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Observable signals of gauge-mediated supersymmetry breaking

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Abstract. The observable consequences of gauge-mediated supersymmetry breaking (GMSB) are reviewed here. Implications of scenarios both with a neutralino and a slepton as the next lightest supersymmetric particle (NLSP) are surveyed in relation to hadronic and e^+e^- colliders. We also discuss the phenomenological consequences of the NLSP decaying slowly, giving rise to delayed events in the detectors.The importance of distinguishing signals of GMSB models from those of the commonly discussed supergravity-type theories is emphasized.

Keywords. Physics beyond the standard model; supersymmetry, colliders.

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1. Introduction

The search for supersymmetry (SUSY) [1] has become, argueably, the hottest pursuit for physics beyond the standard model (SM). The up-and-coming experimental programmes are accordingly investing a great deal of resources in devising SUSY search strategies.

It must be noted, however, that even if SUSY happens to be a truth of nature, its observable consequences cannot be independent of the theoretical model one has in mind. Therefore, it is always useful to introspect as to what are the model assumptions that have gone into the prediction of signals which are supposed to tell us whether SUSY is actually there or not. As far as the overwhelming majority are concerned, the following things are mostly taken for granted:

- The spectrum of superparticles that are phenomenologically relevant are the superpartners of all the particles occuring in the standard model (including, of course, two Higgs doublets).
- The processes that give rise to the signals in the laboratory are controlled by strong, weak and electromagnetic interactions, the role of gravity being insignificant in the whole business.
- Baryon (B) and lepton (L) numbers are conserved.

An immediate consequence of the above assumptions is that the lightest of the superparticles has to be stable in the distance scale of laboratory measurements. It is accordingly called the lightest supersymmetric particle (LSP), and is expected to be uncharged and non-strongly interacting on phenomenological grounds. In most scenarios, the lightest neutralino (a linear combination of the spin-$1/2$ superpartners of the photon, the Z and the two neutral scalars) is the LSP. It also follows that the production of any superparticle(s) in experiments should give rise to decay chains culminating in the LSP which escapes undeteced, carrying with itself a certain amount of missing energy and momentum. Since the current phenomenological limits favours an LSP with mass at least in tens of GeV's, it has become customary to speak of large missing energy (or transverse energy in a hadronic collider) together with jets and/or leptons as the patent signals of SUSY in the minimal framework.

Furthermore, the question as to how SUSY breaks is still unanswered, although everyone agrees that it has to be broken in order to be compatible with reality. The collective wisdom gained over decades of studies on possible breaking mechanisms is that it is easier to have a phenomenologically consistent SUSY model which is embedded within a theory with a larger symmetry, the latter being actually responsible for SUSY breaking, at an energy which is considerably higher than the electroweak scale. An eminently acceptable candidate for this is a scenario based on $N = 1$ supergravity (SUGRA), where SUSY breaking takes place in a 'hidden' sector (at a scale of about 10^{11} GeV) [2]. The hidden sector, consisting of supermassive objects, interacts with the observable sector only gravitationally, and therefore very weakly, thereby leaving as remnants SUSY breaking mass parameters in the range of 100 GeV–1 TeV.

The added advantage of a SUGRA-type scenario is that one has only two SUSY-breaking mass paramaters, m_0 (the universal scalar mass) and $\tilde{M}$ (the universal gaugino mass at the grand unification (GUT) scale), in addition to two soft-breaking terms A and B, corresponding to trilinear and bilinear scalar interactions. All the scalar and gaugino masses at low energy can be derived from these parameters, using the appropriate type of running as one comes down to the electroweak scale. In addition, one needs the parameter $\tan\beta$ (the ratio of the two Higgs vacuum expectation values) and the Higgsino mass parameter μ (which can also be fixed, upto a sign, from the condition of electroweak symmetry breaking). This causes an enormous simplification to the bare form of the minimal SUSY standard model (MSSM) where, with more than hundred free parameters, one is at a complete loss in any attempt to study the phenomenology. An additional artifact of SUGRA is the spin-$3/2$ gravitino ($\tilde{G}$) whose mass is of the same order as that of the other superparticles. The interactions of the gravitino with the other particles can be shown be too feeble to be of any phenomenological interest.

