We consider here the constraints in SUGRA models on the SUSY parameter space due to current experimental bounds on the light Higgs mass \( m_h \), the \( b \rightarrow s \gamma \) decay, the amount of neutralino cold dark matter \( \Omega h^2 \), and the muon magnetic moment. Models with universal soft breaking (mSUGRA) and non-universal gaugino or Higgs masses at \( M_G \) are examined. For mSUGRA, the \( m_h \), \( b \rightarrow s \gamma \) and \( \Omega h^2 \) constraints imply a lower bound on the gaugino mass of \( m_{1/2} \gtrsim 300 \text{GeV} \) implying the gluino and squarks have mass \( m \gtrsim 700 \text{GeV} \), and the neutralino \( \gtrsim 120 \text{GeV} \). The current status of the Brookhaven muon g - 2 experiment is reviewed, and if the Standard Model (SM) contribution evaluated using the \( e^+ + e^- \) data is correct, a \( 2\sigma \) bound on the deviation of experiment from the SM produces an upper bound on \( m_{1/2} \) that eliminates the "focus point" regions of parameter space. Dark matter (DM) detection cross sections range from \( 5 \times 10^{-8} \text{pb} \) to \( 5 \times 10^{-10} \text{pb} \) which would be accessible to future planned detectors. The SUSY decay \( B_s \rightarrow \mu^+ + \mu^- \) is seen to be accessible to the Tevatron Run 2B with 15 fb\(^{-1}\) luminosity for \( \tan \beta \gtrsim 30 \). The most favorable signals of SUSY for linear colliders are stau pair production and neutralino pair production, though it will require an 800GeV machine to cover the full parameter space. Non-universal models can modify some of the above results. Thus a non-universal (heavier) gluino mass at \( M_G \) can significantly reduce the lower bound constraints of \( b \rightarrow s \gamma \) and \( m_h \) giving rise to a lighter SUSY spectrum. A heavier up Higgs mass can open an additional region with allowed relic density arising from annihilation via the \( s\)-channel \( Z \) diagram with an \( O(10) \) larger DM detector cross section.

1. Introduction

We are now approaching the time when experiments will tell us what the new physics is that will replace the Standard Model. Neutrino experiments have already shown the breakdown of the Standard Model with the evidence of neutrino masses. However, this does not shed light on how the new dynamics resolves the gauge hierarchy problem, and there are many suggestions for this: SUSY and SUGRA models, extra dimensions (large and small), string/M-theory models, etc.

SUSY models all contain a large number of parameters to be determined finally by experiment. The more phenomena the model applies to, the more one will be able to limit the parameter space. We consider here SUSY models with R-parity invariance, since these have the unexpected prediction of the existence of dark matter [1, 2]. The requirement that the theory predict the experimentally measured amount of dark matter already puts strong constraints on the parameter space. The MSSM with over 100 free parameters is not very restrictive. At the other extreme is mSUGRA which is consistent with grand unification (up to now the only direct experimental evidence in favor of SUSY!) and has only four new parameters and one sign. It’s natural therefore to start with mSUGRA and see how the current experiments restrict its parameter space, and hence what predictions can be made for future dark matter experiments and for accelerator experiments at the LHC and NLC. We will then

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perturb the mSUGRA framework with non-universal soft breakings that are consistent with current data, and thus get some idea of how robust the mSUGRA predictions are.

The current experiments that most strongly restrict the SUSY parameter space are the following:

1. The amount of cold dark matter (CDM). Global fits to the CMB and other data yield \( \Omega_{\text{CDM}} h^2 = 0.139 \pm 0.026 \) [3], and we take a 2.5\( \sigma \) range around the central value:

\[
0.07 < \Omega_{\text{CDM}} h^2 < 0.21
\]  

The MAP data, due out in the near future, will be able to significantly narrow this range.

2. Higgs mass. The LEP lower bound of \( m_h > 114.1 \) [3] is a significant constraint for lower \( \tan \beta \) (i.e. \( \tan \beta \lesssim 30 \)), but generally will become very significant if the bound were to rise by just a few GeV. Unfortunately, theoretical calculations still have an error of about (2 - 3) GeV, and so we will (conservatively) interpret this experimental bound to mean that the theory calculation of \( m_h \) should obey \( m_h > 111 \text{ GeV} \). mSUGRA predicts \( m_h \lesssim 130 \text{ GeV} \), which could make the light Higgs within the reach of the Tevatron Run2B.

