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Phenomenological Implications of Low Energy Supersymmetry Breaking

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The experimental signatures for low energy supersymmetry breaking are presented. The lightest standard model superpartner is unstable and decays to its partner plus a Goldstino, G. For a supersymmetry breaking scale below a few 1000 TeV this decay can take place within a detector, leading to very distinctive signatures. If a neutralino is the lightest standard model superpartner it decays by $\chi_1^0 \to \gamma + G$, and if kinematically accessible by $\chi_1^0 \to (Z^0, h^0, H^0, A^0) + G$. These decays can give rise to displaced vertices. Alternately, if a slepton is the lightest standard model superpartner it decays by $\tilde{l} \to l + G$. This can be seen as a greater than minimum ionizing charged particle track, possibly with a kink to a minimum ionizing track.

1. Introduction

If nature is supersymmetric, one of the most interesting questions to address experimentally is the scale and mechanism of supersymmetry breaking. Most phenomenological studies of supersymmetric signals at high energy colliders implicitly assume that the messengers of supersymmetry breaking are gravitational strength interactions. The supersymmetry breaking scale in some hidden sector is then necessarily of order 10^{11} GeV. If R-parity is conserved the lightest standard model superpartner is the lightest supersymmetric particle (LSP) and is stable. If the LSP is electrically neutral, it escapes a detector leading to the well known signal for supersymmetry of missing energy. It is possible however that the messenger scale for transmitting supersymmetry breaking to the visible sector is anywhere between the Planck scale and just above the electro-weak scale [1,2]. In this case the gravitino is the LSP, and the lightest standard model superpartner is the next to lightest supersymmetric particle (NLSP). The lightest standard model superpartner is unstable and decays to its partner plus the Goldstino component of the gravitino [3]. For supersymmetry breaking scales below a few 1000 TeV this decay to the Goldstino can take place within a detector. This leads to very distinctive features for low scale supersymmetry breaking, including displaced photons, displaced charged particle or b-jet vertices, or heavy charged sleptons possibly decaying to leptons within the detector [4]. In this note we describe some of the model independent experimental signatures of low scale supersymmetry

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breaking.

The role of the messenger sector is to couple the visible and supersymmetry breaking sectors. Integrating out the messenger sector gives rise to effective operators, which, in the presence of supersymmetry breaking, lead to soft supersymmetry breaking in the visible sector. If the messenger sector interactions are of gravitational strength, the soft terms in the visible sector are logarithmically sensitive to ultraviolet physics all the way to the Planck or compactification scale. In this case patterns within the soft terms might give an indirect window to Planck scale physics. However, the soft terms could then also be sensitive to some sector below the Planck scale which is responsible for the flavor structure of the Yukawa interactions. This generally leads to unacceptably large flavor changing neutral currents, although elaborate flavor symmetries can be imposed to limit this. In contrast, if the messenger scale is well below the scale at which the Yukawa hierarchies are generated, the soft terms can be insensitive to the flavor sector, and naturally small flavor changing neutral currents can result. The lack of flavor changing neutral currents is a significant advantage of low scale supersymmetry breaking.

In the next section the form the superpartner spectrum for the minimal model of gauge-mediated supersymmetry breaking is reviewed. In section three the model independent experimental signatures of supersymmetry breaking at a low scale are presented.

2. Superpartner Spectrum with Gauge-Mediated Supersymmetry Breaking

If supersymmetry is broken at a low scale it is in fact likely that the standard model gauge interactions play some role. This is because the standard model gauginos couple only through gauge interactions. If standard model Higgs scalars received soft masses from non-gauge interactions, the standard model gauginos would then be unacceptably lighter than the electro-weak scale.[2]

[2] The argument for light gauginos in the absence of gauge couplings within a low scale messenger sector only applies if the gauginos are elementary degrees of freedom in the ultraviolet, and would not apply if the gauginos where composite or magnetic at or below the messenger scale.

Particle	Mass (GeV)
$\tilde{Q}_L, \tilde{Q}_R$	870, 835
$\tilde{t}_1, \tilde{t}_2$	760, 860
$A^0, H^0, H^\pm$	515-525
$\chi_3^0, \chi_2^\pm, \chi_4^0$	415-440
$\tilde{l}_L$	270
$\chi_2^0, \chi_1^\pm$	175
$\tilde{l}_R$	140
h^0	105
χ_1^0	95
G	1.5×10^{-9}

Table 1
Typical spectrum with gauge-mediated supersymmetry breaking for $\tan\beta = 3$, and a messenger scale of 80 TeV.