The question that can be asked now is, do the observable signals of SUSY change if one or more of the underlying assumptions mentioned above do not hold? For example, interesting possibilities open up if the LSP is not a stable particle, which can happen if

- B or L is violated, so that the LSP can decay into SM particles.
- The gravitino is very light, and the strength of its interaction with the superparticles (inversely proportional to the gravitino mass) is large enough for it to decay within the detector.

It is clear that in either of the cases the LSP cannot be invisible, and the signals are drastically different from the predictions of the minimal model. The first possibility listed above corresponds to R-parity breaking supersymmetry [3]. The second one is realized in models with gauge-mediated supersymmetry breaking (GMSB). The rest of our discussion is concerned with the observable consequences of the latter.

Conceived of more than a decade ago [4], GMSB gained popularity in recent times [5] when it was speculated that it could be one possible solution to the $ee\gamma\gamma$ event reported by the CDF group at Fermilab. Although this explanation subsequently fell into disfavour, the interest in GMSB still survives, because

- It is a theoretical scenario with an impressive predictability of low-energy parameters.
- It suggests a solution to the problem of flavour-changing neutral currents (FCNC) that still plagues SUGRA models.
- It is, in any case, an alternative answer to the still unsolved puzzle of SUSY breaking.

In § 2, we briefly outline the simplest version of a GMSB model. In §§ 3, 4 and 5, its signals in hadronic and e^+e^- colliders are reviewed for different types of particle spectra. We conclude in § 5.

2. The minimal GMSB model – An outline

As the name suggests, in GMSB models the information of SUSY breaking is conveyed to the observable sector through gauge interactions. This is done with the help of a messenger sector which is possessed with non-trivial quantum numbers with respect to the SM gauge group.

The simplest model [6] requires a messenger sector consisting of vector-like quark and lepton superfields which are coupled to an SM singlet superfield S, through a term in the superpotential of the form

$$W = \lambda S \overline{\Psi}\, \Psi \tag{1}$$

The fields Ψ and $\overline{\Psi}$ lie in a complete $5 + \overline{5}$ representation of $SU(5)$. This is a sufficient condition (though not a necessary one) to maintain gauge coupling unification.[1]

The scalar (S) and auxiliary (F_S) components of S acquire vacuum expectation values (vevs) through their interactions with the hidden sector where SUSY is broken dynamically. These vevs induce masses for the messenger fields and lift the mass-degeneracy between the messenger fermions and sfermions. The breakdown of SUSY is communicated to the visible world radiatively via the SM gauge interactions. The observable gauginos and scalars acquire masses in this way, at the one-loop and two-loop levels respectively.

The expressions for the masses of gauginos ($M_{1/2}$) and scalars (M_0) are

$$\tilde{M}_i(M) = N_m f_1\left(\frac{\Lambda}{M}\right)\frac{\alpha_i(M)}{4\pi}\Lambda, \tag{2}$$

$$M_0^2(M) = 2N_m f_2\left(\frac{\Lambda}{M}\right)\sum_{i=1}^{3} k_i C_i \left(\frac{\alpha_i(M)}{4\pi}\right)^2 \Lambda^2 \tag{3}$$

at the scale M, where $M = \lambda\langle S\rangle$ and $\Lambda = \langle F_S\rangle / \langle S\rangle$. M determines the overall scale of the messenger sector; Λ controls particle-sparticle splitting in that sector as well as sparticle

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[1] Actually, up to four generations of $5 + \overline{5}$ or one $5 + \overline{5}$ and one $10 + \overline{10}$ are allowed. Also, the messenger quark and lepton superfields can occur in representations of a larger gauge group like $SO(10)$.

masses in the observable sector. The messenger scale threshold functions are given by

$$f_1(x) = \frac{1+x}{x^2}\log(1+x) + (x \to -x) \tag{4}$$

$$f_2(x) = f_1(x) - \frac{2(1+x)}{x^2}\left[\mathrm{Li}_2\left(\frac{x}{1+x}\right) - \frac{1}{4}\mathrm{Li}_2\left(\frac{2x}{1+x}\right)\right] + (x \to -x). \tag{5}$$

In (3), $C_i = 0$ for all gauge singlets and is equal to $4/3, 3/4, (Y/2)^2$ for scalars belonging to the fundamental representations of $SU(3)$, $SU(2)$ and $U(1)$ respectively. $Y = 2(Q - T_3)$ is the usual weak hypercharge and $k_i = 1, 1, 5/3$ for these three groups (we do not use grand unification normalization for α_1). N_m is the number of messenger generations.