3. \( b \to s \gamma \) decay. The CLEO data [5] has both systematic and theoretical error, and so we take a relatively broad range around the central value:

\[
1.8 \times 10^{-4} < B(B \to X_s \gamma) < 4.5 \times 10^{-4}
\]  

The \( b \to s \gamma \) rate is significant for large \( \tan \beta \) (\( \tan \beta \lesssim 30 \)) where it produces a lower bound on the gaugino mass \( m_{1/2} \). If the lower bound on the branching ratio were raised, it would increase this lower bound on \( m_{1/2} \).

4. Muon magnetic moment anomaly, \( a_{\mu} \). Since this conference, the Brookhaven E821 experiment has released new results that have halved the statistical error with the central value essentially unchanged [8]. Also, new data from CMD-2 and BES has allowed a better evaluation of the SM contribution and two new theoretical evaluations have appeared [7, 8]. Using the \( e^+ - e^- \) data to evaluate the hadronic contribution, both analyses lead now to a 3\( \sigma \) deviation, e.g. [7]:

\[
\Delta a_{\mu} = 33.9(11.2) \times 10^{-10}
\]  

If, on the other hand, the tau decay data (with CVC breaking corrections included) is used, one finds only a 1.6\( \sigma \) discrepancy [7], and further, the two results are statistically inconsistent. In the following, we will assume that the \( e^+ - e^- \) data is correct, and take a 2\( \sigma \) band around the central value of Eq.(3) to see what this implies. However, it may turn out that the tau data evaluation is correct, under which circumstances, the current \( a_{\mu} \) data will give no significant constraint.

Future experiments at accelerators will eventually determine if SUSY is correct. Thus Run2B at the Tevatron should be sensitive to \( B_s \to \mu^+ + \mu^- \) with 15 fb\(^{-1}\)/detector data [9], and perhaps distinguish different SUGRA mediation models [10]. The LHC can, of course measure SUSY masses and couplings, e.g. for the gluino up to 2.5 TeV (i.e. \( m_{1/2} \lesssim 1 \text{ TeV} \)), while the NLC might observe stau and neutralino production processes.

2. mSUGRA Model

The mSUGRA model depends upon four parameters and one sign. It is convenient to choose these as follows: (i) \( m_0 \), the scalar soft breaking mass at the GUT scale \( M_G \). (2) \( m_{1/2} \), the gaugino mass at \( M_G \). [Note that \( m_{\tilde{\chi}^0_1} \approx 0.4 m_{1/2} \) (where \( \tilde{\chi}^0_1 \) is the lightest neutralino), \( m_{\tilde{\chi}^\pm_1} \approx 0.8 m_{1/2} \) (where \( \tilde{\chi}^\pm_1 \) is the lightest chargino), and \( m_{\tilde{g}} \approx 2.5 m_{1/2} \) (where \( \tilde{g} \) is the gluino).] (3) \( A_0 \) the cubic soft breaking mass at \( M_G \). (4) \( \tan \beta =< H_2 > / < H_1 > \) at the
determinations of  
Thus the MAP (and Planck) satellite data will narrow this band further, with more accurate  
the band, too little early universe annihilation occurs (violating the upper bound of Eq. (1)).  
universe annihilation (violating the lower bound of Eq(1)), while above the upper bound of  
2 < tan β < 55, and |A_0| < 4m_{1/2}.  
For heavy nuclei, the spin independent neutralino-nucleus cross section dominates for  
terrestrial dark matter detectors, which allows one to extract the \( \sigma_{\tilde{\chi}_1^0-p} \) - proton cross section  
\( \sigma_{\tilde{\chi}_1^0-p} \). (Here \( \tilde{\chi}_1^0 \) is the dark matter candidate.) The neutralino scattering by quarks in the  
nuclear target proceeds through s-channel squark states, and t-channel Higgs boson states (\( h, H \)). To calculate the relic density of neutralinos left over after the Big Bang, one needs  
the neutralino annihilation amplitudes. The annihilation proceeds through the s-channel Z  
and Higgs channels (\( h, H, A \)), and t-channel sfermion channels. However, if a second  
particle is nearly degenerate with the \( \tilde{\chi}_1^0 \), one must include it in the early universe annihilation processes, which leads to the co-annihilation phenomena. In SUGRA models this accidental near degeneracy occurs naturally for the light stau, \( \tilde{\tau}_1 \). Co-annihilation then begins at \( m_{1/2} \approx (350-400) \)GeV and the scalar mass \( m_0 \) must be raised as \( m_{1/2} \) increases to keep the \( \tilde{\tau}_1 \) heavier than the \( \tilde{\chi}_1^0 \).  
The neutralino -proton cross section has the following general behavior: \( \sigma_{\tilde{\chi}_1^0-p} \) increases  
with increasing \( \tan \beta \), and decreases with increasing \( m_{1/2}, m_0 \). The maximum value of \( \sigma_{\tilde{\chi}_1^0-p} \)  
then generally occurs at large \( \tan \beta \) and small \( m_{1/2}, m_0 \).  