The standard model gauge interactions act as messengers of supersymmetry breaking if fields within the supersymmetry breaking sector transform under the standard model gauge group. Integrating out these messenger sector fields then gives rise to standard model gaugino masses at one-loop, and scalar masses squared at two-loops [1,2,5]. The scalar and gaugino masses are then very generally of the same order and go roughly as their gauge couplings squared. The B-ino and right handed sleptons gain masses through $U(1)_Y$ interactions, and are therefore lightest. The W-ino's and left handed sleptons, transforming under $SU(2)_L$, are somewhat heavier. The strongly interacting squarks and gluino are significantly heavier than the electro-weak states.

The dimensionful parameters within the Higgs sector, $W = \mu H_u H_d$ and $V = m_{12}^2 H_u H_d + h.c.$, do not follow from the anzatz of gauge-mediated supersymmetry breaking, and require additional interactions which break $U(1)_{PQ}$ and $U(1)_{R-PQ}$ symmetries. At present there is not a good model which gives rise these Higgs sector masses without tuning parameters. The parameters μ and m_{12}^2 are therefore taken as free parameters in the minimal model, and can be eliminated in favor of

$\tan\beta$ and m_Z.

Electroweak symmetry breaking results from the negative one-loop correction to $m^2_{H_u}$ from stop-top loops due to the large top quark Yukawa coupling. Although this effect is formally three-loops, it is larger in magnitude than the electroweak contribution to $m^2_{H_u}$ due to the large squark masses. Upon imposing electro-weak symmetry breaking, μ is typically found to be in the range $\mu \sim (1-2)m_{\tilde{l}_L}$ (depending on $\tan\beta$ and the messenger scale). This leads to a lightest neutralino, χ_1^0, which is mostly B-ino, and a lightest chargino, $\chi_1^\pm$, which is mostly W-ino. A typical spectrum at the low scale for a messenger sector at 80 TeV transforming as $5+\bar{5}$ of $SU(5)$ is given in table 1.

These general patterns within the spectrum should be considered model-dependent features of the minimal model of gauge-mediated supersymmetry breaking. The signatures for decay of the NLSP to its partner plus the Goldstino discussed in the next section are however very model independent.

3. Detecting the Goldstino

The spontaneous breaking of global supersymmetry leads to the existence of a massless Goldstone fermion, the Goldstino. In local supersymmetry the Goldstino becomes the longitudinal component of the gravitino. For supersymmetry breaking scales in the range discussed below, the gravitino is essentially massless on the scale of accelerator experiments. The LSP is for all practical purposes the Goldstino, and the lightest standard model superpartner is the NLSP.

The lowest order couplings of the Goldstino are fixed by the supersymmetric Goldberger-Treiman low energy theorem to be given by [3]

$$\mathcal{L} = -\frac{1}{F} j^{\mu\alpha}\partial_\mu G_\alpha \ + \ h.c. \tag{1}$$

where $\sqrt{F}$ is the supersymmetry-breaking scale, $j^{\mu\alpha}$ is the supercurrent, and G_α is the spin $\frac{1}{2}$ Goldstino. Since the Goldstino acts like the supercharge, it transforms a superpartner into its partner. For $\sqrt{F}$ below a few 1000 TeV, such a decay of a superpartner to its partner plus the Goldstino can take place within a detector. Since the Goldstino couplings are suppressed compared to electroweak and strong interactions, decay to the Goldstino is only relevant for the lightest standard model superpartner (NLSP).

The production of pairs of supersymmetric particles at a high energy collider therefore takes place through standard model couplings (assuming R-parity conservation). The produced states cascade to pairs of NLSP's. The quasi-stable NLSP's eventually decay to their partners plus Goldstinos, which carry away missing energy. The specific signatures which arise from decay to the Goldstino depend crucially on the quantum numbers of the NLSP, as discussed in the following subsections.

Associated production of Goldstinos in particle collisions has been discussed in the past, but is completely irrelevant unless $\sqrt{F}$ almost coincides with the electro-weak scale.

3.1. Neutralino NLSP

It is possible that the lightest standard model superpartner is a neutralino, χ_1^0. It can decay through the gaugino components by $\chi_1^0 \to \gamma + G$ and $\chi_1^0 \to Z^0 + G$, and through the Higgsino components by $\chi_1^0 \to h^0 + G$, $\chi_1^0 \to H^0 + G$, or $\chi_1^0 \to A^0 + G$ if kinematically accessible. These decays lead to very distinctive features if prompt on the scale of a detector.

If χ_1^0 is mostly gaugino, as in the example given in the previous section, it decays predominantly by $\chi_1^0 \to \gamma + G$. At an e^+e^- collider the signature would be $e^+e^- \to \gamma\gamma + \not{E}$. The standard model backgrounds are easily manageable for this signal [4,6]. Since χ_1^0 is a Majorana particle, it can decay to both Goldstino helicities, giving an isotropic decay in the rest frame. The lab photon energy distribution is therefore flat and bounded by $\frac{1}{4}\sqrt{s}(1-\beta) \le E_\gamma \le \frac{1}{4}\sqrt{s}(1+\beta)$, where β is the χ_1^0 lab frame velocity. The end points of the photon spectrum give an important test that the final state particles carrying the missing energy are essentially massless.

