/2}$ is half of the bino mass in the CMSSM for the same $m_{1/2}$. The bino mass also affects the running of the slepton masses such that lower M_1 corresponds to a lower slepton mass. Therefore the 24 will have lower mass sleptons than the CMSSM for a given value of m_0 and $m_{1/2}$. Light sleptons enhance the annihilation of neutralinos via t-channel slepton exchange (giving rise to a WMAP region known as the bulk region). Therefore we expect the bulk region to appear at larger $m_{1/2}$ than in the CMSSM and thus circumvent the Higgs mass bound.

To study this effect, we look at the $(m_0,\ m_{1/2})$ plane with $\tan\beta = 10,\ A_0 = 0$[5] in both the CMSSM and the 24 in figure 1. The CMSSM is shown in the top-left panel, the 24 with μ positive in the top-right panel and the 24 with μ negative is shown in the bottom-left panel.

In the CMSSM scan we can see that low m_0 is ruled out as the stau becomes lighter than the neutralino. Low $m_{1/2}$ is ruled out as $m_h < 111$GeV. The contours of 1 and 2σ for δa_μ (green short and long dashed lines respectively) are plotted in the remaining parameter space, showing that the current measurement of δa_μ favours low m_0 and $m_{1/2}$. Finally the region that satisfies WMAP is plotted as a multicoloured strip that runs alongside the light green region ruled out by a stau LSP. This WMAP strip is mostly red. This colour coding refers to a log measure of the fine-tuning and can be read off via the log-scale on the right hand side. The tuning of the $\tilde{\tau}$ coannihilation strip agrees with our previous findings.

In the second and third panels of figure 1 we once again display the $(m_0,\ m_{1/2})$ plane but this time using the 24 model's soft gaugino masses with μ positive and negative respectively. In both cases, low m_0 is ruled out by a stau LSP and low $m_{1/2}$ is ruled out by a light Higgs.

The δa_μ and $BR(b \to s\gamma)$ values are significantly different in the 24 model than in the CMSSM. Firstly neither 24 plot has a region that agrees with the current measured value

[5] We consider $\tan\beta = 10$ exclusively throughout. This is because we are primarily interested in reproducing the bulk region considered in [32] in a specific GUT model. Varying $\tan\beta$ doesn't significantly alter the phenomenology of the bulk region.