One starts the analysis at \( M_G \) and uses the renormalization group equations (RGE) to  
obtain predictions at the electroweak scale. In carrying out these calculation, it is necessary  
to include a number of corrections and we list some of these here: (1) We use two loop gauge  
and one loop Yukawa RGE in running from \( M_G \) to the electroweak scale \( M_{EW} \), and three loop  
QCD RGE below \( M_{EW} \) for light quark contributions. (2) Two loop and pole mass corrections  
are included in the calculation of \( m_b \). (3) One loop correction to \( m_b \) and \( m_{\tau} \) are included[11].  
(Chargino-neutralino co-annihilation channels are included in the relic density calculation  
[12,13,14].) We do not include Yukawa unifications or proton decay constraints as these depend sensitively on post-GUT physics, about which little is known.  

Figs. 1 and 2 illustrate the allowed regions in the \( m_0 - m_{1/2} \) plane for \( \tan \beta = 10 \) and  
\( \tan \beta = 50 \) for \( A_0 = 0, \mu > 0 \). We note for \( \tan \beta = 10 \), that the lower bound on \( m_{1/2} \) is  
set by the lower bound on the Higgs mass. The narrowness of the dark matter allowed band  
does not imply any fine tuning. Thus the lower edge is determined from the co-annihilation  
effect so that the \( \tilde{\tau}_1 \), which is nearly degenerate with the \( \tilde{\chi}_1^0 \) does not cause too much early  
universe annihilation (violating the lower bound of Eq(1)), while above the upper bound of  
the band, too little early universe annihilation occurs (violating the upper bound of Eq. (1)).  
Thus the MAP (and Planck) satellite data will narrow this band further, with more accurate  
determinations of \( \Omega_{CDM} \). At \( \tan \beta = 50 \), the allowed dark matter band expands at low \( m_{1/2} \)  
due to the fact that the A Higgs becomes light, allowing additional early universe annihilation,  
and this is compensated by raising \( m_0 \). Note here it is the \( b \to s\gamma \) branching ratio that give  
the lower cut off in \( m_{1/2} \). The vertical lines through the dark matter allowed bands represent  
the values of \( \sigma_{\tilde{\chi}_1^0-p} \). We see that the cross sections range from \( 5 \times 10^{-8} \) pb to \( 10^{-9} \) pb. The  
\( \mu < 0 \) possibility (not shown) allows for regions of much smaller dark matter cross sections  
[17,12]. However, if the SUSY contribution to \( a_0 \) is indeed positive (which is the case for the  
e\( e^+ - e^- \) evaluation of the SM contribution), then the \( \mu < 0 \) possibility is eliminated [18,19].
Figure 1. Allowed regions in $m_0 - m_{1/2}$ parameter space for $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$. The left vertical line corresponds to $\sigma_{\chi^0_1 - p} = 5 \times 10^{-9}$ pb and the right to $10^{-9}$ pb.