At a hadron collider mostly gaugino $\chi_1^0\chi_1^0$ production is suppressed by small couplings and large squark mass. Production of $\chi_2^0\chi_1^\pm$, $\chi_1^+\chi_1^-$, and $\tilde{l}_R^+\tilde{l}_R^-$ is however not suppressed. Cascade decays then lead to the final states $WZ\gamma\gamma + \not{E}_T$ or $Wl^+l^- + \not{E}_T$, $WW\gamma\gamma + \not{E}_T$, and $l^+l^-\gamma\gamma + \not{E}_T$, all at comparable rates [7]. For $m_{\chi_1^0} \simeq 100$ GeV the total cross section in all such channels at the Tevatron can be up to 70 fb, and could therefore be seen in current data. The existence of two hard γ's in such events gives a distinctive signature for low scale supersymmetry breaking. In addition, the backgrounds are much smaller than for standard supersymmetric signals [4,7,8], with misidentifications probably being the largest contamination of the signal. If the χ_1^0 decay length is long enough, timing information can also be used to isolate the signal.

If such signatures were observed experimentally, one of the most important challenges would be to measure the distribution of finite path lengths for the decaying χ_1^0's, thereby giving a direct measurement of the supersymmetry breaking scale. For $\sqrt{F}$ between roughly 100-1000 TeV the decay length is between 100 μm and a few m. In the case of $\chi_1^0 \to \gamma + G$, future detectors will be able resolve displaced γ tracks at the level of a few cm. Alternately, the rarer decay mode $\chi_1^0 \to Z^0 + G$ gives rise to displaced charged particle vertices, which can be measured down to the 100 μm level.

If χ_1^0 is mostly Higgsino, it decays (in the decoupling limit) predominantly by $\chi_1^0 \to h^0 + G$. In the mostly Higgsino region of parameter space the states χ_1^0, χ_1^+, and χ_2^0, χ_1^- form approximate $SU(2)_L$ doublets with splittings much smaller than the overall mass scale. At both e^+e^- and hadron colliders the signatures are therefore $h^0h^0X + \not{E}_T$ with $h^0 \to b\bar{b}$, where X represents off-shell W^* and Z^* electro-weak cascades of the heavier Higgsino states to the lightest one. The existence of 4 b-jets which reconstruct m_{h^0} in pairs, along with missing energy is therefore also a distinctive feature of low scale supersymmetry breaking. In this case, displaced b-jet vertices could be measured down to the 100 μm level. Finally, if $m_{H^0}, m_{A^0} < m_{\chi_1^0}$ the decays $\chi_1^0 \to H^0 + G$, and $\chi_1^0 \to A^0 + G$, with H^0 and A^0 undergoing standard model like decays, would represent a gold-mine for Higgs physics.

3.2. Slepton NLSP

With low scale supersymmetry breaking it is equally possible that the lightest standard model superpartner is a charged slepton. For example, a gauge-mediated messenger sector with two generations of $5 + \bar{5}$ generally gives a right handed slepton as the NLSP. In this case it decays by $\tilde{l}_R \to l + G$. These decays also lead to very distinctive signatures.

At an e^+e^- collider the signature for slepton pair production with prompt decay to Goldstinos is $e^+e^- \to l^+l^- + \not{E}$. The standard model backgrounds are easily manageable for this signal. The decay leads to a flat lepton spectrum in the lab frame, with the end points giving an important test that the missing energy is carried by essentially massless particles.

At a hadron collider pair production of NLSP sleptons with prompt decay to Goldstinos also gives final states $l^+l^- + \not{E}_T$. This suffers from fairly large irreducible backgrounds, and does not represent a clean signature. However, production of heavier states which cascade to $\tilde{l}_R$ can give clean signatures with multiple leptons. For example, pair production of $\tilde{l}_L\tilde{l}_L$ followed by the cascade decays $\tilde{l}_L^{\pm} \to \tilde{l}_R^{+} l^- l^{\pm}$ (through on- or off-shell χ_i^0) gives final states $6l + \not{E}_T$. Such signatures do not suffer contamination by standard model backgrounds.

If the decay $\tilde{l} \to l + G$ takes place on the scale of a detector very distinctive charged particle tracks can arise. This is because heavy non-relativistic sleptons are more highly ionizing than ultra-relativistic charged particles. Decay over a finite distance can then be seen as a greater than minimum ionizing track with a kink to minimum ionizing track. Such kinks should be measurable down to the 100 μm level. If the slepton decay length is long enough, timing information can also be applied to isolate such events. Measurement of the decay length distribution would give a direct measure of the supersymmetry breaking scale.