In obtaining the low-energy masses, one also has to take into account the contributions from the usual D-terms and the weak scale threshold corrections while evolving the sfermion masses from messenger scale (M) down to the electroweak scale [7]. In addition there are messenger scale threshold corrections which are model dependent, and are neglected in a simple-minded approach. Λ is the crucial parameter that controls the induced masses, the dependence on M being rather weak. It is also clear from above that the scalar masses generated at the messenger scale are flavour diagonal, since they are produced through gauge interactions only. This allows one to suppress FCNC quite successfully.

The soft-breaking parameters A and B have non-vanishing values at the messenger scale only at levels higher than two-loop. In fact, in the so-called 'minimal messenger models' [8], they are set exactly to zero at that scale, thereby enabling one to get rid of additional CP-violating phases. Thus the phenomenology of GMSB is essentially determined in terms of the parameters $\Lambda, x = \Lambda/M$, $\tan\beta$ (the ratio of the two Higgs vev's) and μ (the Higgsino mass parameter).

It is also evident that $M_{1/2} \sim N_m$ while $M_0 \sim \sqrt{N_m}$. Consequently, if there is a single messenger generation, the lightest neutralino often turns out to the lightest among the standard model superpartners. On the other hand, for $N_m = 3$ or 4, the lightest right-handed slepton (the lighter stau in case of large $\tan\beta$, in particular) is mostly the lightest.

However, the LSP in this scenario is the gravitino whose mass is given approximately by $M_{\tilde{G}} \sim F/M_P$ where M_P is the Planck mass and F is the largest F-term in the SUSY breaking sector. The relation bewteen F and F_S is model-dependent. In any case, the very fact that SUSY breaking takes place at a low-energy causes $M_{\tilde{G}}$ to be as small as a keV or less. Combining cosmological constraints and the collider limits on superparticle masses, it can be said (with a certain degree of model-dependence) that the favoured interval for $M_{\tilde{G}}$ is between 10^{-2} eV and a few keV's. The interaction of such a light gravitino with a particle-sparticle current can be strong enough to cause decay of, say, the lightest neutralino (slepton) into a gravitino and a photon(lepton) within the detector, giving the gravitino a distinctive role in collider phenomenology. The lightest neutralino or the slepton here becomes the next lightest supersymmetric particle (NLSP).

Let us end this section by observing a rather interesting complementarity between the SUGRA and GMSB scenarios. In the former, gravity is the prime messenger of SUSY breaking in the observable sector, but the observed signals have hardly anything to do with gravitino interactions. In the latter, SUSY breaking is brought about by non-gravitational (read gauge) interactions, whereas the gravitino plays a crucial role in experimental signals.

3. Signals in hadron colliders (neutralino NLSP)

In this section we discuss the case of a neutralino NLSP. We begin by assuming that the NLSP can decay into the gravitino within the detector. We shall come back to situations where it is not so.

When the energy scale is large compared to the gravitino mass, gravitino interactions can be approximated by those of the goldstino which forms the longitudinal components of the gravitino. Such an interaction can be written as

$$\mathcal{L} = -\frac{1}{F} J^{\mu} \partial_{\mu} \tilde{G}, \tag{6}$$

where J^{μ} is the supercurrent connecting the particle and sparticle fields, and F is the SUSY-breaking F-term.

Taking, as the simplest case, $N_m = 1$, and assuming that the lightest neutralino is the NLSP, equation (3.1) implies the decay channel

$$\chi_1^0 \longrightarrow \gamma \tilde{G} \tag{7}$$

for the NLSP. A relatively low scale (tens of TeV) of SUSY breaking in the GMSB scenario can thus enable the NLSP (and in the general, case, any superparticle through cascades) to be associated with a photon and missing transverse energy. The signal is thus completely different from that of a SUGRA scenario.

