Non-Universality Effects and Dark Matter in Gravity Mediated SUSY Breaking

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Dark matter detection rates for supergravity models with R-parity where supersymmetry is broken at a scale \( M_G \) are discussed. Non-universal soft breaking masses in both the Higgs and squark sectors are considered, and it is seen that these can effect rates by a factor of 10 - 100 when \( m_{\tilde{\chi}_0^1} \approx 65 \text{ GeV} \) (\( \chi_0^1 \) = lightest neutralino) but otherwise make relatively small corrections. The \( b \to s + \gamma \) branching ratio is seen to correlate with detector event rates, large (small) branching ratios corresponding to small (large) event rates. Effects of precision determinations of cosmological parameters or event rate predictions by future satellite experiments are discussed for the \( \Lambda \text{CDM} \) and the \( \nu \text{CDM} \) models

1. INTRODUCTION

The dark matter problem is a particularly interesting one to examine in supersymmetry since models with R-parity invariance automatically have a dark matter candidate, the lightest supersymmetric particle (LSP). Over most of the parameter space in supergravity models, the LSP is the lightest neutralino (\( \chi_0^1 \)), and so predictions for event rates for detection can be made.

We consider here models based on supergravity, where SUSY is broken in a hidden sector at a scale \( \gtrsim M_G \) (where \( M_G \approx 2 \times 10^{16} \text{ GeV} \) is the GUT scale) with this breaking communicated to the physical sector by gravity \cite{1}, and with radiative breaking of SU(2) x U(1) occurring at the electroweak scale \( \sim M_Z \) \cite{2}. The simplest such model is the minimal one [MSGM] with universal soft breaking at \( M_G \) \cite{1,3}. Such models depend on only four additional parameters and one sign. These can be taken to be \( m_0 \) (the universal scalar soft breaking mass), \( m_{1/2} \) (the universal scalar soft breaking mass), \( A_0 \) (the universal cubic soft breaking parameter), \( B_0 \) (the quadratic soft breaking parameter) and the sign of \( \mu_0 \) (where \( \mu_0 \) is the Higgs mixing parameter in the superpotential, \( W_\mu = \mu_0 H_1 H_2 \)). After SU(2) x U(1) breaking, one may alternately replace \( B_0 \) by \( \tan \beta = \langle H_2 \rangle / \langle H_1 \rangle \) (\( H_{1,2} \) are the two Higgs doublets of SUSY), \( m_{1/2} \) by the gluino mass \( m_\tilde{g} \approx (\alpha_3(M_Z)/\alpha_G) m_{1/2} \), where \( \alpha_G \approx 1/24 \) is the GUT coupling constant) and \( A_0 \) by \( A_t \) (the t-quark A parameter at the electroweak scale).

Until recently, almost all calculations on detection of dark matter (DM) has been done within this universal framework. However, one expects the possibility of non-universalities arising from the following sources: (1) Kahler potential interactions can give rise to non-universal soft breaking. (2) Even if universality holds at a higher scale e.g. the string scale \( M_{\text{str}} \), the running of the renormalization group equations (RGE) will generate non-universalities at \( M_G \). (3) In breaking higher rank grand unified groups to the Standard Model (SM) group, the D terms can generate non-universalities.

The number of parameters needed to describe the non-universality expected at \( M_G \) depends upon the gauge group. For example, for SU(5), neglecting phases and splittings in the first two generations (to suppress flavor changing neutral currents) one needs nine additional observable parameters, of which only four enter significantly for large segments of the parameter space. (This might be compared with the \( \approx 30 \) parameters
of the MSSM). Over the past two years effort has been made to explore this larger parameter space \cite{4,5}, and we will describe here some results that have been obtained. We will see that non-universal masses can occur both in the Higgs and sfermions sectors, and these two sectors can effect each other either constructively or destructively.

There are several phenomena which effect predicted dark matter rates, and we summarize these now:

1. t-quark mass ($m_t \cong 175$ GeV). The heavy top drives the lightest top squark, $\tilde{t}_1$, tachyonic for negative $A_t$, eliminating this part of the parameter space unless $A_t/m_0 \gtrsim -0.5$.

2. $b \rightarrow s + \gamma$ decay. The current CLEO branching ratio is $B[B \rightarrow X_s \gamma] = (2.32 \pm 0.67) \times 10^{-4}$ \cite{6} which can be compared with the SM calculation (with NLO corrections) of $B[B \rightarrow \gamma] = (3.28 \pm 0.33) \times 10^{-4}$ \cite{7}. It is clear that already the experimental value constrains any new physics corrections that raise the theoretical value, and one finds that most of the $A_t/\mu < 0$ region is already eliminated at the 95% C.L. Combined with the t-quark effect above, most of the $\mu < 0$ part of the parameter space has been eliminated \cite{5}.

