Dark matter in the finely tuned minimal supersymmetric standard model

Aaron Pierce[1,2]

[1]*Theory Group, Stanford Linear Accelerator Center, Menlo Park, CA 94025*
[2]*Institute for Theoretical Physics, Stanford University, Stanford, CA 94305*
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We explore dark matter in the finely-tuned minimal supersymmetric standard model (MSSM) recently proposed by Arkani-Hamed and Dimopoulos. Relative to the MSSM, there are fewer particles at freeze-out, so the calculation of the relic abundance simplifies. Similarly, the predictions for direct detection of the dark matter sharpen. There is a large region of mixed bino—higgsino dark matter where the lightest supersymmetric particle will be accessible at both the LHC and future direct detection experiments, allowing for a conclusive identification of the dark matter particle. Typical dark matter-nucleon cross sections are $10^{-45} - 10^{-44}$ cm^2. This model also possesses a novel region where the dark matter annihilates via an s-channel Higgs boson resonance.

I. INTRODUCTION

In the minimal supersymmetric standard model (MSSM) [1], new particles are placed at the weak scale to stabilize the Higgs boson mass hierarchy. This theory has two important successes: gauge coupling unification [2] and the presence of a natural dark matter candidate[1,3]. Both features arise from new particles at the weak scale. Once R-parity is imposed, the existence of dark matter and the unification of gauge couplings can be viewed as predictions of the theory.

Recently, Arkani-Hamed and Dimopoulos argued that in light of the cosmological constant problem, issues of naturalness should be treated delicately. The end result of this argument was a finely-tuned minimal supersymmetric standard model where the higgsinos and gauginos are kept light by chiral symmetries, while all scalars are ultraheavy [4]. While this model solves many of the problems associated with the MSSM, from the low-energy perspective the lightness of the standard model-like Higgs is accomplished via a fine-tuning. This scenario was recently christened "split supersymmetry" by Giudice and Romanino.

Since this model is unconcerned with softening the divergence in the Higgs boson mass, it seems at first unclear what masses to expect for the new fermions. Luckily, a hint is given by the existence of dark matter. A stable, weakly coupled particle gives a cosmologically interesting abundance only if its mass is at the weak scale [5]. After the gauginos have been placed at the weak scale to give the dark matter, gauge coupling unification becomes as a successful "prediction" of the theory. In split supersymmetry, dark matter provides the sole link between the masses of the new particles and the weak scale. Thus, understanding the dark matter has strong implications for both future collider searches and for direct dark matter detection experiments. We find that there is a large region of parameter space accessible to both future direct detection experiments and the Large Hadron Collider (LHC).

II. RELIC ABUNDANCE

At first, it might seem possible to compute the dark matter relic density in split supersymmetry by taking a MSSM relic abundance calculation [6], and simply eliminating all diagrams containing the (now decoupled) scalars. However, the situation is more subtle: there are several differences between the low-energy physics of split supersymmetry and the MSSM with the scalars eliminated. These should be accounted for in an accurate relic abundance calculation.

Perhaps the most salient differences between the MSSM and split supersymmetry are in the properties of the lightest Higgs boson. In the MSSM, the quartic coupling of the Higgs boson is related to the standard model gauge couplings: $\lambda = (g^2 + g'^2)/8$, leading to the tree level relation $m_h^2 = M_Z^2 \cos^2 2\beta$. In split supersymmetry, this relation exists only above the masses of the scalars, m_S. Below this scale, the quartic coupling flows away from its supersymmetric value. The result is that the Higgs boson may be as heavy as 170 GeV for large values of m_S [4,7]. Because of the large mass, the width of the Higgs will be substantially different. At 130 GeV, a standard model-like Higgs has a width of a few MeV; at 170 GeV, the width approaches 1 GeV. Even for $m_h > 130$ GeV, the Higgs boson decays dominantly to WW^*, a situation not normally found in the MSSM. For our relic density and direct detection calculations, we utilize a modified version of DarkSUSY [8]. DarkSUSY only incorporates two-body final states; it was necessary to change the package to take into account the process $\chi^0\chi^0 \to h \to WW^*$.