JHEP10(2007)106

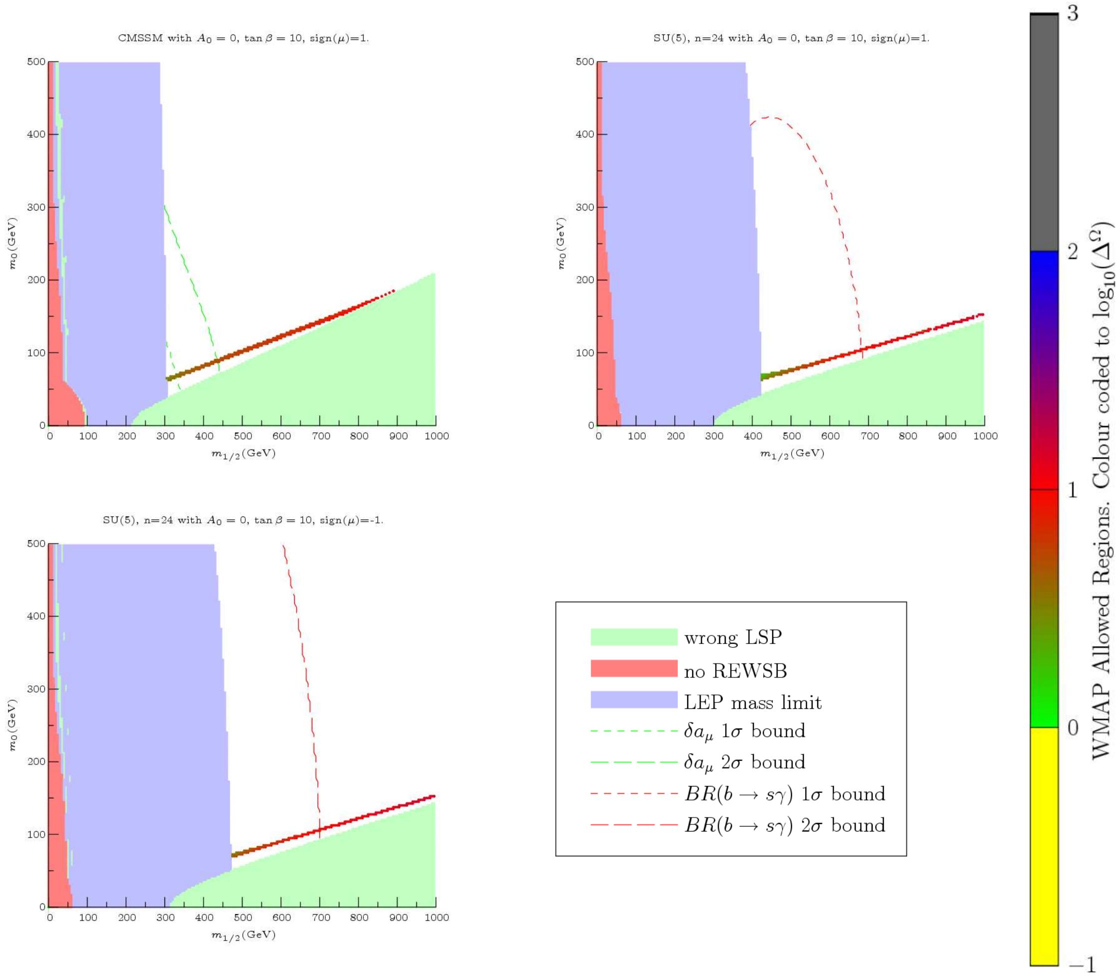

Figure 1: The parameter space for the CMSSM (top-left), the 24 model with sign(μ) +ve (top-right) and with sign(μ) −ve (bottom). Low m_0 is ruled out as the $\tilde{\tau}$ becomes the LSP(light green). Low $m_{1/2}$ is ruled out as $m_h < 111$GeV. In the remaining parameter space, the only strip of allowed dark matter is a $\tilde{\tau} - \tilde{\chi}_1^0$ coannihilation strip which shows comparable degrees of tuning in all plots.

of δa_μ (they both give $\delta a_\mu \pm \mathcal{O}(10^{-10})$). Secondly $BR(b \to s\gamma)$ becomes an important constraint. For μ +ve, the model agrees with the measured value of $BR(b \to s\gamma)$ at 1σ for large $m_{1/2}(> 700\,\text{GeV})$ and agrees at 2σ for low $m_{1/2}$. With μ −ve, only the parameter space at $m_0 > 700\,\text{GeV}$ fits $BR(b \to s\gamma)$ at 2σ. Lower m_0 exceeds this limit.

Now consider the change in the dark matter strip. We expected to be able to access the bulk region in this model as we would have a lighter bino neutralino and lighter sleptons in the 24 model than in the CMSSM. This should move the bulk region to larger values of $m_{1/2}$ and out from under the region ruled out by the LEP2 bound on the lightest Higgs boson.

Contrary to our naive expectations, though the bulk region has moved to larger $m_{1/2}$ in the 24 model, it remains ruled out. This is because the gaugino mass relations in the 24 also result in a lighter Higgs mass than the CMSSM, for the same m_0, $m_{1/2}$. The only

