Abstract

We investigate the split supersymmetry (SUSY) scenario recently proposed by Arkani-Hamed and Dimopoulos, where the scalars are heavy but the fermions are within the TeV range. We show that the sparticle spectrum in such a case crucially depends on the specific details of the mechanism underlying the SUSY breaking scheme, and the accelerator signals are also affected by it. In particular, we demonstrate in the context of a braneworld-inspired model, used as illustration in the original work, that a new fermion $\psi_X$, arising from the SUSY breaking sector, is shown to control low-energy phenomenology in several cases. Also, SUSY signals are characterised by the associated production of the light neutral Higgs. In an alternative scenario where the gauginos are assumed to propagate in the bulk, we find that gluinos can be heavy and short-lived, and the SUSY breaking scale can be free of cosmological constraints.
Most attempts at phenomenological modeling of a supersymmetric nature envision supersymmetry (SUSY) breaking at the energy scale of a TeV or below in the observable sector of elementary particles. This is motivated by an aspired solution to the naturalness problem. However, it has been recently argued [1] that SUSY may have nothing to do with the naturalness problem, although it may be the necessary ingredient of a fundamental theory of nature like string theory where SUSY is most often a necessary ingredient. Such an argument has its origin in the observation that a broken SUSY introduces a cosmological constant proportional to the fourth power of the SUSY breaking scale, thereby requiring fine-tuning of a much more severe degree than what is required to make the Higgs boson mass free of quadratic divergence. Appeal has therefore been made to the so-called ‘landscape’ scenario [2], where a large multitude of universes exist, corresponding to different vacua of string theory. It is thus statistically feasible [3] for us, it is argued, to live in a universe fine-tuned in the way we have it, thereby having both a small cosmological constant and an electroweak scale stabilised in the 100 GeV range.

A recently proposed SUSY scenario [1], inspired by such a philosophy, has postulated that the SUSY breaking scale may be as large as $10^{10} - 10^{13}$ GeV, having all scalar masses (excepting that of the light neutral Higgs) of such high values. However, it can have fermions (gauginos/Higgsinos) with masses within the TeV range. While the heavy scalars provide a natural suppression of flavour-changing neutral currents, the light fermions can (a) present an appropriate cold dark matter candidate in the form of the lightest SUSY particle (LSP), and (b) help in the unification of the three forces [4]. Although it has been suggested [5] that this is not absolutely necessary for Grand Unification, such a ‘split SUSY’ scenario is nonetheless of considerable interest, both from theoretical and phenomenological viewpoints [6]. In this note we wish to point out a few phenomenological possibilities which may have implications in accelerator experiments.

We demonstrate these possibilities with reference to a particular SUSY breaking scheme discussed in reference [1], based on a braneworld scenario. This scenario is stabilised by a new chiral supermultiplet (X) whose fermionic component ($\psi_X$) turns out to be as light as the gauginos and Higgsinos. We illustrate the different situations that arise corresponding to the different relative masses of these fermions, resulting in different types of SUSY phenomenology. Furthermore, we suggest that some variants of such a model, where the gauginos are kept in the bulk rather than confined to the visible brane, can make the gauginos heavier and cause them (for example, the gluino) to decay quite fast. This alleviates the cosmological problems associated with a long-lived gluino while the field $\psi_X$ can still be a viable dark matter candidate.

The model consists of five-dimensional supergravity (SUGRA) compactified on $S_1/Z_2$ orbifold with radius r [7]. Apart from the SUGRA multiplet the low energy effective action at the tree level includes the radion chiral superfield $T = r + \theta^2 F_T$ and the chiral compensator field $\phi = 1 + \theta^2 F_{\phi}$ [8]. It is further assumed that there is a constant superpotential $c$ on one of the two branes (the one not containing the standard model superfields) which are located at the two orbifold fixed points [9]. This scenario is shown to break supersymmetry in a way which is equivalent to the
coordinate dependent compactification scheme proposed by Scherk and Schwarz [10]. Such constant superpotential which may originate from gluino condensation[11] in the hidden sector on the brane, gives rise to a non-vanishing vacuum expectation value (vev) of the auxiliary component of $T$ leading to the breakdown of supersymmetry with the gravitino mass given by $m_{3/2} = c/r$. Although the cosmological constant vanishes at the tree level, the one-loop gravitational Casimir energy gives rise to a negative potential which goes to a minimum for $r = 0$. To make the braneworld stable, $N$ bulk hypermultiplet of mass $M$ are included which because of their repulsive Casimir energy stabilises the minima of the potential at $r = M^{-1}$. However, the minimum of the potential being still negative, one introduces a chiral superfield $X$ with non-vanishing $F_X$ to make the cosmological constant zero. More precisely, one requires