Another difference between split supersymmetry and the MSSM is in the couplings between the gauginos, higgsinos, and the Higgs boson:

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$$\mathcal{L} \ni \tilde{B}(\kappa_1' h^\dagger \tilde{H}_1 + \kappa_2' h \tilde{H}_2) + \tilde{W}^a(\kappa_1 h^\dagger \tau^a \tilde{H}_1 + \kappa_2 \tilde{H}_2 \tau^a h). \tag{1}$$

In the MSSM, these couplings are related by supersymmetry to the gauge couplings:

$$\kappa_1' = \sqrt{\frac{3}{10}} g_1 \sin\beta \qquad \kappa_2' = \sqrt{\frac{3}{10}} g_1 \cos\beta$$
$$\kappa_1 = \sqrt{2} g_2 \sin\beta \qquad \kappa_2 = \sqrt{2} g_2 \cos\beta.$$

In split supersymmetry, this relation only exists above the scale m_S. Below m_S, these couplings must be run down to their low-energy values, accomplished here by using the one-loop renormalization group equations of [7,9].

The couplings of Eq. (2) also feed into the off-diagonal entries of the chargino and neutralino mass matrices. They become:

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -\frac{\kappa_2' v}{\sqrt{2}} & \frac{\kappa_1' v}{\sqrt{2}} \\ 0 & M_2 & \frac{\kappa_2 v}{\sqrt{8}} & -\frac{\kappa_1 v}{\sqrt{8}} \\ -\frac{\kappa_2' v}{\sqrt{2}} & \frac{\kappa_2 v}{\sqrt{8}} & 0 & -\mu \\ \frac{\kappa_1' v}{\sqrt{2}} & -\frac{\kappa_1 v}{\sqrt{8}} & -\mu & 0 \end{pmatrix},$$
$$M_{\chi^\pm} = \begin{pmatrix} M_2 & \frac{v\kappa_1}{2} \\ \frac{v\kappa_2}{2} & \mu \end{pmatrix}, \tag{2}$$

with $v = 246$ GeV. Taking these modifications into account, it is possible to calculate the relic abundance of the dark matter.

A. Bino dark matter

The most interesting region for both colliders and direct detection involves a $\tilde{B}$-like LSP (lightest supersymmetric particle), where $M_1 < M_2, \mu$. Assuming universal boundary conditions for M_1 and M_2 at the high scale, we expect this condition to hold due to the renormalization group evolution.

In the MSSM, there are many ways in which the $\tilde{B}$'s may annihilate in the early universe. For example, there exist regions in the MSSM parameter space where the $\tilde{B}$ can coannihilate with a tau slepton or top squark. In split supersymmetry, however, the scalars are quite heavy and are absent at the time of freeze-out due to the Boltzmann suppression. Similarly, no "funnel" region exists where the LSP annihilates through the pseudoscalar Higgs boson. Also, there is no t-channel exchange of sleptons. In fact, in a theory where all scalars are decoupled, a pure bino is completely noninteracting. Therefore, in split supersymmetry, the only relevant interactions of a $\tilde{B}$-like LSP occur through the mixing of the $\tilde{B}$ with the $\tilde{H}$ and the $\tilde{W}$.

Figure 1 shows the points with the correct relic abundance in the μ-M_1 plane. We have used the post-WMAP (Wilkinson microwave anisotropy probe) 2σ allowed
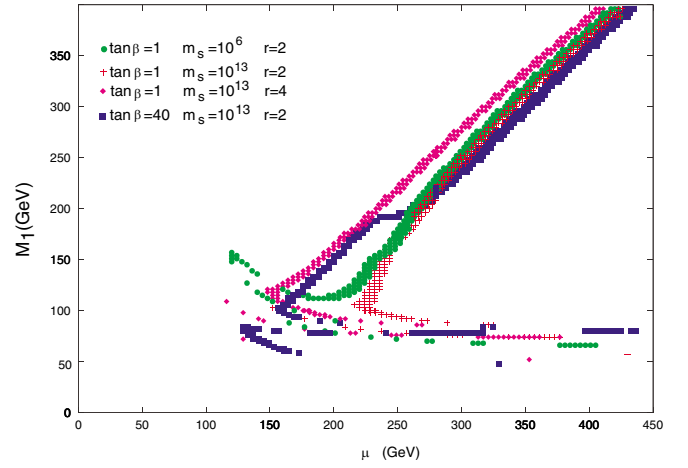