JHEP10(2007)106

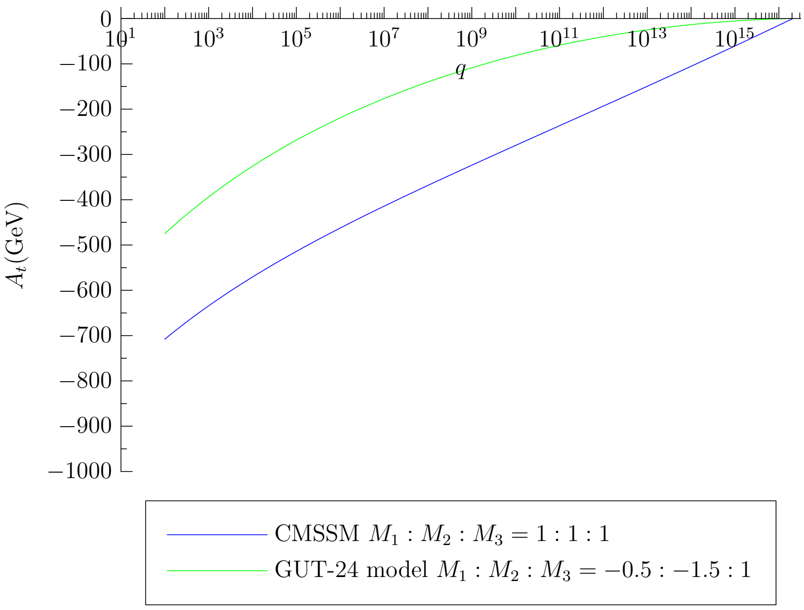

Figure 2: Here we show the running of A_t from the GUT scale value of $A_t = 0$ to the weak scale for the point $m_0 = 100\text{GeV}$, $m_{1/2} = 350\text{GeV}$, $\tan\beta = 10$, $A_0 = 0$. The running for the CMSSM is shown in blue, the running for the 24 model is shown in red.

difference between the CMSSM and the 24 model is the magnitude and sign of the M_1 and M_2 gaugino masses. Therefore the Higgs mass must be sensitive either to the sign difference between $M_{1,2}$ and M_3 or the larger value of M_2.

First consider the effect of the relative sign between $M_{1,2}$ and M_3. In most RGEs the gaugino masses appear squared, however the trilinear RGEs have the form:

$$\frac{dA_t}{dt} = \frac{1}{8\pi^2}\left[6|Y_t|^2 A_t + |Y_b|^2 A_b + \left(\frac{16}{3}g_3^2 M_3 + 3g_2^2 M_2 + \frac{13}{15}g_1^2 M_1\right)\right] \tag{4.1}$$

If all M_i are positive, then the gauginos provide a large positive contribution to the RGE and so help to push the trilinear negative through the running. This in turn affects the running of the Higgs mass. In the 24 case, the sign of $M_{1,2}$ are opposite to that of M_3 and so they reduce the contribution from the Gauginos and thus reduce the magnitude of the running, resulting in a small absolute value of the trilinear coupling at the electroweak scale. Now we note that the contribution of $M_{1,2}$ are suppressed relative to that of M_3 by a factor of g_i^2, but this is partially compensated by the fact that $|M_2| > |M_3|$ at the GUT scale. Therefore both the sign and magnitude of $M_2(\text{GUT})$ are responsible for a substantial change in the running of the trilinears. This is shown in figure 2.

The change in the trilinear affects the running of $m_{H_u}^2$ via the RGE:

$$\begin{aligned}\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\Big[&3\,|Y_t|^2\left(m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + |A_t|^2\right)\\ &-\left(3g_2^2\,|M_2|^2 + \frac{3}{5}g_1^2\,|M_1|^2\right)\Big]\end{aligned} \tag{4.2}$$

JHEP10(2007)106

Mass	A $(1+24)$	B $(1+75)$	C $(1+200)$
M_1	$m^1_{1/2} - 0.5\ m^{24}_{1/2}$	$m^1_{1/2} - 5\ m^{75}_{1/2}$	$m^1_{1/2} + 10\ m^{200}_{1/2}$
M_2	$m^1_{1/2} - 1.5\ m^{24}_{1/2}$	$m^1_{1/2} + 3\ m^{75}_{1/2}$	$m^1_{1/2} + 2\ m^{200}_{1/2}$
M_3	$m^1_{1/2} + m^{24}_{1/2}$	$m^1_{1/2} + m^{75}_{1/2}$	$m^1_{1/2} + m^{200}_{1/2}$

Table 2: The gaugino mass relations for the different $(1+n)$ SUSY breaking scenarios.

A smaller top trilinear results in a smaller running of the Higgs mass and a lighter Higgs. Therefore, as the 24 model results in a smaller value of A_t at all energies below the GUT scale, it gives a smaller mass for the lightest Higgs than for the same model point in the CMSSM. This means that the LEP mass bounds for the lightest Higgs are more restrictive in the 24 model than in the CMSSM. Unfortunately, this results in the LEP Higgs bound ruling out the bulk region for all interesting regions of parameter space of the 24 model.