3. The Muon Magnetic Moment Anomaly

As discussed in the introduction, it is still unclear if the current measurements of the muon magnetic moment indicate a deviation with the Standard Model prediction. In this section we will assume that the analysis based on the $e^+ - e^-$ data, which yields the $3\sigma$ deviation of Eq.(3), is correct, in order to see what restriction on the SUSY parameter space this possibility allows. In supersymmetry, one expects a contribution to the muon magnetic moment of characteristic size $10 \times 10^{-10}$ arising from chargino-sneutrino and neutralino-smuon loops (with the photon attached to any charged line). If the final result requires $a^{\text{SUSY}}_\mu$ to be much smaller than $10 \times 10^{-10}$, it would mean that the SUSY squark and gluino masses are in the TeV domain, while a value of $a^{\text{SUSY}}_\mu \gtrsim 40 \times 10^{-10}$ would exclude mSUGRA [20]. Thus the allowable range for $a^{\text{SUSY}}_\mu$ is already somewhat restricted. Fig.3 exhibits the effect of the muon magnetic moment anomaly for the case of $\tan \beta = 40$, $A_0 = 0$, $\mu > 0$. The shaded region in the upper right would be the part of the parameter space excluded at the $2\sigma$ level (assuming the $e^+ - e^-$ evaluation of the SM). Combined with the dark matter constraint, one sees that the $a_\mu$ constraint give rise to an upper bound $m_{1/2} \lesssim 800$GeV or $m_{\tilde{\chi}^0_1} < 320$ GeV, $m_{\tilde{\chi}^\pm_1} < 640$ GeV and $m_{\tilde{g}} < 2$ TeV. The $b \to s\gamma$ constraint gives a lower bound of $m_{1/2} > 350$GeV, and thus the parameter space is constrained at both ends. Note also that it would not take a significantly larger value then the central value of $33 \times 10^{-10}$ to exclude the full parameter space for this value of $\tan \beta$. Thus a resolution of the Standard Model contribution to $a_\mu$ is of great importance for SUSY models.
Figure 2. Same as Fig. 1 with $\tan \beta = 50$, and $\sigma_{\tilde{\chi}^0_0-p} = 5 \times 10^{-8}$ (left) and $2 \times 10^{-9}$ (right).

4. The $B_s \to \mu^+ + \mu^-$ Decay

The $B_s \to \mu^+ + \mu^-$ decay [21, 9, 22, 23] offers another window for investigating the mSUGRA parameter space. The Standard Model predicts a branching ratio that is quite small i.e. $B[B_s \to \mu^+ + \mu^-] = (3.1 \pm 1.4) \times 10^{-9}$. However, the SUSY contribution can become quite large for large $\tan \beta$. An example of one of the important graphs for this process is shown in Fig. 4, where the amplitude grows as $(\tan \beta)^3$, and hence the rate grows as $(\tan \beta)^6$. This process has become interesting because it appears possible to observe it at Run2B of the Tevatron [9]. A set of cuts eliminating the background (e.g. gluon splitting of $g \to b\bar{b}$ and non-b background) exits and leads to a sensitivity for CDF for a luminosity of $15 \text{fb}^{-1}$ of

$$B[B_s \to \mu^+ + \mu^-] \gtrsim 1.2 \times 10^{-8}$$

(and if a similar sensitivity can be obtained by D0 the combined sensitivity would be $0.65 \times 10^{-8}$). Fig. 5 shows the branching ratio for different $\tan \beta$ for the case $m_0 = 300\text{GeV}$, $A_0 = 0$, $\mu > 0$, and Fig. 6 shows the expected limit on the branching ratio observable by CDF as a function of luminosity. We see that with $15 \text{fb}^{-1}$, CDF should be sensitive to this decay for $\tan \beta \gtrsim 30$, and in fact too large a branching ratio could exclude mSUGRA with $2 \text{fb}^{-1}$.

5. NLC Reach

We consider here two possible accelerators at energies of $500\text{GeV}$ and $800\text{GeV}$ to examine what part of the SUSY spectrum would be available to linear colliders. We’ve seen that
the \( m_h \) and \( b \to s\gamma \) bounds already means that \( m_{1/2} \gtrsim (350 - 400) \) GeV, and so for mSUGRA, gluinos and squarks would generally be beyond the reach of such machines. The most favorable SUSY signals are then

\[
\begin{align*}
e^+ + e^- &\to \tilde{\chi}_2^0 + \tilde{\chi}_1^0 \to (l^+ + l^- + \tilde{\chi}_1^0) + \tilde{\chi}_1^0 \\
e^+ + e^- &\to \tilde{\tau}_1^+ + \tilde{\tau}_1^- \to (\tau + \tilde{\chi}_1^0) + (\tau + \tilde{\chi}_1^0)
\end{align*}
\]  

