Implications of Supersymmetry Breaking with a Little Hierarchy between Gauginos and Scalars

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Abstract

From a theoretical point of view it is not hard to imagine gaugino masses being much lighter than scalar masses. The dominant contributions to gaugino masses are then their anomaly-mediated values. Given current lower bounds on gauginos, which are near the $W$ mass scale, considering a little hierarchy between weak-scale gauginos and much heavier scalars requires suspending normal intuition on finetuning and naturalness of the Higgs potential. Nevertheless, tantalizing perks come from the hypothesis: lessened flavor and CP violation problems, more compatibility with gauge coupling unification and third generation Yukawa unification, suppressed dimension-five proton decay operators, and no problems satisfying the current Higgs mass constraint for any value of $\tan \beta$ consistent with the top and bottom Yukawa couplings remaining finite up to the grand unified scale. The Tevatron has little chance of finding any evidence of this theory given current constraints. The LHC does well looking for pair production of gluinos which three-body decay into potentially spectacular final states. Dark matter relic abundance can be cosmologically interesting, but table-top experiments will not see LSPs scattering off nucleons. On the other hand, experiments looking for monochromatic photons from LSP annihilations in the galactic halo may find them.
1 Introduction

Of the various motivations for supersymmetry, perhaps none is more powerful than its ability to stabilize disparate scales in a natural way. Unfortunately, the supersymmetric cure to the quadratic-sensitivity malady has introduced several iatrogenic illnesses. Results from flavor changing neutral current experiments ($K - \bar{K}$ mixing, $\mu \rightarrow e\gamma$, etc.), CP violation experiments (e.g., electric dipole moments of the neutron and electron), and Higgs mass searches ($m_h > 114$ GeV at 95% C.L.) all struggle to be consistent with low-scale supersymmetry. One must make additional assumptions about the superpartner spectrum, such as the squarks must be degenerate and CP phases of superpartner parameters ($\mu$, gaugino masses, $A$-terms) must be nearly zero. Proton decay is another problem. Proposed solutions based on natural R-parity arguments mollify dimension-four concerns, but dimension-five operators still frighten the grand unified theory enthusiasts.

It is often assumed that superpartner masses need to be less than about 1 TeV if the weak scale is not fine-tuned. The problem is that no one has a rigorous and defensible definition for “about”. If superpartner masses are at $10^8$ TeV most would agree that supersymmetry would have little to do with stabilizing the weak scale to the quadratic divergences of the Standard Model (SM) effective theory. But what about 3 TeV or 48 TeV? In the Yukawa coupling sector we have an apparent tuning of $y_e/y_t = m_e/m_t \simeq 3 \times 10^{-6}$. If $\tilde{m} \simeq 150$ TeV we have a similar apparent finetuning in the electroweak sector of $v^2/\tilde{m}^2 \simeq y_e/y_t$. This is not a complete argument, but rather a meek invitation to be less restrictive in thinking about what is finetuned since an apparent finetuning might not be a real finetuning once we learn more about the origin of Yukawa couplings and superpartner masses.

The primary phenomenological motivation for considering a trans-TeV superpartner spectrum is that it automatically solves most of the above-mentioned illnesses of supersymmetry. Several approaches along these lines have been presented in the literature, with heavy emphasis on naturalness arguments. Most emphasize heavy first two generation scalars [1]-[4], while others lift all three generation scalars [5].
In any case, electric dipole moments of the neutron and electron are suppressed to well below experimental limits with trans-TeV squarks and pseudo-scalar Higgs. Kaon physics and B physics are identical to the Standard Model within current experimental sensitivities if the squarks are sufficiently massive — tens of TeV for kaon physics, less for B physics.

Another soothing effect of the little hierarchy of scalars to gauginos is the suppression of proton decay in supersymmetric grand unified theories. As the squark masses increase, the troubling dimension-five proton decay operators are suppressed and proton decay is much less of a concern [6]. In ordinary supergravity models with a Bino lightest supersymmetric particle (LSP), the relic abundance increases to unacceptable levels in much of parameter space when the scalar masses are increased. This is because the Bino annihilates most efficiently through $t$-channel sleptons, but when those masses are too high the annihilation efficiency drops and the relic abundance climbs very high such that the universe is matter dominated too early. We will see shortly that the supersymmetry spectrum discussed in this letter gives the Wino the honor of being the LSP. The Wino LSP annihilates very efficiently through ordinary gauge bosons and so the masses of the scalars are mostly irrelevant to dark matter issues. More will be said about the dark matter situation in a subsequent section.

Yet another soothing effect of heavy scalars is the compatibility with the Higgs boson mass constraint. If all scalar superpartner masses are above 5 TeV the lightest Higgs mass boson is generally always above 114 GeV for all values of $\tan \beta$ consistent with perturbative top and bottom Yukawa couplings up to the GUT scale. Thus, the interesting low-$\tan \beta$ quasi-infrared fixed point region close to $\tan \beta \sim 2$ can be reincarnated without worrying about the Higgs mass.