It should be mentioned that attempts were initially made [9] to explain the $ee\gamma\gamma + \not{E}_T$ event [10] found by the CDF collaboration some time ago in terms of GMSB, postulating that right-selectrons produced at the Tevatron were decaying into neutralino NLSP's. However, most of the GMSB parameter space for a neutralino NLSP corresponds to χ_1^0 being largely dominated by the Bino. Consequently, the NLSP cannot be pair-produced through s-channel, and t-channel production in $p\bar{p}$ annihilation is strongly suppressed by the extremely large squark masses in such models. Consequently, most of the NLSP's have to be produced through cascades, from, say, the lighter chargino and the second lightest neutralino which come in greater abundance. Such cascades in turn imply a large number of (m photons $+ n$ leptons $+\not{E}_T$) signals accompanying the $ee\gamma\gamma + \not{E}_T$ event [11]. The absence of such events makes GMSB a rather disfavoured explanation; in fact, the relevant region of the GMSB parameter space has been practically excluded by a recent limit given by the D0 collaboration, based on the channels mentioned above [12]. This limits excludes $m_{\chi_1^0} \leq 75\,\text{GeV}$ and $m_{\chi^+} \leq 150\,\text{GeV}$, χ^+ being the lighter chargino eigenstate.

As we have mentioned before, an analysis of the above type assumes that the NLSP decays within the detector. However, this depends on the value of F which therefore has to be recognised as a fundamental parameter in GMSB phenomenology. It is straightforward to see that for an NLSP of mass $100\,\text{GeV}$, $\sqrt{F} = 100\,\text{TeV}$ gives a decay length of about 1.5 cm for the NLSP, whereas the length increases to about 20 meters for $\sqrt{F} = 2000\,\text{TeV}$. Thus all the experimental searches and limits can explore F on the lower side. For large values of F, NLSP decays outside the detectors, thus making the signals similar to those of SUGRA models (unless, of course, one has a slepton NLSP which will give rise to a conspicuous charged track). Rather interesting possibilities follow for intermediate values of F, for which the NLSP may decay not within the electromagnetic calorimeter but, say, somewhere in the outer hadronic calorimeter, giving rise to 'delayed photon' events. It has been claimed that looking for the latter may considerably expand the $\Lambda - F$ parameter space that one can explore in a hadronic machine [13].

4. Signals in e^+e^- colliders (a neutralino NLSP)

In e^+e^- colliders, A neutralino NLSP has its most spectacular signal through the process

$$e^+e^- \longrightarrow \chi_0^1\chi_0^1 \longrightarrow \gamma\gamma + \not{E} \tag{8}$$

which manifests itself in acoplanar two-photon events with missing energy [14]. In addition, cascades from right-handed selectrons or the second lightest lightest neutralino, if they are kinematically allowed, are likely to provide signals of a rather clean nature. The LEP is an obvious place to look for such events if the GMSB spectrum is light enough.

Based on the runs at $\sqrt{s} = 161$ GeV and 172 GeV, the published bound on GMSB so far is $M_{\chi_0^1} \geq 71$ GeV [15], a limit closely comparable with the one obtained by the D0 collaboration. This analysis assumes the mass of the right selectron to be 1.5 times that of the NLSP; however, a calculation based on the detailed mass relationship yields very similar results. Also, decay of the NLSP within the detector is assumed. It can be estimated that the limit is valid for $\sqrt{F}$ within 600 GeV approximately.

With higher superparticle masses, a higher energy electron-positron collider is obviously necessary. As we shall see below, such a (linear) collider is also extremely suitable for eliminating the standard model backgrounds, and for effectively distinguishing between GMSB and SUGRA-type scenarios.

The standard model background to the two-photon signal mainly comes from $e^+e^- \longrightarrow \nu\bar{\nu}\gamma\gamma$. It should be noted that if the decay length for the lightest neutralino is greater than a few centimeters (which corresponds to $\sqrt{F}$ exceeding about 100 GeV), the decay gap is helpful in distinguishing the acoplanar photons in GMSB. In general, the backgrounds can be subtracted [16] using the following methods:

- A cut on $|M_{\text{inv}} \sim M_Z|$, (where $M_{\text{inv}} =$ missing invariant mass)
- Cuts on the polar angle/p_T of each photon.
- Study of the photon energy distributions
- The use of polarised electron beams.