5. Two SU(5) sectors

We have seen that neither the CMSSM, corresponding to a singlet SUSY breaking sector, nor the 24 model is capable of accessing the bulk region of neutralino parameter space. Equally, as the 75 and 200 models have $|M_1| > |M_3|$, these sectors are even worse. In this section we therefore consider the next simplest possibility, namely that of two different SUSY breaking SU(5) representations acting together. Indeed, once one has accepted the existence of a single 24, 75 or 200 dimensional SUSY breaking sector, it seems perfectly natural to allow the standard singlet SUSY breaking sector at the same time. In practice it may be difficult to avoid this scenario.

Therefore we shall focus on the three simplest scenarios. We take the cases of a SUSY breaking sector consisting of:

A $(1+24)$
B $(1+75)$
C $(1+200)$

If we were to extend our model to allow three or four SU(5) representations contributing to SUSY breaking at once, we would be able to produce any pattern of non-universal gaugino masses. By constraining our model to two sectors we provide restrictions on the choice of gaugino masses which makes access to the bulk region non-trivial, and provides insight into what ingredients are required to achieve it.

Within these models, we have different gaugino mass relations, shown in table. 2. By varying the soft gaugino masses $m^{1,n}_{1/2}$, we describe three planes in the $M_{1,2,3}$ parameter space.

Our aim is to access the bulk region. In [32] we found that the bulk region can be accessed in a model with non-universal gaugino masses for $m_0 = 50 - 80\,\text{GeV}$. Therefore we fix $m_0 = 70\,\text{GeV}$, $A_0 = 0$ and $\tan\beta = 10$. In figures 3(a)-(d) we plot the $(M_1,\ M_2)$