The primary theoretical motivation for considering a trans-TeV superpartner spectrum is the rather large hierarchy generated between superpartner scalars and gauginos when there is no singlet to feel and transmit supersymmetry breaking. Supersymmetry breaking can be parametrized by a chiral supermultiplet $S = S + \sqrt{2}\psi\theta + F_S\theta^2$ whose non-zero $F_S$ component is the source of supersymmetry breaking.
Gaugino masses are generated via

\[
\int d^2 \theta \frac{S}{M_{Pl}} \mathcal{W} \mathcal{W} \sim \frac{m_{3/2}}{2} \lambda \lambda \tag{1}
\]

where \( m_{3/2} = \langle F_S \rangle / M_{Pl} \). The scalar masses are generated by

\[
\int d^2 \theta d^2 \bar{\theta} \frac{S^\dagger S}{M_{Pl}^2} \Phi_i^\dagger \Phi_i \rightarrow m_i^2 \phi_i^* \phi_i. \tag{2}
\]

If \( S \) is charged (i.e., not a singlet), eq. \( 2 \) is unaffected, whereas eq. \( 1 \) is no longer gauge invariant. (I am neglecting the grand unified theory possibility that a representation of \( S \) charged under the unified group paired with that of the Adj \( 2 \) contains a singlet \([7]\).) This is the generic expectation in dynamical supersymmetry breaking where supersymmetry breaking order parameters are charged and singlets are hard to come by \([8]\). In this case the leading-order contribution to the gaugino mass is the anomaly-mediated value \([9, 10]\),

\[
M_\lambda = \frac{\beta(g_\lambda)}{g_\lambda} m_{3/2} \tag{3}
\]

where \( \lambda \) labels the three SM gauge group. The gaugino masses are therefore one-loop suppressed compared to the persisting scalar mass result of eq. \( 2 \). Some phenomenological implications of this anomaly-mediated scenario with heavier squark masses was presented in \([10]\).

Charged supersymmetry breaking therefore creates a one-loop hierarchy between the gaugino masses (and \( A \) terms) and the scalar superpartners. With finetuning issues in play, attempts have been made to suppress the scalar masses via a specialized Kähler potential of the no-scale variety. Brane separations in extra dimensions was one hope for this scenario \([9]\), but it looks less likely when more complete models are constructed \([11]\). String theory might provide other ways to suppress the scalar mass below \( m_{3/2} \) \([12]\). Although ideas along these lines might work out, the phenomenology presented here is of the simplest version of the model where scalar masses are near the gravitino mass.
2 Superpartner Spectrum

The numerical values of the light gaugino spectrum are

\[ M_1 \simeq m_{3/2}/120 \]  \hspace{1cm} (4)
\[ M_2 \simeq m_{3/2}/360 \]  \hspace{1cm} (5)
\[ M_3 \simeq m_{3/2}/45. \]  \hspace{1cm} (6)

As discussed above, the heavy superpartner spectrum of squark, slepton and sneutrino masses \( \tilde{m}_i \) should have masses within factors of \( \mathcal{O}(1) \) near the gravitino mass \( m_{3/2} \),

\[ \tilde{m}_i \sim m_{3/2} \text{ (scalar masses)} \]  \hspace{1cm} (7)

unless there is a suppression from a special Kähler potential.

In minimal supergravity the region \( m_0 \gg m_{1/2} \) is the closest match to the spectrum outlined above. It is well-known that radiative electroweak symmetry breaking does not work well in this region. The origin of the problem is universal soft masses. When the Higgs and top squark masses are all the same at the high scale, one needs a significant \( m_{1/2} \) to feed into the top squark mass to make it much heavier than the Higgs soft masses at the low scale. This drives \( m_{H_u}^2 \) negative from loop effects, which enables the theory to satisfy the radiative electroweak symmetry breaking constraint equation,

\[ \frac{1}{2} m_Z^2 + \mu^2 = \frac{m_{H_u}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} \]  \hspace{1cm} (8)

If \( m_0 \gg m_{1/2} \) one finds that \( m_{1/2} \) effects are insignificant for the top squark, and loop effects are not big enough to drive electroweak symmetry breaking.

However, universality is not needed in any way for the heavy scalar spectrum of supersymmetry considered here, and one can readily identify generic properties of the superpartner spectrum that would give radiative electroweak symmetry breaking. At the high scale, if the soft masses satisfy,

\[ m_{H_u}^2 < m_{H_d}^2 < m_{\tilde{t}}^2, \]  \hspace{1cm} (9)
electroweak symmetry breaking normally will develop — this ordering of masses makes it easier to satisfy eq. 8.