Because of the larger Yukawa coupling, the $\tilde{\tau}_R$ can be lighter than $\tilde{\mu}_R$ and $\tilde{e}_R$ from renormalization group evolution. If $m_{\tilde{\tau}_R} + m_\tau + m_\mu < m_{\tilde{\mu}}$ the electro-weak decay $\tilde{\mu}_R^{\pm} \to \tilde{\tau}_R^{+}\tau^-\mu^{\pm}$, through the B-ino component of off-shell χ_i^0, can compete with the decay $\tilde{\mu} \to \mu + G$, and likewise for $\tilde{e}_R$. It is possible then that nearly all cascades lead to $\tilde{\tau}_R$ and that all the slepton signatures discussed above occur with τ's in the final state. Alternately, if $m_{\tilde{\tau}_R} + m_\tau + m_{\mu,e} > m_{\tilde{\mu},\tilde{e}}$, all the right handed sleptons are stable against three body electro-weak decays at lowest order, and the decay $\tilde{l}_R \to l + G$ can dominate. In this case the above signatures occur with equal rates for all three generations.

If the supersymmetry breaking scale is well above a few 1000 TeV, the decay $\tilde{l} \to l + G$ takes place well outside the detector. At both e^+e^- and hadron colliders the signature for supersymmetry would then be $\tilde{l}_R^+ \tilde{l}_R^- X$, i.e. heavy charged particle pair production without missing energy! This very non-standard signature should not be overlooked in the search for low scale supersymmetry breaking.

3.3. Model Independent Signatures

As discussed above, the quantum numbers and composition of the lightest standard model superpartner (NLSP) are model dependent. Although attention in the literature has been focused on the the mostly gaugino neutralino case, it is important to allow for all possibilities in the search for low scale supersymmetry breaking, and decays to the Goldstino. From the above discussion, the model independent signatures break up into two exclusive possibilities

1. Neutralino NLSP
   - $\gamma\gamma X+ \not{E}_T$
   - $\gamma b b X+ \not{E}_T$
   - $b b b b X+ \not{E}_T$
2. Slepton NLSP
   - Multi-leptons + $\not{E}_T$, or
   - Heavy charged particle pairs

The precise form of X results from cascade decays and can yield interesting information about the superpartner spectrum and composition of low lying states. X often contains leptons, which helps to reduce standard model backgrounds.

4. Conclusions

If the messenger scale for supersymmetry breaking is not too far above the weak scale the existence of the essentially massless Goldstino can lead to very distinctive experimental signatures. For a neutralino NLSP final states with $\gamma\gamma$, γbb, or $bbbb$ and missing energy represent an important signature for decay to the Goldstino. For a slepton NLSP final states with multi-leptons and missing energy or heavy charged particles with kinks to minimum ionizing tracks can result from decay to the Goldstino. A measurement of the decay length distribution to the Goldstino would give a measurement of the supersymmetry breaking scale. Supersymmetry breaking at a low scale clearly provides many experimental challenges and opportunities.

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REFERENCES

1. M. Dine, W. Fischler, and M. Srednicki, Nucl. Phys. B **189** (1981) 575; S. Dimopoulos and S. Raby, Nucl. Phys. B **192** (1981) 353; M. Dine and W. Fischler, Phys. Lett. B **110** (1982) 227; M. Dine and M. Srednicki, Nucl. Phys. B **202** (1982) 238; L. Alvarez-Gaumé, M. Claudson, and M. Wise, Nucl. Phys. B **207** (1982) 96; C. Nappi and B. Ovrut, Phys. Lett. B **113** (1982) 175.
2. M. Dine and W. Fischler, Nucl. Phys. B **204** (1982) 346; S. Dimopoulos and S. Raby, Nucl. Phys. B **219** (1983) 479.
3. P. Fayet, Phys. Lett. B **70** (1977) 461; P. Fayet, Phys. Lett. B **84** (1979) 416; R. Casalbuoni, S. De Curtis, D. Dominici, F. Feruglio, and R. Gato, Phys. Lett. B **215** 313.
4. M. Dine, S. Dimopoulos, S. Raby, and S. Thomas, hep-ph/9601367, Phys. Rev. Lett. **76** (1996) 3484.
5. M. Dine, A.E. Nelson and Y. Shirman, Phys. Rev. D **51** (1995) 1362; M. Dine, A.E. Nelson, Y. Nir and Y. Shirman, Phys. Rev. D **53**

(1996) 2658.
6. D. Stump, M. Weist, and C. P. Yuan, hep-ph/9601362.
7. S. Dimopoulos, S. Thomas, and J. D. Wells, hep-ph/9604452, to appear in Phys. Rev. D.
8. S. Ambrosanio, G. Kane, G. Kribs, and S. Martin, hep-ph/9605398.