FIG. 1 (color online). Points in the $\mu - M_1$ plane that satisfy the relic abundance constraint from WMAP. The region at low M_1 extending to large μ is the Higgs resonance region; the dark matter can be very nearly bino in this region. The diagonal line represents a mixed bino-higgsino dark matter region. The allowed region is shown for various values of $\tan\beta$, scalars masses, m_S, and $r \equiv M_2/M_1$. The top-quark mass is set to 178 GeV.

region for the dark matter, $0.094 < \Omega_{DM} h^2 < 0.129$ [10]. We plot points satisfying the relic density constraint, starting with a base case of $\tan\beta = 1$ (at the high scale), $m_S = 10^{13}$ GeV, and imposing the phenomenological relation $r \equiv M_2/M_1 = 2$ (at low energies).[1] To get a feeling of how the allowed region depends on these parameters, we show the allowed region when the scale of supersymmetry breaking is changed to $m_S = 10^6$ GeV, when $\tan\beta$ is changed to 40 and when $r = 4$. In the MSSM, $\tan\beta = 1$ is not allowed due to the LEP limit on the Higgs boson mass, here there is no such difficulty. For much lower values, a Landau pole for the top Yukawa coupling would be encountered not far above the scale m_S.

There are several distinct regions visible in the plot. First, consider the diagonal stripe cutting across the parameter space. This is a region of mixed bino-higgsino dark matter. Writing

$$\chi_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_u + N_{14}\tilde{H}_d, \tag{3}$$

we can define the higgsino fraction $h_f \equiv |N_{13}|^2 + |N_{14}|^2$. Near the base of this stripe of parameter space, $h_f \sim 0.2$. In this region, the relic abundance is largely controlled by the process $\chi\chi \to W^+ W^-$. This process receives contributions from t-channel exchange of charginos, s-channel

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[1] It is natural to impose a unified relation on the gaugino masses. Where this condition is imposed is model dependent. One possibility is the grand unified scale. Another arises in the case of the Scherk-Schwarz breaking model of [4], where the unified condition is imposed at the scale $1/R$. Given this model dependence, we choose to impose a phenomenological relation at the low scale.

exchange of a Z boson, and s-channel exchange of the Higgs boson. This region is nearly a straight line in the $\mu - M_1$ plane because all the above diagrams depend on h_f, which in turn can be written as a function of the slope M_1/μ. The top-quark threshold at $M_1 \sim 175$ GeV is visible. Note, for $r = 4$ the stripe is shifted somewhat, the larger M_2 affects the chargino masses, and thus the annihilation rate. This stripe of parameter space provides a region where the both the LSP and charginos can be visible at the LHC. This stripe does connect continuously with an experimentally difficult region of purely higgsino dark matter at high mass, which we will discuss momentarily. The region above and to the left of this stripe the LSP does not provide all of the dark matter; another component would be needed to make up the remainder.

The horizontal bands at $M_1 \sim 80$ GeV represent a region where the LSP annihilates resonantly via a Higgs boson in the s-channel. This region has special importance in split supersymmetry. In the usual MSSM, the Higgs boson has a mass less than 130 GeV, and a tiny width, making resonant annihilation unlikely. In split supersymmetry, the Higgs boson can be much heavier, ~ 160 GeV, where the width approaches a GeV. If the LSP has mass, $m_\chi \sim 0.5 m_h$, annihilation through the Higgs pole can be very efficient, and the composition of the dark matter can be very binolike. In the resonance region, the relevant couplings for annihilation are κ'_1, κ'_2, which must be run down from their supersymmetric values at m_S. Looking at Fig. 1, the exact location of this region in the $M_1 - \mu$ varies. Comparing the region for $m_S = 10^{13}$ GeV, $\tan\beta = 1$, $r = 2$ to $m_S = 10^{13}$ GeV, $\tan\beta = 40$, $r = 2$, and $m_S = 10^{13}$ GeV, $\tan\beta = 1$, $r = 2$ to $m_S = 10^6$ GeV, $\tan\beta = 1$, $r = 2$ a dependence on both m_S and $\tan\beta$ is visible. This is because these parameters affect the Higgs mass. In this region, the lightness of the LSP should allow it to be probed at the LHC.