JHEP10(2007)106

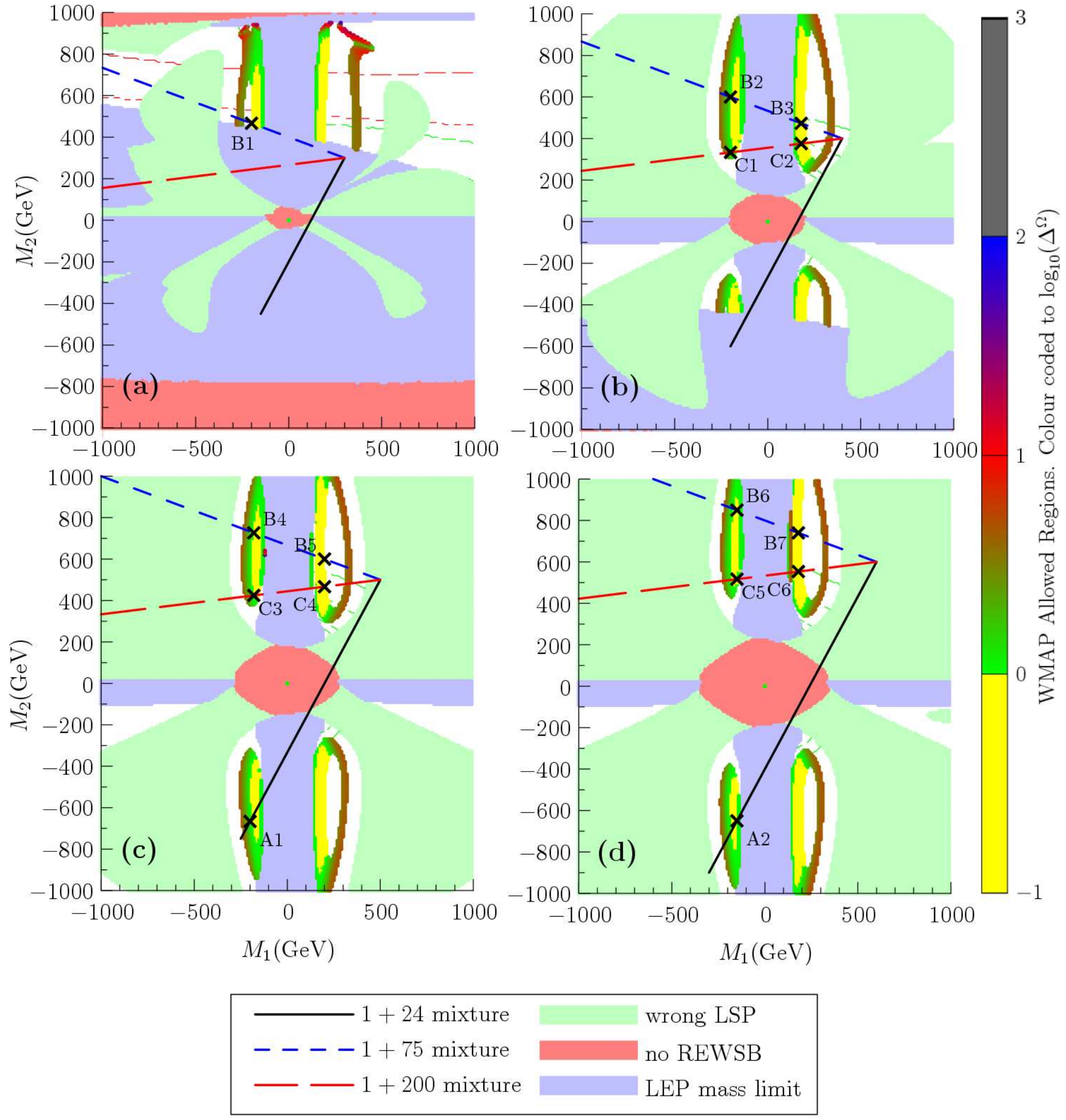

Figure 3: The $(M_1,\ M_2)$ plane with non-universal gaugino masses defined at the GUT scale. We take $m_0 = 70\,\mathrm{GeV}$, $A_0 = 0$ and $\tan\beta = 10$ throughout vary M_3: (a) $M_3 = 300\,\mathrm{GeV}$, (b) $M_3 = 400\,\mathrm{GeV}$, (c) $M_3 = 500\,\mathrm{GeV}$, (d) $M_3 = 600\,\mathrm{GeV}$. For fixed M_3, the allowed parameter space for each GUT mixture is plotted as a line the $(M_1,\ M_2)$ parameter space. The WMAP allowed regions correspond to the elliptical regions in each quadrant, and are partially obscured by disallowed regions in panels (a) and (b). The $BR(b \to s\gamma)$ and δa_μ regions are displayed as in figure 1 and discussed in the text.

plane for increasing values of M_3, from $300 - 600\,\mathrm{GeV}$. As M_1 and M_2 can in general be either positive or negative in $(1+n)$ scenarios, we allow M_1 and M_2 to take positive and negative values. For a given M_3, the gaugino mass relation of table 2 constrain each of the $(1+n)$ scenarios to a line in the $(M_1,\ M_2)$ plane. We plot these lines for each case.

As each model has the singlet representation as a limit when $m^n_{1/2} \to 0$, all the lines

JHEP10(2007)106

Parameter	A1		A2	
	value	Δ^Ω	value	Δ^Ω
m_0	70	1.43	70	0.96
$m^1_{1/2}$	33.3	0.026	100	0.39
$m^{24}_{1/2}$	466.7	0.075	500	1.02
A_0	0	0	0	0
$\tan\beta$	10	0.37	10	0.21
Max		1.43		0.96
M_1	-200	0.19	-150	0.59
M_2	-666.7	0.21	-650	0.38
M_3	500	0.075	600	0.0088

Table 3: The fine-tuning for points A1 and A2 that lie within the bulk region for the (1+24) model. For both points $m^{24}_{1/2} > m^1_{1/2}$, so the gaugino masses arise predominantly from the 24. In the lower section of the table we give the corresponding GUT scale M_i for each point. As the tunings plotted in figure 3 are calculated with respect to the parameter set $a \in \{m_0,\ M_1,\ M_2,\ M_3,\ A_0,\ \tan\beta\}$, we give the relevant tunings with respect to the individual M_i for comparison.

JHEP10(2007)106

converge at a point. At this point the model is precisely that of the CMSSM, and as such is ruled out for almost all M_3 by a $\tilde{\tau}$ LSP or the LEP bound on the lightest Higgs. The other end of each line corresponds to the opposite limit $m^1_{1/2} = 0,\ m^n_{1/2} = M_3$.