The first selection criterion removes the neutrino pairs from a real Z. The angular and p_T cuts identify central events, which are what one expects when a massive neutralino decays into a massless photon. The potential backgrounds from double-radiative Bhaba scattering, with both the electron and the positron lost along the beam pipe, are also taken care of by these cuts [17]. The photon energy distribution in GMSB should show a maximum and a minimum, as opposed to the continuum for the SM background. And lastly, polarized electron beams are of great help since most of the standard model backgrounds are generated by left-handed electrons. This should be contrasted with GMSB where right selectrons are much lighter than left ones, as a result of which the t-channel diagrams with right selectrons give much larger contributions, making right-polarised electrons the obvious choice in searches for GMSB signals [16, 18]. The fact that electrons can be polarised up to 90 per cent in most projected high energy linear electron-positron colliders has, therefore, a very significant bearing on searches for scenarios like GMSB where the mass-spectrum is highly chirality-sensitive.

However, it is also important to find out whether similar signals can be faked by certain regions in the parameter space of a SUGRA theory. This is possible, for instance, in a situation where the second lightest neutralino χ_0^2 can be pair-produced, and χ_0^2 has a large branching ratio for the one-loop decay [19] into a photon and a χ_0^1, the latter being invisible. The circumstances under which this loop decay can dominate has been investigated in detail [20]. It is more or less clear that the tree-level decays of the second lightest neutralino can be suppressed both dynamically (i.e. with either χ_0^1 or χ_0^2 being Higgsino dominated) and kinematically (with their mass difference being less than 10 GeV or so). However, one obtains a substantial portion of the SUSY parameter space satisfying these requirements only when one is willing to relax the assumption of gaugino mass unification corresponding to the $SU(2)$ and $U(1)$ interactions. It has been found that over a large part of this region, the radiative neutralino decay signals can survive the cuts applied to eliminate the SM backgrounds and have rates comparable with those expected in GMSB.

It is perhaps desirable from the viewpoint of search strategies to take such phenomenological possibilities seriously, and devise ways of differentiating the two-photon signals of GMSB with those potentially coming from a neutralino LSP scenario [21]. The first possibility to think of is in terms of polarized beam studies again. Clearly, the signal for GMSB will have a larger cross-section with right-polarized electron beams. Therefore, if the signal rates are higher with left-handed beams, it will clearly rule out GMSB as a potential source. However, a detailed study reveals that although the signals from about 60% of the SUGRA parameter space can be distinguished in this manner, the rest of it still gives higher rates with right-polarized electron beams. This is because when gaugino mass unification is relaxed, it is conceivable to have situations corresponding to χ_0^2 having a large Bino-component while χ_0^1 is Higgsino-dominated. In such cases, a spectacular difference in the two types of signals can be observed if one considers the distribution in the combined energy of the two photons. In the GMSB case, with all four massless particles in the final state, the distribution shows a clear peak at half the centre-of-mass energy [21]. With a neutralino LSP (with a mass in tens of GeV), on the other hand, the peak is considerably below, making it possible to distinguish the two types of scenarios from each other if one has the requisite integrated luminosity.

While it has been widely known that a neutralino NLSP in a GMSB theory is dominated by the Bino and hence decays mainly into the $\gamma\tilde{G}$ channel, it is nevertheless possible to discern the trace of the other states in the neutralino as well. For example, an exhaustive analysis reveals that the branching ratio for the NLSP going into a Z and a gravitino can be as high as more than 20% [22]. It has been also shown in the above reference that in such cases, one can get interesting single photon events (SPE) through

$$e^+e^- \longrightarrow \chi_0^1\chi_0^1 \longrightarrow Z\gamma\tilde{G}\tilde{G} \tag{9}$$

followed by the Z decaying invisibly into a pair of neutrinos. The use of right-polarised electron beams can give a 5–10 σ effect over SM backgrounds, and the energy- and angular distributions of the photons are qualitatively different from what can be expected in a SUGRA framework. Since single photon events are in any case looked for in electron-positron annihilation experiments, the above facts may provide us with some guidelines in testing the composition of the NLSP, and in verifying the universal character of gravitino couplings to a supercurrent.

One remark may be in order before we end this section. Whenever one considers the signals of GMSB through any process involving the nth lightest neutralino, identical final states can be faked by cascades mediated by the $(n+1)$th lightest neutralino of a supergravity-type model. Fortunately, the latter are most of the time suppressed kinematically as well as from the standpoint of branching ratios.

5. Slepton NLSP

As we have already mentioned, for a large number (3 or 4) of messenger generations, the lightest right-handed slepton (with $U(1)$ interaction only) often turns out to be the NLSP. In addition, it can also happen in some regions of the parameter space with one generation, too, especially with a large value of $\tan\beta$ [23].