3. Amount of cold dark matter (CDM). The astronomical determinations of the various cosmological parameters at present have large uncertainties. Thus the Hubble constant, $H = h$ (100 km/s Mpc, has the range of $0.5 \lesssim h \lesssim 0.75$. The density of matter $\rho_i$ of type $i$ can be measured by $\Omega_i = \rho_i/\rho_c$ where the critial density $\rho_c$ is given by $\rho_c = 3H^2/8\pi G_N \cong 1.88 \times 10^{-29}h^2$ gm/cm$^3$. The determinations for cold dark matter (non-relativistic matter at the time of galaxy formation) are in the range $0.3 \lesssim \Omega_{CDM} \lesssim 0.75$. Thus one has

$$0.1 \lesssim \Omega_{CDM}h^2 \lesssim 0.4 \quad (1)$$

We will assume here that this CDM are the relic neutralinos $\chi_i^0$. Eq. (1) represents the cosmological abundance of $\chi_i^0$. Terrestrial detectors can observe the CDM in the Milky Way impinging on the solar system. This local density of $\chi_i^0$ has uncertainties due to modeling of the halo of the Galaxy and the amount of machos in the Galaxy. We will assume here that the local density is $\rho_{\chi_i} = 0.3$ GeV/cm$^3$, though this number could be in error by a factor of 2 or more.

The calculation of predicted event rates then proceeds as follows: one first calculates the relic density given by \cite{8}

$$\Omega_{\chi_i^0} h^2 \cong 2.45 \times 10^{-11} \left( \frac{T_{\chi_i^0}}{T} \right)^3 \left( \frac{A}{2.73} \right)^3 \times N_{1/2}^1/J(x_f) \quad (2)$$

where $J(x_f) = \int_0^{x_f} dx < \sigma v > GeV^{-2}$, $x_f = kT_f/m_{\chi_i^0}$, $T_f$ is the freezeout temperature, $N_{1/2}$ the number of degrees of freedom at freezeout, $< >$ is the $\chi_i^0$ annihilation cross section, $\sigma$ is the $\chi_i^0$ branching ratio to $\gamma$ and $v$ is the relative velocity, and $\geq < >$ means thermal average. We restrict the SUSY parameter space such that $\Omega_{\chi_i^0} h^2$ falls within the allowed window of Eq. (1), and also that the SUSY bounds from LEP, Tevatron and CLEO be obeyed. Within this restricted parameter space, one then calculates the detector event rate $R$ given by \cite{9}

$$R = (R_{SI} + R_{SD})(\rho_{\chi_i^0}/0.3 GeV cm^{-3})$$

$$\frac{(v_{\chi_i^0}/320 km s^{-1})}{kg d} \quad (3)$$

where $R_{SI} = 16 m_{\chi_i^0} m_N^2 |M_{\chi_i^0} M_N|^2 |A_{SI}|^2$ and $R_{SD} = 16 m_{\chi_i^0} m_N |M_{\chi_i^0} M_N|^2 |A_{SD}|^2$. Where $M_N$ is the target nuclear mass and $J$ is its spin, and $A_{SI}$, $A_{SD}$ are the spin independent, spin dependent scattering amplitudes. Note that for large $M_N$ one has $R_{SI} \sim M_N$, while $R_{SD} \sim 1/M_N$ thus favoring the spin independent scattering with heavy nuclei.

2. $\mu^2$ Dependence on Soft Breaking Masses

We will assume here that the first two generations of sfermions are degenerate (to suppress
flavor changing neutral currents) and allow for non-universal soft breaking masses in the Higgs and third generation sfermions. We parameterize these at $M_G$ as follows:

$$m_{H_1^2} = m_0^2(1 + \delta_1); \quad m_{H_2^2} = m_0^2(1 + \delta_2)$$ (4)

$$m_{q_L}^2 = m_0^2(1 + \delta_3); \quad m_{u_R}^2 = m_0^2(1 + \delta_4);$$

$$m_{d_R}^2 = m_0^2(1 + \delta_5)$$ (5)

$$m_{	ilde{d}_L}^2 = m_0^2(1 + \delta_6); \quad m_{	ilde{t}_L}^2 = m_0^2(1 + \delta_7)$$ (6)