We also plot the $BR(b \to s\gamma)$ and δa_μ constraints. The only region that doesn't fit $BR(b \to s\gamma)$ within 2σ is panel (a) at large M_2. The values of δa_μ are insensitive to M_3. In the quadrant with M_1 and M_2 +ve we have the largest SUSY contribution to δa_μ, enabling the model to fit δa_μ at 1σ. In the quadrant with M_1 +ve, M_2 -ve, the model can fit δa_μ at 2σ. For negative M_1 we get a negative SUSY contribution, δa_μ. If we were to plot the parameter space with μ negative, δa_μ would have the opposite sign and the model would fit the observed value of δa_μ for negative M_1.

Finally, we plot the dark matter regions with colours corresponding to their fine-tuning calculated with respect to the general non-universal gaugino model with parameters: $a \in \{m_0,\ M_1,\ M_2,\ M_3,\ A_0,\ \tan\beta\}$. This allows us to easily pick out the bulk region as it is 'supernatural' with $\Delta^\Omega < 1$ and is therefore plotted in yellow. We use this to pick out the points at which each $(1+n)$ representation provides access to the bulk region. We take these points and calculate the dark matter fine-tuning with respect to the $(1+n)$ model in question.

First consider the $1+24$ model. In figures 3(a), (b) the model does not access the bulk region. This fits with our results of section 4 as low $m_{1/2}$ is ruled out by a light Higgs in the 24 scenario. In figures 3(c), (d), we can access the bulk region with a mixture that is primarily 24. We show the corresponding fine-tuning for both points in table 3. Note that for both points $m^{24}_{1/2} > m^1_{1/2}$, so the gaugino masses arise predominantly from the 24.

Next consider the $1+75$ model. This model lies along the blue short dashed line. The 75 limit is not shown. This is because in the pure 75 scenario $M_1 = -5M_3$. Therefore

Parameter	B1		B2		B3		B4	
	value	Δ^{Ω}	value	Δ^{Ω}	value	Δ^{Ω}	value	Δ^{Ω}
m_0	70	0.91	70	1.18	70	0.86	70	1.0
$m_{1/2}^{1}$	217	0.78	300	0.64	363	1.4	387	1.1
$m_{1/2}^{75}$	83.3	1.4	100	0.91	36.7	0.67	113	1.5
A_0	0	0	0	0	0	0	0	0
$\tan\beta$	10	0.13	10	0.29	10	0.14	10	0.32
Max		1.4		0.91		1.4		1.5
M_1	-200	0.66	-200	0.38	180	0.67	-180	0.51
M_2	467	0.086	600	0.032	473	0.096	727	0.075
M_3	300	0.13	400	0.071	400	0.061	500	0.047

Parameter	B5		B6		B7	
	value	Δ^{Ω}	value	Δ^{Ω}	value	Δ^{Ω}
m_0	70	0.75	70	0.95	70	0.84
$m_{1/2}^{1}$	450	1.8	475	1.7	530	2.0
$m_{1/2}^{75}$	50	0.99	125	2.4	70	1.2
A_0	0	0	0	0	0	0
$\tan\beta$	10	0.15	10	0.32	10	0.22
Max		1.8		2.4		2.0
M_1	200	0.80	-150	0.55	180	0.64
M_2	600	0.038	850	0.082	740	0.031
M_3	500	0.014	600	0.16	600	0.12

Table 4: The fine-tuning for points B1-7 that lie within the bulk region for the $(1+75)$ model. For all points $m_{1/2}^{75} < m_{1/2}^{1}$, so the gaugino masses arise predominantly from the singlet. In the lower section of the table we give the corresponding GUT scale M_i for each point. As the tunings plotted in figure 3 are calculated with respect to the parameter set $a \in \{m_0,\ M_1,\ M_2,\ M_3,\ A_0,\ \tan\beta\}$, we give the relevant tunings with respect to the individual M_i for comparison.

the 75 limit lies outside the range plotted for all M_3 that we consider. In such a limit, as studied in [8, 10], the lightest neutralino is predominantly higgsino. As discussed earlier we cannot access the bulk region in such a limit. This limit lies off the plots and we do not consider it further here.