The area near the intersection of the diagonal stripe and the horizontal band represents a particularly complicated region where many processes are at work contributing to the relic abundance. Here, for our choice of $r \equiv M_2/M_1 = 2$, it is possible to get dark matter that has a comparable fraction of wino, higgsino and bino. If r is increased, the wino fraction decreases. Furthermore, coannihilations can be in this region.

Finally, for the $m_S = 10^{13}$, $\tan\beta = 40$, $r = 2$ and $m_S = 10^{13}$, $\tan\beta = 40$, $r = 4$ regions, a few points are visible at $M_1 \sim 50$ GeV. There the Z-resonance becomes important. These points are not visible for the lower values of $\tan\beta$ or r because they are excluded by the chargino mass bound. This region should be easily accessible at colliders.

B. Higgsino and wino dark matter

In the case of purely Higgsino dark matter, constraints from LEP force the LSP to be heavy enough so that the coannihilation with charginos to $W^\pm$ bosons are allowed.

So, a light Higgsino annihilates away too efficiently to make up the dark matter. As the mass of the Higgsino is increased, the WW threshold is reached, and the problem worsens. Nevertheless, by making the Higgsino heavier, it is eventually possible to make up the observed dark matter, but this is always for $\mu > 1$ TeV, the exact value is sensitive to $\tan\beta$. In this case, it would be very challenging to observe the dark matter (or any signature of supersymmetry) at the LHC.

A similar situation exists for wino dark matter. It can (co)annihilate very efficiently to gauge boson(s), and only by making it heavy can the right relic abundance be achieved. To achieve the correct relic abundance, $M_2 \sim 2.4$ TeV, making this a difficult scenario for colliders indeed. While this scenario is unlikely to occur in a model with unified boundary conditions, $r < 1$ can occur when the gaugino masses are dominated by the anomaly mediated supersymmetry breaking (AMSB) contribution [11,12], a situation that is naturally realized if the hidden sector does not have a singlet. In AMSB, the masses of the gauginos are suppressed by a loop factor relative to the gravitino mass, $m_{3/2}$. Then the dark matter calculation above sets $m_{3/2} \sim 1000$ TeV. If the scalar masses are unsuppressed relative to this scale, they will heavy enough to satisfy constraints from dimension-5 proton decay, flavor changing neutral currents and electric dipole moments, making this a theoretically attractive, but experimentally difficult implementation of split supersymmetry[2].

III. DIRECT DETECTION

In the MSSM, it is somewhat complicated to discuss the prospects for direct detection. There are several intermediate particles that can contribute to the spin-independent cross section: the light Higgs boson, the heavy Higgs boson, and squarks. The frustrating possibility of a cancellation between various intermediate states exists; in principle, the cross section for direct detection can go nearly to zero[14]. In split supersymmetry, there is a single dominant diagram for direct detection: the exchange of the Higgs boson, utilizing the $\tilde{B} - \tilde{H} - h$ or $\tilde{W} - \tilde{H} - h$ vertices. These couplings provide a coherent contribution to the spin-independent scattering amplitude off nuclei.

We display the prospects for direct detection of binolike dark matter in split supersymmetry in Fig. 2. We