Here $q_L = (u_L, d_L)$ are the doublet of squarks, $\ell_L = (\nu_L, e_L)$ the doublet of sleptons and the reference mass $m_0$ is taken to be the common mass of the first two generations. In addition there are the t, b and $\tau$ cubic soft breaking parameters $A_{t\ell}, A_{ob}, A_{o\tau}$. For grand unified models with GUT groups containing an SU(5) subgroup (e.g. SU(N), $N \geq 5$; SO(N), $N \geq 10$, $E_6$ etc.) and with matter in the usual $10 + \bar{5}$ of SU(5), one has

$$\delta_3 = \delta_4 = \delta_5; \quad \delta_6 = \delta_7; \quad A_{ob} = A_{o\tau}$$ (7)

In the following, we will limit our parameter space so that $m_0, m_{\tilde{g}} \leq 1 \text{ TeV}, \tan\beta \leq 25$ and $-1 \leq \delta_i \leq 1$. For $\tan\beta$ in this domain, results are generally insensitive to $\delta_5, \delta_6, \delta_7, A_{ob}$ and $A_{o\tau}$, and we will set these parameters to zero. The radiative breaking of SU(2) $\times$ U(1) determines $\mu^2$ to be

$$\mu^2 = \frac{\mu_1^2 - \mu_2^2}{t^2 - 1} - \frac{1}{2} M_Z^2; \quad t = \tan\beta$$ (8)

where $\mu_1^2 = m_{H_1}^2 + \Sigma_i$ and $\mu_2^2$ are the running Higgs masses, and $\Sigma_i$ are loop corrections. One finds [5]

$$\mu^2 = \frac{t^2}{t^2 - 1} \left[ \left( \frac{1 - 3 D_0}{2} + \frac{1}{t^2} \right) \right. + \left( \delta_3 + \delta_4 \right) \left( \frac{1 - D_0}{2} - \delta_2 - \frac{1 + D_0}{2} \right) + \left. \delta_1 \right] m_0^2 + \frac{t^2}{t^2 - 1}$$

where $D_0 = 1 - (m_t/200 \sin\beta)^2$, $A_R \equiv A_t - 0.61 m_{\tilde{g}}, S_0 = Tr Y m^2$. In this domain, results are generally insensitive to $\delta_5, \delta_6, \delta_7, A_{ob}$ and $A_{o\tau}$, and we will set these parameters to zero. The radiative breaking of SU(2) $\times$ U(1) determines $\mu^2$ to be

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where $D_0 = 1 - (m_t/200 \sin\beta)^2$, $A_R \equiv A_t - 0.61 m_{\tilde{g}}, S_0 = Tr Y m^2$, Y is the hypercharge and $m^2$ in $S_0$ are the scalar masses at $M_G$. $D_0$ vanishes at the t-quark Landau pole, and in general is small ($D_0 \approx 0.25$). $A_R$ is the residue at the Landau pole. One sees several features of Eq. (9). For $t^2 \gg 1$ (i.e. $t \gg 3$) $\delta_1$ does not enter sensitively in $\mu^2$. Further, since $D_0$ is small, we see that $\delta_3$ and $\delta_4$ acts oppositely to $\delta_2$, i.e. the squark non-universalities can contribute constructively or destructively to the Higgs non-universality. One thus cannot consider only one type of non-universality.

In general, one can expect important modifications due to non-universal soft breaking to occur when, for some reason, the universal terms are small. This can occur if $D_0 \approx \frac{1}{4}$, or when the residue at the Landau pole vanishes ($A_t \approx$)}
0.6m_3), or if m_3 is small (i.e. if m_{#chi^0_1} is small since for much of the parameter space \mu^2/M_Z^2 \gg 1 and one has the scaling m_{#chi^0_1} \simeq (1/7)m_3 \[10\]). These effects are enhanced for small tan \beta. We illustrate some of these effects for DM detection event rates. \mu^2 gives rise to small event rates and small \mu^2 plays a key role here in that it governs the interference between the Higgsino and gaugino parts of the \chi^0_1 in the SI part of the \chi^0_1 - nuclear scattering cross section. In general, large \mu^2 gives rise to small event rates and small \mu^2 to large event rates \[11\]. Fig. 1 shows the maximum and minimum event rates for a xenon detector for universal and non-universal soft breaking masses. Here \delta_3 = 0 = \delta_4. One sees the non-universal effects are small for large neutralino masses (m_{#chi^0_1} \gtrsim 60 \text{ GeV}). For \delta_2 = -1 = -\delta_1, there can be a reduction of a factor \sim 10 - 100 in the minimum event rates (where tan\beta is small) for small m_{#chi^0_1}, since then by Eq. (9) \mu^2 is increased by the non-universalities. Correspondingly, for \delta_2 = 1 = -\delta_2, \mu^2 is decreased and event rates can be increased by a factor \sim 10. Fig. 2 shows the corresponding curves for \delta_1 = \delta_2 = \delta_3 = 0. One sees that the \delta_4 = +1 dotted curve, resembles the \delta_2 = -1 curve of Fig. 1, and the \delta_4 = -1 dashed curve resembles the \delta_2 = +1 curve of Fig. 1, as one would expect from Eq. (9).