The only problem left to have a full understanding of electroweak symmetry breaking is the origin of the $\mu$ term. Here, I offer no special insights into this recurring problem in supersymmetric theories; however, there are many ideas one can contemplate to explain the origin of the $\mu$ term in this context [10]. To be conservative in the subsequent phenomenology discussion, I will assume that $\mu \sim \tilde{m}_i$. If $\mu \sim m_Z$, additional higgsino superpartner states may be accessible, and detectability would be enhanced in the discussion that follows.

3 Collider Searches

For colliders, the most important implication is that gauginos are the only superpartners accessible. The neutral Wino $\tilde{W}^0$ is the lightest supersymmetric partner (LSP), and its charged gauge partner $\tilde{W}^\pm$ is very close by in mass. The mass splitting in the limit of very massive $\mu$ term is

$$m_{\pi^\pm} < m_{\tilde{W}^\pm} - m_{\tilde{W}^0} < 165 \text{ MeV}$$

(10)
as long as $m_{\tilde{W}} > 80 \text{ GeV}$. This is the maximally most challenging mass splitting for experiment because it is too large for $\tilde{W}^\pm$ to be long-lived, which would generate a spectacular signature of a long, rigid charged track decaying into a curling-up pion, and it is too small to yield energetic and triggerable decay products $X$ in $\tilde{W}^\pm \rightarrow \tilde{W}^0 + X$ decays.

Analysis have been done at LEP [13], and the result is that $m_{\tilde{W}^\pm} > 88 \text{ GeV}$. Searches at the Tevatron are more difficult and focus on the production of $\tilde{W}^+\tilde{W}^- + \text{jet}$. If one can trigger on a jet in the events where its transverse energy is high enough and then at the analysis stage look for curled-track soft pions in the saved events, there is some hope of discovery. However, it is unlikely that sensitivities will exceed that of the LEP II results [14].

Analyses at the LHC should focus on gluino production. In minimal supergravity
Figure 1: Production cross-section of gluino pairs at the $\sqrt{s} = 14$ TeV LHC in the limit that all squarks are much heavier than the gluino. The final states associated with gluino pair production are at least four jets plus missing energy.

the primary source of jets plus missing transverse energy is gluino production in association with squarks. However, there are no accessible squarks here, and we therefore must ask how well gluino pair production alone can probe gluino masses.

Fig. 1 shows the expected production cross-section of gluino pairs at the 14 TeV LHC in the applicable limit of much heavier squark masses [15]. All events from $\tilde{g}\tilde{g}$ production will produce at least four jets plus missing energy. This is a spectacular signature in that draconian cuts on SM background can still allow passage of the majority of the signal. One LHC year at low luminosity is expected to be about 10 fb$^{-1}$. Accumulating 100 fb$^{-1}$ of data enables probes of the gluino up to an estimated mass scale of 2 TeV. Such a high gluino mass would correspond to a Wino mass of just over 700 GeV and scalar superpartner masses of nearly 100 TeV. Therefore, a 2 TeV gluino search is certainly more than impressive from a weak-scale naturalness point of view.

The decay branching fractions of the gluino are usually three body through virtual
squarks. Two-body loop decays $\tilde{g} \rightarrow g\chi_0^i$ are negligible in the limit that all squarks are equal in mass and the $\mu$ term is large compared to the gaugino masses. However, if the top squarks are split and more than a factor of two lighter than the other squarks one could get a sizeable $B(\tilde{g} \rightarrow g\chi_0^i)$ of several tens of percent. In all cases, the branching fractions are sensitive to the relative mass ordering of the squarks. For example, if the top squarks are lighter than other squarks, as would be generally expected through renormalization group running effects, one finds that gluino decays will produce a high-multiplicity of top quarks. This lends itself to discovery-friendly final states such as

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}W^0\bar{W}^0 \text{ and } t\bar{b}b\bar{b}W^-\bar{W}^-, \text{ etc.} \quad (11)$$

The $\bar{W}^-$ acts like a charged LSP in these events as it escapes all detection because its SM decay products are too soft. Both final states listed above come with plenty of missing energy for further discrimination from the Standard Model.

4 Dark Matter

In ordinary minimal supergravity the lightest superpartner is the bino, superpartner of the hypercharge gauge boson. The thermal relic abundance of this sparticle is more or less compatible with the universe’s cold dark matter needs in much of the parameter space [17]. The price one pays for this success is the gravitino and moduli problem. The gravitino, which is roughly the same mass as the LSP, decays during big bang nucleosynthesis if its mass is less than a few TeV. The gravitino and moduli must be inflated away and not regenerated too copiously during the reheat phase in this scenario.