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[2]In Ref. [13], a similar construction was utilized, but it was assumed that the dark matter was generated nonthermally. This allowed the $\tilde{W}$'s to be lighter, with possible interesting collider phenomenology. However, this approach is at odds with our philosophy that the thermal abundance of the dark matter is what puts the fermions at the weak scale. Some discussion of the phenomenology of AMSB with unsuppressed scalar masses was also contained in the earlier [12].
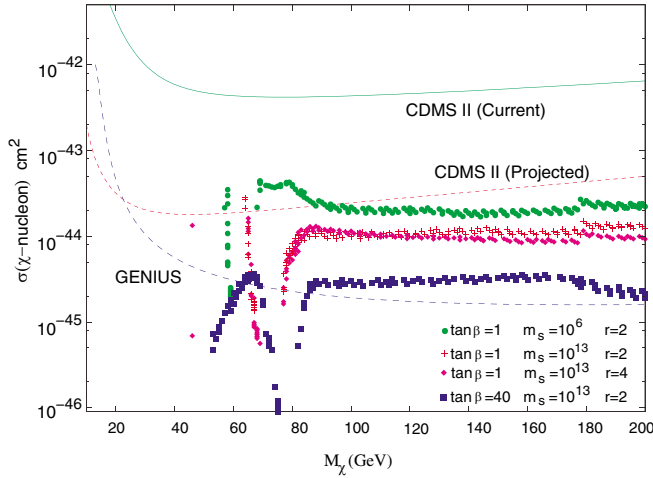
FIG. 2 (color online). The spin-independent LSP-nucleon scattering cross section for point agreeing with the WMAP relic density constraint. Curves are plotted for various values of m_S (the scale of the scalar masses), $\tan\beta$ (set at m_S), and $r \equiv M_2/M_1$. The flat regions for $m_\chi \gtrsim 80$ GeV correspond to mixed bino-higgsino dark matter. The sharp decrease at lower masses is due to resonant annihilation through the Higgs boson and Z-boson poles. Also shown are the current bound from the results of the CDMS at Soudan [16], the projected bounds from this experiment [17], and projected bounds from a representative next generation dark matter experiment, GENIUS [18].

show four sets of points corresponding to the models scanned in Fig. 1.

First we discuss some general features. In the binolike dark matter case, there is always a heavy higgsino component, particularly in the diagonal stripe of Fig. 1. There, the $\tilde{B} - \tilde{H}$ mixing selects a fixed value for the $\chi - \chi - h$ vertex. The diagonals in Fig. 1 correspond to the flat horizontal bands seen in Fig. 2 for each model above roughly $m_\chi \gtrsim 80$ GeV.

Changing m_S from 10^{13} GeV to 10^6 GeV causes an increase in the scattering cross section. This may largely be explained by the change in the Higgs boson mass, which increases as m_S increases:

$$\sigma_{\chi N} \propto \frac{1}{m_h^4}. \qquad (4)$$

For $m_S = 10^6$ GeV, the Higgs boson mass is roughly 140 GeV, while for $m_S = 10^{13}$ GeV, the Higgs boson mass is roughly 160 GeV. For all cases considered here the Higgs boson is heavier than in the MSSM; the result is a suppression in the detection rate. Yet the change in the Higgs boson mass does not explain the difference in cross section completely. Even after correcting for this factor, the direct detection rates for $m_S = 10^6$ GeV and $m_S = 10^{13}$ GeV still can differ by order 10%. This is because the κ' parameters, important for detection, run differently from the two m_S scales.

In Fig. 2, it can be seen that the rate for $\tan\beta = 40$ is suppressed relative to $\tan\beta = 1$ case. In the decoupling

limit ($\cos\alpha = \sin\beta$, $\sin\alpha = -\cos\beta$), the amplitude for scattering via the light Higgs boson in the MSSM is given by [6]

$$A_h \propto (g_2 N_{12} - g_Y N_{11})(N_{14}\sin\beta - N_{13}\cos\beta). \qquad (5)$$

In split supersymmetry, the gauge couplings (and β's) are replaced at low energies by κ parameters. However, since the κ's do not deviate drastically from the supersymmetric values, traditional MSSM formulas are still useful to gain intuition. It is instructive to examine the higgsino like limit, where [15]

$$\sigma_{\chi-\text{nucleon}} \propto \left(\frac{1 + \sin2\beta}{\mu - M_1}\right)^2 \qquad (6)$$

In this limit, we can see that the cross section can be enhanced by roughly a factor of 4 relative to the large $\tan\beta$ limit at $\tan\beta \approx 1$. This is in rough agreement with Fig. 2; there is some deviation due to the mixed $\tilde{B} - \tilde{H}$ nature of the LSP. We expect $\tan\beta = 1$ to give scattering cross sections near maximal for this model.