$$F(X) \simeq m^2 \simeq \frac{1}{4\pi r^2}$$  \hspace{1cm} (1)$$

This chiral superfield $X$ is localized on the same brane where the standard model superfields also reside. Together with the radion superfield $T$ and the chiral compensator field $\phi$ (both propagating in the bulk), $X$ gives contributions to the Kahler potential and the superpotential, which are given by

$$K = \phi^\dagger \phi \left[ X^\dagger X + \frac{a_1}{M_5^2} (X^\dagger X)^2 + \text{higher powers} \right]$$  \hspace{1cm} (2)$$

and

$$W = \phi^3 m^2 X$$ \hspace{1cm} (3)$$

where the five-dimensional Planck mass is related to the four-dimensional Planck mass by

$$M_4^2 = \pi r M_5^3$$  \hspace{1cm} (4)$$

Using the above model, different terms in the SUSY Lagrangian generate masses for the sfermions, gauginos, Higgsinos as well as the scalar and spinor components of $X$. Although these are indicated in reference [1], we summarise in table 1 the exact expressions for the different mass terms that arise from the corresponding terms in the Lagrangian. It may be noticed that we have used some general coefficients in our Kahler potential as well as in the interaction terms. The purpose of doing so is to convey the message that the strengths of these terms are prima facie unrelated, and that the different masses induced by them can be ordered in different ways in a general scenario. These different parameters can appear, for example, in a string-inspired scenario via the vev’s of the moduli of the compact dimensions.

The ‘split’ character of the (s)particle spectrum here has to do with the fact that

(a) $\langle X \rangle \sim m^2/M_5$ while $\langle F_X \rangle \sim m^2$, and
(b) $m \sim 1/r$ while $r$ relates the four-and five-dimensional Planck masses as in equation (4). One needs to have $M_5$ in the range $10^{16–17}$ GeV in order to have a SUSY dark matter candidate within the TeV scale [1]. Also, the universal gaugino
mass parameter derived above is subject to the usual running before the different gaugino masses at the electroweak scale are obtained.

Table 1: The different terms in the SUSY Lagrangian contributing to the sfermion and fermion masses including the Higgsino mass parameter $\mu$. The corresponding expressions for the masses derived are also shown, in terms of the different coefficients and the power-law dependence on the four- and five-dimensional Planck scales.

|      | Origin in $\mathcal{L}_{\text{SUSY}}$ | Expression |
|------|---------------------------------------|------------|
| $m_f$ | $\int d^4\theta_0 X^\dagger X Q^\dagger Q / M_5^2$ | $\alpha_0 \pi M_5^5 / M_4^4$ |
| $m_X$ | $\int d^4\theta a_1 (X^\dagger X)^2 / M_5^2$ | $a_1^{1/2} \pi M_5^5 / 2 \sqrt{2} M_4^4$ |
| $m_{\psi X}$ | $\int d^4\theta a_1 (X^\dagger X)^2 / M_5^2$ | $a_1 \pi^2 M_5^9 / 12 M_4^8$ |
| $M_{1/2}$ | $\int d^2\theta a_1 m^2 X W_\beta W^\beta / M_5^3$ + h.c. + $\int d^4\theta a_2 X^\dagger X W_\beta W^\beta / M_5^3$ | $(\alpha_1 + \alpha_2) \pi^2 M_5^9 / M_4^8$ |
| $\mu$ | $\int d^2\theta a_3 m^2 X H_u H_d / M_5^2$ + $\int d^4\theta a_4 X^\dagger X H_u H_d / M_5^2$ + $\int d^4\theta a_5 m^2 X H_u H_d / M_5^2$ | $(\alpha_3 + \alpha_4 + \alpha_5) \pi^2 M_5^9 / M_4^8$ |

where $W$ can be expressed in terms of the components of a gauge supermultiplet as

$$ W_\alpha = 4i\lambda_\alpha - \left[ 4\delta_\alpha^\beta D + 2i(\sigma^\mu \bar{\sigma}^\nu)_{\alpha \beta} V_{\mu \nu} \right] \theta_\beta + 4\theta^2 \bar{\sigma}^\mu_{\alpha \beta} \partial_\mu \bar{\lambda}^\beta $$

(5)

$D$ and $V_{\mu \nu}$ being respectively the auxiliary part of the superfield and the field strength of the gauge boson $V_\mu$.

Our next step is to examine the different possible SUSY spectra in the fermionic sector, and outline the way they are likely to affect SUSY cascades at collider experiments. Before we enter into such an analysis, it is important to mention a few points.