Fig. 3 exhibits the fact that when \delta_3 = 1 = \delta_4 (as expected in GUT models) and \delta_2 = 1, the squark and Higgs non-universal effects act coherently to significantly increase the maximum event rates up to \sim 10 \text{ event/kg d} (which is the current level of dark matter detector sensitivity \[4\]). However, for \delta_2 = -1 = -\delta_1, the two effects mostly cancel, yielding event rates close to predictions of universal soft breaking.

3. Cosmological Parameters

As discussed in Sec. 1, the various cosmological parameters are at present not well determined. However, future satellite experiments, MAP and PLANCK \[12\] will be able to measure the angular power spectrum quite accurately, and this will allow the determination of the Hubble constant, the amount of dark matter, the cosmological constant etc. at the level of (1-10)\% \[13,14\]. Such determinations would considerably restrict the SUSY
paramter space, and hence sharpen significantly the predictions of DM detection rates. To illustrate what might be expected from these determinations, we consider two cosmological models.

(i) $\Lambda$CDM Model

One assumes there that CDM and baryonic dark matter (B) exists with a cosmological constant $\Lambda$ such that the universe is flat: $\Omega_{CDM} + \Omega_B + \Omega_\Lambda = 1$. As an example, we assume that the measured central values of the parameters are $\Omega_{CDM} = 0.40$, $\Omega_B = 0.05$, $\Omega_\Lambda = 0.55$ and $h = 0.62$, which are consistent with current astronomical measurements. Then using the estimated accuracy that could be achieved by the PLANCK satellite [13], one finds

$$\Omega_{CDM} h^2 = 0.154 \pm 0.017 \quad (10)$$

This window is much narrower than what is currently assumed, i.e. Eq. (1). Eq. (10) produces two interesting results for the event rates: the minimum event rates are significantly raised for $m_{\chi_1^0} \lesssim 60$ GeV, and the upper bound on $\Omega_{\chi_1^0} h^2$ produces an upper bound on allowed values of $m_{\chi_1^0}$. One finds at the 1σ (2σ) ranges that $m_{\chi_1^0} \lesssim 70$ (77) GeV, and by scaling this produces a corresponding bound $m_{\chi_1^0} \lesssim 520$ (560) GeV. In addition $m_{\chi_1^0} \lesssim 150$ GeV and for the light Higgs one has $m_h \lesssim 120$ GeV. It is interesting to compare these results with the reach of the upgraded Tevatron with 25 $fb^{-1}$ of data where the gluino would be observable if $m_{\tilde{g}} \lesssim 450$ GeV [15], the chargino if $m_{\tilde{\chi}_1^+} \lesssim 235$ GeV for about 2/3 of the parameter space and the Higgs if $m_h \lesssim 120$ GeV [16].

As discussed in Sec. 1, the $b \to s + \gamma$ decay branching ratio plays an important role in limiting the SUSY parameter space, as there is already some strain between the experimental branching ratio and the SM prediction. In addition, there exists an interesting correlation between the DM event rate R and $B(b \to s + \gamma)$. Large R occurs mainly for large $\tan\beta$ where destructive interference between the SM and SUSY contributions to the $b \to s + \gamma$ occurs. Small R occurs mainly at small $\tan\beta$ where there is constructive interference in the $b \to s + \gamma$ decay and hence correlates with large B ($b \to s + \gamma$). This can be seen in Fig. 4 where a scatter plot for R vs. $B(b \to s + \gamma)$ for a Xe detector for the $\Lambda$CDM model with universal soft breaking masses and $\mu > 0$.