(5)

where \( l^\pm \) is any charged lepton. Since in mSUGRA \( m_{\tilde{\chi}_2^0} \approx 2m_{\tilde{\chi}_1^0} \) one has for the kinematic mass reach \( 1/2m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^0} \lesssim 165(265) \) GeV for \( \sqrt{s} = 500(800) \) GeV, and \( m_{\tilde{\tau}_1} \lesssim 250(400) \) GeV for \( \sqrt{s} = 500(800) \) GeV. In general the stau is the lightest slepton and so will be the

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**Figure 3.** Allowed region in the \( m_0 - m_{1/2} \) plane for \( \tan \beta = 40, A_0 = 0, \mu > 0 \). The shaded upper region is excluded at the 2\( \sigma \) level for \( a_\mu \) obeying Eq.(3).

**Figure 4.** A leading diagram for the decay \( B_s \to \mu^+ + \mu^- \). The vertices with the heavy dot are proportional to \( \tan \beta \).
major signal, as the selectron and smuon will not be accessible for most of the parameter space. There are a number of backgrounds however, and appropriate cuts have to be arranged to suppress them. This is currently being studied [bdutta4].

6. The mSUGRA Parameter Space

We now summarize the effects on the mSUGRA parameter space of the constraints from $m_h$, $b \to s \gamma$, dark matter, and $a_\mu$ (assuming Eq. (3) is valid). We will also see what effect might be expected from measurement of the $B_s \to \mu^+\mu^-$ decay at the Tevatron, and examine the NLC reach for SUSY. Fig. 7 exhibits these effects for $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$. We see that for low $\tan \beta$, the $a_\mu$ constraint eliminates most of the parameter space, and the NLC with $\sqrt{s} = 500$ GeV would be able to scan the full remaining space with either the stau or neutralino signal. The $\sigma_{\tilde{\chi}_2^0 - \mu}$ cross sections are small, but of the size that future experiments hope to achieve (e.g. GENIUS, Cryoarray, ZEPLIN IV, CUORE). Of the two NLC signals, the $\tilde{\chi}_0^0 - \tilde{\chi}_1^0$ is sensitive to large $m_0$, while the $\tilde{\tau}_1 - \tilde{\tau}_1$ is sensitive to relatively large $m_{1/2}$. Due to the dark matter constraint, the latter appears to be the more important signal.

Fig. 8 shows similar information for $\tan \beta = 40$. For larger $\tan \beta$, the possibility of observing the $B_s \to \mu^+\mu^-$ signal at the Tevatron becomes significant, and assuming the combined CDF and D0 data were available, it could cover the full parameter space for an $a_\mu$ anomaly $> 10 \times 10^{-10}$. The NLC (500GeV) tau-tau signal would now cover only about one half the allowed parameter space, while for 800GeV the full parameter space could be examined.

Figure 5. The branching ratio of $B_s \to \mu^+\mu^-$ as a function of $m_{1/2}$ for different values of $\tan \beta$[9].
For very large tanbeta, a new feature of a “bulge” occurs in the dark matter channel at low $m_{1/2}$ in the allowed dark matter channel. This is due to the fact the heavy Higgs $A$ and $H$ become light, and allow a more rapid annihilation in the early universe through the $A$ and $H$ s-channel poles. Figs. 9 and 10 for $\tan \beta = 50$ and 55 exhibit this feature. (We note in general that the results for $\tan \beta \geq 45$ become very sensitive to the precise values of $m_t$ and $m_b$. We are here using the central values of $m_t(pole) = 175$ GeV and $m_b(m_b) = 4.25$ GeV, but the figures would change significantly if one were to go one or two $\sigma$ away from the mean.) We see from the figures that the $\tilde{\tau}_1 - \tilde{\tau}_1$ LC signal would be able to cover the full parameter space of $\tan \beta = 50$ for an 800 GeV collider, but not quite cover it all for $\tan \beta = 55$. Of course, for these large tanbeta, the $B_s \rightarrow \mu^+ \mu^-$ signal is greatly enhanced, as is the dark matter detector cross sections.