First, this scenario admits of Higgsino-Higgs-$\psi_X$ couplings of the form

$$ \mathcal{L} = (\alpha_3 + \alpha_4) \pi \left( \frac{M_5}{M_4} \right)^4 \bar{\psi} \bar{H}_u H_d + \text{h.c.} $$

(6)

When electroweak symmetry is broken, such interaction also leads to Higgsino-$\psi_X$ mixing which, however, is suppressed by $\left( \frac{M_5}{M_4} \right)^4$. It can be easily verified that such small off-diagonal terms in the
neutralino mass matrix are of little consequence in determining the composition of states, and therefore the states obtained in the corresponding MSSM case remain valid here as well.

Secondly, the above interaction term can lead to the decay $\psi_X \rightarrow \tilde{H} h^0$ where $h^0$ is the lightest neutral scalar, for $m_{\psi_X} > (\mu + M_{h^0})$. Alternatively, a heavier Higgsino can decay into the Higgs and $\psi_X$. The decay width for any of these modes is driven by the suppressed coupling given above. However, one finds that for a Higgs mass of 120 GeV, and with the heavier/lighter of the two fermions being of mass 250 (100) GeV, the lifetime varies between $10^{-2}$ and $10^{-10}$ seconds for $\frac{M_5}{M_4}$ varying between $10^{-3}$ and $10^{-2}$. Such lifetimes are small compared to the cosmological scale, but can sometimes lead to displaced vertices in detectors.

Thirdly, the coupling of a gaugino to a gauge boson and $\psi_X$ arises from the terms proportional to $\alpha_1$ and $\alpha_2$ in table 1, and is of the form

$$\mathcal{L} = 2(\alpha_1 + \alpha_2)\pi \frac{M_3^3}{M_4^4} \bar{\psi} \sigma^{\mu \nu} \Lambda V_{\mu \nu} + h.c. \quad (7)$$

This interaction is heavily suppressed; the fact that it arises from a dimension-five term involving $V_{\mu \nu}$ never allows the decay to recover from suppression by the Planck mass. Therefore, the gluino has to decay via squark propagators, and is long-lived when the latter involve large masses. The electroweak gauge bosons, however, have unsuppressed gauge couplings with the Higgs superfields and therefore allow quick decays for them if kinematically allowed.

Let us now consider the different ways the masses of the electroweak gauge boson, the Higgsinos and $\psi_X$ can be ordered. Various possibilities can arise here depending on the values of the parameters $a_1$ and $\alpha_i$ (i = 1-5). Based on the observations listed above, these possibilities can lead to different types of SUSY phenomenology discussed below. We are assuming that the gluino is on the heavier side; in any case it will remain long-lived in all cases since it does not couple to Higgsinos.

1. $M_{\text{gaugino}} > M_{\psi_X} > \mu$. Here the gluino is long-lived as expected, but not the electroweak gauginos, which have unsuppressed decays into $h^0$ and a Higgsino. Therefore, the electroweak gauginos (which are within experimentally accessible range), once produced in colliders, can decay quickly into the Higgsino LSP which is also the dark matter candidate. The field $\psi_X$, too, is within the TeV range, and can also decay into the LSP fast enough, but its production in experiments is suppressed, as shown in equations (6) and (7). The conclusion, therefore, is that $\psi_X$ does not play any significant role in superparticle cascades. Such cascades end up in a Higgsino LSP, accompanied by the production of the lighter neutral scalar $h^0$ if it can be produced on-shell, or a $b\bar{b}$ pair otherwise.

2. $M_{\text{gaugino}} > \mu > M_{\psi_X}$. Here, together with a long-lived gluino, the electroweak gauginos have the unsuppressed decay into the Higgs-Higgsino pair, where the latter, however, is liable to go

\[1\text{In the case of the charged gaugino } \tilde{W}^+, \text{ the cascade also associates the production of real or virtual W's.}\]
again to an $h^0$ (real or virtual) and the $\psi_X$. The time scale for the second decay is in the range $10^{-2} - 10^{-10}$ s, as mentioned earlier. Thus $\psi_X$ marks the culmination of all SUSY cascades, and is actually the LSP as well as the dark matter candidate, thus governing the final-state kinematics whenever superparticles (except gluinos) are produced in colliders. This is the case where $\psi_X$ enters seriously into accelerator phenomenology. Again, the simultaneous appearance of one or more light neutral Higgses is a characteristic feature of SUSY signals. For charged gauge bosons/Higgsinos, the final states also include either the W-boson or pairs of fermions typical of charged Higgs decays.

3. $M_{\psi_X} > M_{\text{gaugino}} > \mu$. Obviously, $\psi_X$ has extremely suppressed production rate and has no role in phenomenology here. The electroweak gauginos (unlike the gluino) again decay immediately into the $h^0$ and the Higgsino LSP.