In the 75, M_1 is negative. This results in two scenarios in which $M_1 < M_3$. For a small $m_{1/2}^{75}$, the negative contribution results in a small, positive, M_1. For a slightly larger $m_{1/2}^{75}$, we get a small, negative M_1. This is shown in the plots and is the reason that the $1+75$ accesses the bulk region twice for most values of M_3, once for each sign of M_1. We study the 7 resulting points in the bulk regions in table 4. Note that for all points $m_{1/2}^{75} < m_{1/2}^{1}$, so the gaugino masses arise predominantly from the singlet.

Finally consider the case of the $1+200$ model. The lines corresponding to this model are plotted in red with long dashes. As in the $1+75$ case, in the 200 limit the lightest neutralino is higgsino and we cannot access the bulk region. This limit lies off the plots

JHEP10(2007)106

Parameter	C1		C2		C3	
	value	Δ^{Ω}	value	Δ^{Ω}	value	Δ^{Ω}
m_0	70	1.6	70	0.89	70	1.1
$m^1_{1/2}$	467	0.11	424	1.7	576	1.4
$m^{200}_{1/2}$	-66.7	0.40	-24.4	0.93	-75.6	2.2
A_0	0	0	0	0	0	0
$\tan\beta$	10	0.79	10	0.25	10	0.54
Max		1.6		1.7		2.2
M_1	-200	0.19	180	0.67	-180	0.56
M_2	333	0.83	376	0.31	424	0.59
M_3	400	0.75	400	0.22	500	0.39
Parameter	C4		C5		C6	
	value	Δ^{Ω}	value	Δ^{Ω}	value	Δ^{Ω}
m_0	70	0.78	70	0.97	70	0.86
$m^1_{1/2}$	533	2.3	683	2.3	647	2.5
$m^{200}_{1/2}$	-33.3	1.3	-83.3	3.1	-46.7	1.7
A_0	0	0	0	0	0	0
$\tan\beta$	10	0.23	10	0.43	10	0.25
Max		2.3		3.1		2.5
M_1	200	0.80	-150	0.59	180	0.63
M_2	467	0.25	517	0.49	553	0.22
M_3	500	0.13	600	0.20	600	0.047

Table 5: The fine-tuning for points C1-6 that lie within the bulk region for the $(1+200)$ model. For all points $|m^{200}_{1/2}| < |m^1_{1/2}|$, so the gaugino masses arise predominantly from the 1. We also give the corresponding GUT scale M_i for each point. As the tunings in figure 3 are calculated with respect to the parameters $a \in \{m_0,\ M_1,\ M_2,\ M_3,\ A_0,\ \tan\beta\}$, we give the tunings with respect to M_i for comparison.

and we do not consider it further here.

As the 200 has all gaugino masses positive, and large M_1, we cannot access the bulk region in the 200 limit. However by combining with the singlet we can get $|M_1| < |M_3|$ by taking a small, negative $m^{200}_{1/2}$. This allows such a model to access the bulk region for positive and negative small M_1. We study the resulting 6 points in the bulk region in table 5.In all points $|m^{200}_{1/2}| < |m^1_{1/2}|$ so the gaugino masses arise predominantly from the 1.

The hierarchy of the weak scale SUSY spectrum is fairly stable for all the points shown in Fig 3. Table 6 lists the neutralino, chargino and sfermion masses along with M_1, M_2 and the Higgsino mass parameter μ for the point B5 as an example. In contrast to the CMSSM the bino is lighter than the wino by a factor of 6. Correspondingly the right and left slepton masses are split by a large factor. The small value of m_0 also ensures that the right handed sleptons are considerably lighter than the wino. Hence a large fraction of wino decay is predicted to proceed via $\tilde{\tau}_1$, resulting in one or more tau leptons

JHEP10(2007)106

Particle	Mass (GeV)
$\tilde{\chi}_1^0$ (bino)	78.1
$\tilde{\chi}_2^0$ (wino)	457
$\tilde{\chi}_3^0$ (higgsino)	614
$\tilde{\chi}_4^0$ (higgsino)	636
$\tilde{\chi}_1^+$ (wino)	461
$\tilde{\chi}_2^+$ (higgsino)	635
M_1^{EW}	81
M_2^{EW}	470
M_3^{EW}	1120
μ	611
$\tilde{g}$	1150
$\tilde{\tau}_1$	104
$\tilde{\tau}_2$	399
$\tilde{e}_R, \tilde{\mu}_R$	115
$\tilde{e}_L, \tilde{\mu}_L$	399
$\tilde{t}_1$	793
$\tilde{t}_2$	1025
$\tilde{b}_1$	980
$\tilde{b}_2$	1000
$\tilde{q}_{1,2,R}$	~ 1005
$\tilde{q}_{1,2,L}$	~ 1070