7. Non-universal Models

Our previous discussion has been within the framework of mSUGRA with universal soft breaking occurring. It is interesting to investigate what aspects of these results would survive in the presence of some non-universal soft breaking. One peculiar feature of mSUGRA is the narrow dark matter allowed bands due in part to the “accidental” near degeneracy of the $\tilde{\tau}_1$ and the $\tilde{\chi}^0_1$. This phenomena would be maintained even if the gaugino masses were non-universal at $M_G$, since $m_{\tilde{\tau}_1}^2 - m_{\tilde{\chi}^0_1}^2$ depends mainly on $\tilde{m}_1$. Thus this type of co-annihilation effect is generic. A second feature of mSUGRA, that the combined effects of the $m_b$ and $b \rightarrow s \gamma$ experimental bounds put a lower limit $m_{1/2} > (300 - 400)$ GeV for all tanbeta, is however sensitive to the mSUGRA assumption of universal gaugino masses at $M_G$. Thus if one assumes gluino breaking of this universality at $M_G$,

$$\tilde{m}_1 = \tilde{m}_2 = \tilde{m}_3(1 + \tilde{\delta}_3),$$

then a positive $\tilde{\delta}_3$ raises the stop mass and effects strikingly both the $b \rightarrow s \gamma$ branching ratio and the value of $m_h$. This is illustrated in Fig. 11 for the case of $\tilde{\delta}_3 = 1$, $\tan \beta = 50$, $A_0 = 0$, $\tan \beta = 55$. (We note in general that the results for $\tan \beta \geq 45$ become very sensitive to the precise values of $m_t$ and $m_b$. We are here using the central values of $m_t(pole) = 175$ GeV and $m_b(m_b) = 4.25$ GeV, but the figures would change significantly if one were to go one or two $\sigma$ away from the mean.) We see from the figures that the $\tilde{\tau}_1 - \tilde{\tau}_1$ LC signal would be able to cover the full parameter space of $\tan \beta = 50$ for an 800 GeV collider, but not quite cover it all for $\tan \beta = 55$. Of course, for these large tanbeta, the $B_s \rightarrow \mu^+ \mu^-$ signal is greatly enhanced, as is the dark matter detector cross sections.
$\mu > 0$. One sees that both the $b \to s\gamma$ and $m_h$ constraint is moved strongly towards lower $m_{1/2}$, and now the lower bound on $m_{1/2}$ is only $m_{1/2} \sim 190$ GeV. The Higgs lines are also moved and lie approximately 150 GeV lower in $m_{1/2}$. The $a_\mu$ bound, however, becomes somewhat more constraining.

A second non-universality that might naturally arise is with the scalar soft breaking masses. Thus while flavor changing neutral current constraint require squark masses to be nearly degenerate at the GUT scale, there is little theoretical reason to require that the Higgs masses be degenerate. We consider here the simple model where at $M_G$

$$m_{H_1}^2 = m_0^2 (1 + \delta_1); \quad m_{H_2}^2 = m_0^2 (1 + \delta_2)$$  \(7\)

where $m_0$ is the universal squark and slepton masses. While this introduces two new parameters into the model, one may qualitatively understand the effects of $\delta_{1,2}$. In SUGRA models, the $\mu$ parameter governs much of the physics, and if $\mu^2$ decreases (increases), then the Higgsino content of the neutralino $\tilde{\chi}_1^0$ increases (decreases). The RGE with radiative breaking shows that $\mu^2$ is indeed sensitive to $\delta_2$ (but only slightly sensitive to $\delta_1$). For $\delta_2$ positive, $\mu^2$ decreases, and this produces two effects: (1) it increases the dark matter detection cross section $\sigma_{\tilde{\chi}_1^0-p}$ since this quantity depends on the interference between the Higgsino and gaugino parts of the neutralino. (2) It increases the $\tilde{\chi}_1^0 - \tilde{\chi}_1^0 - Z$ coupling, allowing more early
Figure 8. Same as Fig. 7 with dashed lines giving $B_s \to \mu\mu$ Tevatron reaches. The left solid dark line corresponds to $\sigma_{\chi_1^0 - p} = 3 \times 10^{-8}$ and the extreme right to $1 \times 10^{-9}$.

Figure 9. Same as Fig. 8 for $\tan\beta = 50$, with the left solid line corresponding to $\sigma_{\chi_1^0 - p} = 5 \times 10^{-8}$pb and the right to $2 \times 10^{-8}$pb.
universe annihilation of the neutralinos through the Z s-channel. This then opens another channel of allowed relic dark matter in the $m_0 - m_{1/2}$ plane at relatively low $m_{1/2}$ but high $m_0$ (so that too much annihilation doesn’t occur). These effects are seen in Figs. 12 and 13. Fig. 12 shows the new $Z$-channel allowed dark matter region at high $m_0$, along with the usual stau co-annihilation narrow band at low $m_0$ for $\tan \beta = 40$. Fig. 13 shows the corresponding values of $\sigma_{\tilde{\chi}_0^1-p}$, the upper dashed band corresponding to the $Z$-channel of Fig. 13. One sees that the detector cross section for this possibility can be a factor of ten or more larger than the usual stau band.