4. $M_{\psi_X} > \mu > M_{\text{gaugino}}$. This is a situation similar to the previous one, excepting that it has a gaugino-dominated LSP this time. The Higgsinos appear via direct production or in cascades but decay fast into the $h^0$ and LSP. The heavier electroweak gauginos (namely, the lighter chargino $\chi_1^\pm$ and the second lightest neutralino $\chi_2^0$) in this case also decay into the LSP, but such decays are controlled by the small overlap between the LSP and the neutral SU(2) gaugino $\tilde{W}_3$. Again, a sizeable fraction of SUSY cascades in collider experiments includes real or virtual $h^0$ in the final state.

5. $\mu > M_{\text{gaugino}} > M_{\psi_X}$. Here the Higgsino states have unsuppressed decays into the electroweak gauginos (the gluino as usual is long-lived). The neutral Higgsino, of course, can still have the decay into the $\psi_X$, but such a decay has a very small branching ratio compared to that into gauginos, as seen from equation (6). The decay of the lightest neutralino, on the other hand, is suppressed by the Planck mass. Thus the $\psi_X$-state, although it is the LSP, is never reached within a measurable time in SUSY cascades, and is decoupled from phenomenology. This situation is in contrast with that in case 2 above, where the $\psi_X$ has a role to play as the LSP. The lightest neutralino, as a quasi-stable particle, actually turns out to be a parallel dark matter candidate; also the other charginos and neutralinos decay into it, thereby making it the effective LSP.

6. $\mu > M_{\psi_X} > M_{\text{gaugino}}$. Again, the phenomenology is controlled by the Higgsinos and gauginos, with the $\psi_X$ having practically no role in experimental signals. All fermions excepting the gluino and the $\psi_X$ are short-lived. The LSP is gaugino-dominated and is a dark matter candidate, but so also is $\psi_X$, being quasi-stable due to equation (7).

Finally, we consider a special case, where the gauginos propagate in the bulk and explore whether this helps to reduce the lifetime of the gluino. It has been shown in reference [1] that a long-lived gluino imposes a constraint on the SUSY breaking scale. This is because the presence of extremely long-lived gluinos could lead to the formation of abnormally heavy isotopes. Therefore, one may
demand that the gluino lifetime be smaller than the age of the nucleosynthesis era. As gluino decays involve heavy squark propagators, an upper limit on the squark masses and consequently on the SUSY breaking scale can therefore be obtained. In principle, equation (7) also leaves room for the decay $\tilde{g} \rightarrow g\psi_X$. A quick look at equation (7), however, tells us that this decay is suppressed by the Planck scale in the denominator. We show that this suppression can be offset if the gauginos exist in the bulk, and consequently acquire large masses.

When gauginos propagate in the bulk, they can couple to the radion field as:

$$L = \int d^2 \theta T W^\alpha \bar{W}_\alpha + h.c$$

Such interaction yields a gaugino mass of the form

$$M_{gaugino} = \frac{<F_T>}{M_5} = \frac{m^2}{M_5}$$

If now the rate for such a gluino decaying into a gluon and the $\psi_X$ is calculated from the gluino-$\psi_X$-gauge boson coupling as given in equation (7), we find after using equations (1) and (4) that the lifetime of a gluino is on the order of $10^{-10}$ seconds! Thus the gluino has a fast enough decay to avoid all cosmological problems, irrespective of what the squark masses are. The constraint derived in reference [1] on the SUSY breaking scale $M_S$, namely, $M_S \leq 10^{13}$ GeV for a TeV-scale gluino, is no longer applicable, and SUSY can be broken at even higher scales. Of course, a scenario of this kind will decouple all the gauginos from accelerator experiments. The only low-energy signatures of SUSY will come from the Higgsinos (and the field $\psi_X$ if its mass happens to be lighter than $\mu$). It is, however, obvious that the gauginos in such a case become far too heavy to provide the right threshold for gauge coupling unification. Thus a bulk gaugino scenario of the above kind helps to avoid the problem of long-lived hadrons at the cost of sacrificing the gauge coupling unification via supersymmetry. To achieve grand unification in this scenario some other new physics will have to exist [5].

In conclusion, we have explored the consequences of a split supersymmetry scenario, and shown that details of the mechanism underlying the splitting between the scalar and fermion masses can have a crucial role to play in low-energy SUSY phenomenology. We have demonstrated this with special reference to a SUGRA-based scenario used by Arkani-Hamed and Dimopoulos, where a chiral superfield $X$ plays a pivotal role. We have examined the different types of mass spectra that can emerge in the process. In particular, the spinor component of $X$ is the LSP in some of the scenarios, and its role in the collider signatures of SUSY can be noticeable. Another remarkable prediction is that in practically all the cases the observed SUSY signals will be accompanied by the production of the lightest neutral Higgs boson. Finally, we have shown that an alternative scenario where the gauginos are assumed to propagate in the bulk leads to heavy but short-lived gluinos, whereby the upper limit on the SUSY breaking scale disappears.

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