However, in our situation with anomaly-mediated gaugino masses, the Wino is the LSP, which annihilates and coannihilates very efficiently through SM gauge bosons. The thermal relic abundance is [10]

$$\Omega_{\text{th}}h^2 \simeq 5 \times 10^{-4} \left( \frac{M_2}{100 \text{ GeV}} \right)^2 \quad (12)$$
and is cosmologically insignificant for weak-scale gauginos. However, if the Wino LSP mass is above about 2.5 TeV one finds that the thermal relic abundance is unacceptably high. If all notions of finetuning are rejected this would be perhaps the most important bound on the entire superpartner spectrum in this scenario.

In this little hierarchy of scalars to gauginos, the gravitino mass is necessarily in the tens of TeV region. Since it decays gravitationally, knowledge of its mass is all that is needed to compute the decay lifetime. The decays take place after the putative freeze-out time but before big bang nucleosynthesis. Besides being an interesting solution to the gravitino/moduli problem of weak-scale supersymmetry, it also generates a non-thermal gravitino and moduli decay source for relic LSPs [18], which can naturally account for all the cold dark matter.

Detecting Wino dark matter when squarks and the \( \mu \)-term are in the tens of TeV is not possible with table-top detectors of LSP-nucleon scattering. The coherent scattering cross-section falls like \( 1/\mu^2 \). In other words, a Higgsino component of the LSP is necessary to be sensitive to LSP-Nucleon interactions, and since the LSP is nearly pure Wino the higgsino component is not available for service. The spin-dependent contribution goes to zero as the \( \mu \) term and the sfermions are very heavy and so they also do not contribute to scattering. Therefore, the dark matter is invisible to table-top experiments.

However, Winos annihilate very efficiently and so one expects that all experiments looking for LSP annihilations in the galactic halo would have an enhanced sensitivity. For example, annihilations that produce \( \bar{p} \)'s and \( e^+ \)'s are enhanced. The annihilation channel that perhaps gains the most if nature has Wino dark matter is the monochromatic two-photon final state [19, 20]. The wino annihilation rate is even higher than the higgsino rate, which is known to be large. The cross-section for Winos annihilating into two photons [21] is a fairly constant value

\[
2\sigma v(\gamma\gamma) = (3 - 5) \times 10^{-27} \text{ cm}^3 \text{s}^{-1}
\]

for \( m_{\tilde{W}} = 0.1 \text{ TeV} - 1 \text{ TeV} \).

The virialized dark matter is moving at non-relativistic speeds of only a few
hundred kilometers per second, and so the photons that result from this annihilation are monochromatic with energy \( E_\gamma = m_{\tilde{W}_0} \). Under some astrophysical models developed independently of dark-matter detection prospecting, the combination of GLAST and next generation Cerenkov detectors may be able to see a signal for cross-sections above \( 3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \) for all dark matter masses between 100 GeV and 1 TeV \[20\]. This bodes well for detecting Wino LSPs. Another photon line from annihilations into \( Z\gamma \) might also be detectable at the energy

\[
E_\gamma = m_{\tilde{W}_0} \left( 1 - \frac{m_Z^2}{4m_{\tilde{W}_0}^2} \right) \quad \text{(from } \tilde{W}^0\tilde{W}^0 \rightarrow Z\gamma). \quad (14)
\]

Detecting a monochromatic photon line at the mass of the LSP would be a tremendous aid to our understanding of what is happening at the LHC. In some circumstances at the LHC, mass differences of sparticles can be measured to sub-GeV precision \[22\]. However, measuring the overall mass of a sparticle is difficult. A monochromatic photon line from LSP annihilations in the galactic halo would not only announce the the discovery of dark matter, an important qualitative result, but it would also give us a very valuable number otherwise difficult to obtain: the mass of the LSP.

5 Conclusions

There are other theoretical and phenomenological implications of a little hierarchy between the gauginos and scalars. For example, recently it has been understood that \( b-\tau-t \) unification works well for very large values of \( \tan \beta \simeq 50 \) but small finite \( b \)-quark mass corrections \[23\]. This can be obtained naturally, from the Yukawa unification point of view, if scalar superpartners are very heavy. Furthermore, gauge coupling unification in the supersymmetric standard model is more exacting at the high-scale (i.e., less high-scale slope needed) when the superpartners are in the multi-TeV region \[24\], although when supersymmetry gets too high (hundreds of TeV and above) the compatibility with gauge coupling unification fades.

The unification successes of supersymmetry, both gauge and Yukawa unification,
are not diminished when the scalars are very heavy. We have also seen that supersymmetric dark matter considerations do not cast dispersions on the idea either. Only the naturalness of the electroweak symmetry breaking potential apparently weakens with the increased scalar masses considered here. Interestingly, this aspect of supersymmetry is the least quantifiable success of supersymmetry, and it may be that data will end up adjusting what we presume as natural.

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