There can in general be two broad classifications of the slepton NLSP scenario:

(a) Small $\tan\beta$ region: In this case, normally the right-handed selectron is closely degenerate with the corresponding smuon and stau, such that each of them can decay only into a lepton and the gravitino. In such a situation, the three sleptons can be called co-NLSP's.

(b) Large $\tan\beta$ region: Here, due to the fact that left-right mixing in the charged lepton sector is driven by a term proportional to $\tan\beta$, the lighter stau mass eigenstate is considerably lighter than the right-selectron or smuon. It may be possible in such cases for the selectron or smuon to undergo three-body decays [24] into the lighter stau which, in turn, decays into a tau and the gravitino.

Considering case (b) first, it has been shown [25] that the multiplicity of taus in the final state make the signals easy to identify. This is especially true if one is also able to produce the lightest neutralino, causing the latter to decay into a stau and a tau.

The tracking down of selectron NLSP's is somewhat trickier. In the context of e^+e^- colliders, this can be appreciated from the fact that there is a huge WW background. This poses particular problems for LEP-2 where beam polarisation is not feasible. (Otherwise, right-polarised electron beams filter out the GMSB signals rather well). One way out is to consider the angular distribution of the electrons in the final state, where the electrons from the W-pair production show a distinct peaking behaviour in the direction of the initial electron beam due to helicity correlation in t-channel prodcution. In GMSB, the fact that the neutralino in the t-channel propagator is heavier than the selectron makes the s-channel contribution more significant, contrary to what happens in a SUGRA-type model. Thus the final state electron helicity is relatively uncorrelated with that of the initial electron, yielding a flat angular distribution [14]. This effect is more pronounced in case of smuons. Thus, at least for energies upto about 200 GeV, dimuons may well turn out to be better probes of GMSB than dielectrons.

There remains, however, the persistent question about how to distinguish GMSB from the signal of SUGRA-type scenarios, for which also pair-produced selectrons would lead to identical final states viz. $e^+e^- + \not{E}$. Again, the use of polarised beams may not be very effective unless one knows in which region of the parameter space one is. As a general guideline, it may be useful to look at the electron energy distributions (individual and combined) where the massless gravitinos make considerable differences from massive invisible neutralinos.

A rather clear distinction is offered if one goes to the $e\gamma$ mode of a high-energy linear collider [26]. There, once a selectron-neutralino pair is produced, the final states are completely different in the SUGRA case as compared to that in GMSB with a selectron NLSP. In the former, the selectron decays, and there is one electron with missing energy in the final state. For the latter, the selectron gives rise to an electron and a gravitino, but at the same time the (lightest) neutralino is liable to decay into an electron and a selectron, the end result being three electrons with missing energy. It has been shown in reference [26] that after one applies the necessary cuts to remove SM backgrounds, selectrons upto about 120 GeV can be effectively identified as coming from GMSB in the $e\gamma$ mode of a 500 GeV linear e^+e^- collider with right-polarised electron beams.

So far we have assumed that the slepton NLSP decays within a time scale that is prompt enough for the events to registered within the electromagnetic calorimeter (or the hadronic one in the case of a stau NLSP). Interesting effects can be envisioned if the NLSP decay is a slower process. Firstly, since they are charged, they will not be invisible, but can rather show up in the form of highly ionized tracks. Also, delayed decays of such sleptons may take them as far as the muon detectors, thereby causing an apparent excess of muonic events and a violation of lepton universality. The importance of looking for such event characteristics in constraining GMSB has been emphasized in recent times [27].

6. Conclusion

There is really not much of a conclusion to reach unless one discovers experimental signals of SUSY in any form whatsoever. Till that prospect comes true, there are two things to be kept in mind. First of all, if at all one observes such signals, it is imperative to find out what kind of SUSY it is that nature has chosen, and thus to devise experimental methods of contrasting the various SUSY-breaking scenarios. Secondly, so long as we don't have any experimental signature, and are on our way up in ruling out a SUSY spectrum, it is certainly not enough to confine ourselves to a simplified organising picture (like supergravity), for the very example of GMSB shows that the observed consequences of SUSY can be quite different. For an objective search programme, openness to all possibilities is therefore a desideratum.

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