The precipitous drop in the cross section below 80 GeV is due to the presence of the Higgs resonance region. In the Higgs resonance region, the LSP can be very pure bino, which leads to a small LSP coupling to the Higgs boson. While the s-channel resonance compensates for this in the early universe, the resonance effect is not available in direct detector experiments. A second drop is visible for the lowest mass points on the the $\tan\beta = 40$, $m_S = 10^{13}$ GeV, $r = 2$, and $\tan\beta = 1$, $m_S = 10^{13}$ GeV, $r = 4$ curves. These are points where the Z-pole is important for determining the relic abundance.

The glitch in the curves at a LSP mass of $m_\chi \sim 175$ GeV is physical. As the top threshold opens up, the higgsino fraction, h_f, necessary to maintain the measured relic abundance changes. This, in turn, affects the direct detection rate.

Note that for the case where $r = 2$, $\tan\beta = 1$, and $m_S = 10^{13}$ GeV, there is a region near $m_\chi \sim 80$ GeV where the cross section increases somewhat. This region is due to the presence of dark matter that has a non-negligible wino fraction. In this case, the κ couplings, rather than the κ' couplings can enter. Unsurprisingly a similar region is not visible for the $r = 4$, $\tan\beta = 1$, $m_S = 10^{13}$ GeV. In this case, the wino fraction of the LSP is suppressed.

Cross sections can reach a few $\times 10^{-44}$ cm^2, a level that will be covered soon by direct search experiments such as the cryogenic dark matter search (CDMS) experiment in the Soudan mine (see Fig. 2) [16]. A planned upgrade (CDMS III) should reach a roughly a factor of 3 below the CDMS II projection [17]. Future planned experiments, such as GENIUS [18] could reach the 10^{-45} cm^2 level. This would allow coverage of much of the horizontal region in Fig. 2. Relocating a CDMS-like experiment to a site with even lower neutron background than the

Soudan mine could conceivably reach the 10^{-46} cm^2 level [19]. In this case, even parts of the resonance regions would be accessible.

For the case of very pure higgsino and very pure wino dark matter, the direct detection cross section is strongly suppressed. Since the dominant contribution to the spin-independent cross section comes from the $\tilde{H} - \tilde{B} - h$ and $\tilde{H} - \tilde{W} - h$ vertices, nonmixed dark matter is difficult for detection. Unfortunately, scattering cross sections can be astonishingly low: $\sigma_{\chi N} \lesssim 10^{-50}$ cm^2.

This study also has interesting implications for dark matter detection in the traditional MSSM with low-energy supersymmetry. Consider the generic case where the dark matter of the MSSM is mixed $\tilde{H} - \tilde{B}$, and resonances and coannihilations are unimportant for determining the relic abundance. Becuase the Higgs boson mass is heavier in split symmetry than in the MSSM, in the absence of accidental cancellations between detection diagrams, the horizontal band with $m_S = 10^{13}$, $\tan\beta = 40$ of Fig. 2 actually represents a very conservative *lower* bound on the detection cross section for MSSM dark matter. Thus, the cross section 10^{-45} cm^2 represents an exciting target for direct detection both for split supersymmetry and the usual MSSM.

IV. CONCLUSIONS

We have explored dark matter in split supersymmetry. It is exciting that there is a large region of binolike dark matter where the LSP is light. This could allow for the discovery of charginos and neutralinos at the LHC. There do also exist regions that are troublesome for colliders and direct detection: both pure higgsino and pure wino dark matter would be quite heavy ($\gtrsim 1$ TeV), and would have a very small scattering cross section off nuclei.

It would be interesting to explore the indirect detection of the dark matter in this model, especially in this troublesome region where direct detection becomes more difficult. In the pure wino case, it might be possible to observe the annihilation of the dark matter to $\gamma\gamma$ at a future experiment such as GLAST (gamma ray large area space telescope) [20].

Away from the Higgs resonance, the model can have mixed bino—higgsino dark matter which should be detectable at future direct detection experiments. It is especially encouraging that a region exists where the dark matter could be observed at both the LHC and direct detection experiments. This would allow for a conclusive demonstration that the particle seen at accelerator is in fact responsible for the dark matter.

Note added—While this work was being completed, [9] appeared, which has some overlap. It does not discuss the Higgs resonance region.

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