8. Conclusions and Summary

We have examined here for SUGRA models of neutralino dark matter, the constraints on the SUSY parameter space that arise from current experiments, and have considered models both with universal soft breaking (mSUGRA) and with non-universal soft breaking.

For mSUGRA, co-annihilation effects and the current bounds on the relic density generally restrict the allowed parameters to be in a narrow band in the $m_0 - m_{1/2}$ plane with relatively low $m_0$ (except in the low $m_{1/2}$ region where for very large $\tan \beta$ a “bulge” can exist). If the SUSY contribution to the muon magnetic moment anomaly is $\lesssim 10 \times 10^{-10}$ (which is the current $2\sigma$ bound for the $\mu^+ - \mu^-$ data analysis of the SM contribution\[7, 8\]), then the “focus point” region \[25\] of very large $m_0$ is also eliminated. The current bounds on $m_h$ and $b \to s\gamma$ further produce a lower bound on $m_{1/2}$ of $m_{1/2} \gtrsim (300 - 350)$ GeV over the full tanbeta domain. This implies that $m_{\tilde{\chi}_1^0} \gtrsim 120$ GeV, $M_{\tilde{\chi}^\pm_1} \gtrsim 240$ GeV and $m_\tilde{g} \gtrsim 750$.

Figure 10. Same as Fig. 8 for $\tan \beta = 55$. 

[Diagram showing the constraints on the SUSY parameter space for $\tan \beta = 55$.]
GeV. These mass bounds are larger than what exists now from accelerators. In general we find that dark matter direct detection neutralino -proton cross sections range from $\sim 5 \times 10^{-8}$ to $\sim 5 \times 10^{10}$, which are mostly within the range of sensitivity of future planned dark matter detectors. The $B_s \rightarrow \mu\mu$ decay will be accessible to the Tevatron over much of the parameter space for $\tan\beta > \sim 30$ with 15 fb$^{-1}$ of luminosity. The accessibility of the $\tilde{\tau}_1 - \tilde{\tau}_1$ and $\tilde{\chi}_1^0 - \tilde{\chi}_2^0$ SUSY signals for the NLC was examined.

To see how robust the above results are, we examined two types of non-universal soft breaking models: those with non-universal gaugino masses at the GUT scale, and those with non-universal Higgs masses. In general for these types of models, the co-annihilation effects still remain. However, an increased non-universal gluino mass can significantly reduce the lower bound constraints on $m_{1/2}$ arising from the $b \rightarrow s\gamma$ and $m_h$ constraints, making these constraints less significant. (The $a_\mu$ constraint is simultaneously somewhat strengthened). Non-universal Higgs soft breaking masses can also produce some striking effects. Thus an increase of the $H_2$ mass at the GUT scale increases the Higgsino part of the neutralino, which then increases the $\chi_1^0 - \chi_1^0 - Z$ coupling and opens a new $Z$ s-channel annihilation region at low $m_{1/2}$ and high $m_0$ with acceptable amount of relic dark matter. In this region the $\tilde{\chi}_1^0 - p$ detection cross section is a factor of 10 or more larger than that from the $\tilde{\tau}_1$ co–annihilation region, making it accessible to the next round of dark matter detector experiments. However, SUSY signals in such regions would be difficult to detect for a 500 GeV NLC.
Figure 12. Allowed region in the $m_0 - m_{1/2}$ plane for $\delta_2 = 1$, $\tan \beta = 40$, $A_0 = m_{1/2}$, $\mu > 0$. The lower narrow band is the usual stau co-annihilation band, and the upper band is due to the $Z$-channel annihilation.

Figure 13. Dark matter detection cross section for the two allowed regions in the $m_0 - m_{1/2}$ of Fig. 12. The upper dashed band is for the $Z$-channel annihilation, and the lower line is for the $\tilde{\tau}_1 - \tilde{\chi}_1^0$ co-annihilation channel. [12]
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