![Figure 4. Scatter plot of R vs. $B(b \to s + \gamma)$ for a Xe detector for the $\Lambda$CDM model with universal soft breaking masses and $\mu > 0$.](image)

(ii) $\nu$CDM Model

If neutralinos have mass of order of a few eV, they could represent a hot dark matter component to the dark matter. As an example of such a model, we assume that the measured central values of the cosmological parameters are

$$\Omega_\nu = 0.20, \quad \Omega_{CDM} = 0.75,$$
$$\Omega_B = 0.05, \quad h = 0.62 \quad (11)$$

The PLANCK satellite would then determine $\Omega_{CDM} h^2$ with the following accuracy [13,14]:

$$\Omega_{CDM} h^2 = 0.288 \pm 0.013 \quad (12)$$
For this case, the narrowing of the $\Omega h^2$ window, narrows the event rates in the region $m_{\chi_1} \lesssim 65$ GeV, and for the 1std range $(0.158 \lesssim \Omega_{\chi_1} h^2 \lesssim 0.301)$ produces forbidden gaps when $m_{\chi_1} > 65$ GeV (which, however, get filled in for the 2 std range). Since $\Omega_{\chi_1} h^2$ is larger for this case then in the $\Lambda$CDM model, the upper bounds on the gaugino masses are larger. One finds for the 1 std (2 std) bounds that $m_{\tilde{g}} \lesssim 95 (100)$ GeV, $m_\chi \lesssim 700 (720)$ GeV and for the chargino $m_{\chi^\pm} \sim 200$ GeV. Thus for this model, the LHC would most likely be needed to discover SUSY.

The above two examples are meant to be illustrative of what future astronomical measurements of the basic cosmological parameters will be able to achieve. In particular one sees how astronomical measurements can impact on accelerator searches for SUSY particles.

4. Conclusions

We have considered here dark matter detection rates within the framework of supergravity grand unification with R-parity where SUSY breaks at a scale $\sim M_G$, the breaking being communicated to the physical sector by gravity. Such models automatically imply the existence of cold dark matter, and over a large amount of the parameter space in amounts consistent with astronomical measurements.

The detection rates expected for cases of non-universal soft breaking masses have been compared with the minimal universal SUGRA models. Non-universal effects can increase or decrease event rates (depending on the signs of the non-universalities) by factors of $\sim 10 - 100$ in the domain $m_{\chi_1}^0 \lesssim 65$ GeV (equivalently when $m_{\tilde{g}} \lesssim 400$ GeV) but generally have small effects at higher masses. One must also consider the possibilities of both Higgs and squark mass non-universalities, as both these enter in the analysis with comparable size. Thus the Higgs and squark non-universalities can either cancel or enhance each other in the detection rates.

Future $b \to s + \gamma$ decay data may play an important role in uncovering new physics, and indeed may be the first place that new physics is seen. Already the current data strongly restricts the SUSY parameter space. Thus combined the fact that the top quark is heavy ($m_t \cong 175$ GeV) the current branching ratio for $b \to s + \gamma$ forbids most of the $\mu < 0$ part of the parameter space, eliminating most of the high event rate region for $\mu < 0$. The event rates for $\mu < 0$ are then $\sim 100$ times smaller than for $\mu > 0$, and this phenomena holds with or without non-universal soft breaking masses. As error flags go down, the $b \to s + \gamma$ decay may more strongly restrict the allowed regions of SUSY parameter space, making supergravity predictions more precise.

One of the striking features of recent years is the “astro-particle connection” where developments in particle theory effect astronomical and cosmological theory, and astronomical measurements can influence what is expected at high energy accelerators. One may expect this interaction to strengthen in the future. Thus new satellites (MAP and PLANCK), balloon and ground based experiments should be able to measure the basic cosmological parameters very accurately (at the few percent level), and hence determine the amounts of different types of dark matter. This will put further restrictions on the allowed SUSY parameter space. In this connection we have considered two examples of cosmological models, the $\Lambda$CDM model (which limit the gaugino masses to be $m_{\chi_1}^0 \sim 75$ GeV, $m_{\tilde{g}} \sim 550$ GeV and $m_{\chi^\pm} \sim 150$ GeV, and the $\nu$CDM model (where $m_{\chi_1}^0 \sim 100$ GeV, $m_{\tilde{g}} \sim 700$ GeV and $m_{\chi^\pm} \sim 200$ GeV. In the first model the upgraded Tevatron might be able to see SUSY, while in the second model one likely needs the LHC (or NLC). In either case the astronomical measurements would correlate with accelerator searches for SUSY. There is also a correlation between the $B(b \to s + \gamma)$ branching ratio and expected dark matter detection rates. Thus for $B > 3 \times 10^{-4}$ (i.e. $B$ in range expected from the SM) the dark matter detector event rates are generally small i.e. $R \sim (10^{-1} - 10^{-4})$ events/kg d, while if $B < 3 \times 10^{-4}$ (smaller than the SM prediction) event rates in general will be large i.e. $R \sim (0.05 - 1)$ events/kg d. Thus accelerator measurements would correlate with astronomical
searches for dark matter.

5. Acknowledgements

This work was supported in part by NSF grants PHY-9411543 and PHY-9602074.

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