Table 6: The SUSY mass spectrum of point B5 from figure 3. This spectrum is characteristic of all bulk region points we have studied. We display the hierarchy and flavour of the neutralino and chargino sectors. We also display the values of the neutralino mass parameters for completeness. For the squarks we take a typical squark mass rather than list the full squark spectrum. The exceptions are the 3rd family squarks that we list separately. Finally, the sneutrinos are degenerate with $\tilde{e}, \tilde{\mu}_L$.

in the final state in addition to the missing-E_T. Though the light selectron and smuon have negligible left-handed components, and so cannot take part in the wino decay, the heavier selectron and smuon are still lighter than the wino in all points we consider. A wino decay via a left-handed selectron/smuon would give a distinctive signal in the form of hard electron(s)/muon(s) in addition to the missing-E_T. Thus one expects a distinctive SUSY signal from squark/gluino cascade decays at LHC containing hard isolated leptons in addition to the missing-E_T and jets.

We have focused on the low m_0, $m_{1/2}$ region of the parameter space in this study. This is not to say that only the low m_0, $m_{1/2}$ region is allowed. $(g-2)_\mu$ favours low m_0

JHEP10(2007)106

and $m_{1/2}$, but there are no hard bounds that limit us to this corner of parameter space.[6] Instead, we have focused on this region because it has allowed us to examine the bulk region we found in [32] in the framework of a specific GUT model, and found that the GUT model provides a mechanism for accessing such a region with low tuning.

6. Conclusions

In previous work we found that a model with non-universal gaugino masses could access the bulk region in which t-channel slepton exchange alone could account for the observed dark matter relic density. The bulk region is an attractive prospect as it allows SUSY to account for the observed dark matter relic density without any appreciable fine-tuning. However, a model with entirely free gaugino masses is very unconstrained. Such non-universality must arise from a deeper structure and such structures should impose restrictions on the precise form of the gaugino masses at the GUT scale.

In this paper we have considered neutralino dark matter within the framework of SUSY GUTs with non-universal gaugino masses. We have taken the specific case of an SU(5) GUT model where the gaugino masses arise from different irreducible representations of the symmetric product of the adjoint representations. In particular we focused on the case of SU(5) with a SUSY breaking F-term in the 1, 24, 75 and 200 dimensional representations. We discussed the 24 case in some detail, and showed that the bulk dark matter region cannot be accessed in this case. In general if we just take the simplest case in which the gaugino masses arise from only one representation, we find that as far as achieving the bulk region is concerned, there is no advantage over the CMSSM. This is in part due to the surprising result that the sign and magnitude of M_2 with respect to M_3 has an important effect on the lightest Higgs mass through its effect on the top trilinear.

We then went on to consider the case of the singlet SUSY breaking F-term combined with an admixture of one of the 24, 75 or 200 dimensional F-terms. Such a scenario is natural once we allow the higher dimensional representations in our theory. In all these cases we showed that it becomes possible to access the bulk regions corresponding to low fine-tuned dark matter. In addition, the degree of fine-tuning required to access the bulk region remains small in the GUT models. Therefore we conclude that such models can access the bulk region and naturally account for the observed dark matter relic density.

Finally we note that the results in figure 3 are presented in the (M_1, M_2) plane for fixed M_3 and so are useful for considering general GUT models, as well as more general non-universal gaugino models. The hierarchy of weak scale SUSY spectrum is fairly stable for all the points shown in figure 3. Both the right and left sleptons are lighter than the wino, implying a large leptonic BR of wino decay. This promises a distinctive SUSY signal from squark/gluino cascade decays at LHC in the form of hard isolated leptons in addition to the missing-E_T and jets.

[6]The fine-tuning required for REWSB is also minimised by keeping m_0 and $m_{1/2}$ small. We do not provide details of the electroweak tuning here but we have checked that it remains similar to that of the non-universal gaugino model presented in [32].

JHEP10(2007)106

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JHEP10(2007)106