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## The heterotic string yields natural supersymmetry

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### ABSTRACT

The most promising MSSM candidates of the heterotic string reveal some distinctive properties. These include gauge-top unification, a specific solution to the  $\mu$ -problem and mirage pattern for the gaugino masses. The location of the top- and the Higgs-multiplets in extra dimensions differs significantly from that of the other quarks and leptons leading to a characteristic signature of suppressed soft breaking terms, reminiscent of a scheme known as natural supersymmetry.

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String theory might provide us with a consistent ultraviolet completion of the minimal supersymmetric standard model (MSSM) with unified gauge and gravitational couplings. To analyze this ansatz we have to identify ways to embed the MSSM into string theory and then study properties of realistic models. In the present Letter we report on progress in model building within the heterotic string [1,2] and its implications for supersymmetry (SUSY) at the large hadron collider (LHC) at CERN. The emergent picture from the heterotic braneworld can be summarized as follows:

- large gravitino mass ( $m_{3/2}$ ) and heavy string moduli, all in the multi-TeV range or even heavier (at least of order  $m_{3/2} \cdot \log(M_{\text{Planck}}/m_{3/2})$ ),
- gaugino masses and  $A$ -terms in the TeV-range, suppressed with respect to  $m_{3/2}$  by a factor  $\log(M_{\text{Planck}}/m_{3/2})$ ,
- a mirage pattern for gaugino masses (compressed spectrum),
- top squarks ( $\tilde{t}_L, \tilde{b}_L$ ) and  $\tilde{t}_R$  in the TeV-range,
- other squarks in the multi-TeV-range of order the gravitino mass.

These properties are similar in some aspects to a bottom-up approach called “natural SUSY”.<sup>1</sup> The origin of the pattern can be traced back to two distinct properties of realistic MSSM candidates from heterotic string theory: (i) specific localization properties of

fields (specifically the top quark) in extra dimensions and (ii) the appearance of mirage mediation (mixed modulus anomaly mediation) of supersymmetry breakdown. This mirage pattern [4]<sup>2</sup> seems to be pretty generic in string theory. It was first observed [6–8] in type IIB theory in the framework of the KKLT scenario [9] and it appears naturally in the heterotic string theory as well [10]. It is characterized by the appearance of a factor

$$\log(M_{\text{Planck}}/m_{3/2}) \quad (1)$$

that suppresses the soft terms of modulus mediation compared to the gravitino mass (and enhances the masses of the moduli by the same factor). Radiative corrections to the soft terms as in anomaly mediation [11] become competitive resulting in a mixed modulus-anomaly mediation. Specific properties of the MSSM  $\beta$ -functions (negative for SU(3), positive for SU(2) and U(1)) lead to the appearance of a mirage scale, where soft terms coincide. This leads to a compressed spectrum of soft terms that improves the so-called little hierarchy problem [12], improves precision gauge coupling unification [13] and alters predictions – compared to pure modulus mediation – for potential LHC observation significantly, see [14] and references therein. Properties of the mirage scheme turn out to be pretty robust for gaugino masses and  $A$ -parameters, while soft scalar masses are strongly model dependent. In fact, it was shown in [15] that masses of squarks and sleptons are less protected and tend to become as large as the gravitino mass. This scheme, with sfermion masses in the multi-TeV-range and gaugino masses (and  $A$ -terms) at the TeV scale seems to be pretty generic in type II and heterotic string theory.

A more detailed picture requires explicit model building and this brings us to the main result of this Letter. Such a picture arises from model building in heterotic string theory as observed

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<sup>1</sup> The terminology “natural SUSY” appeared to our knowledge first in [3], where references to the earlier literature on similar models with non-universal scalar masses can be found. There it was motivated from bottom-up arguments while here it emerges in a top-down construction from heterotic string theory.

<sup>2</sup> For an explanation of the terminology see [5].

e.g. in the Minilandscape [1,2] of orbifold compactifications. The benchmark models presented there [2] show distinctive properties shared by a majority of the models. There is only one pair of Higgs doublets (no Higgs triplets),  $H_u$  and  $H_d$ , both in the untwisted sector such that the Higgs bilinear  $H_u H_d$  is neutral under all selection rules. This leads to a solution of the  $\mu$ -problem via a (discrete)  $R$ -symmetry [16] and guarantees Minkowski vacua before supersymmetry breakdown. In these realistic models, the top quark plays a special role. Both  $(t_L, b_L)$  and  $t_R$  “live” in the untwisted sector while other quark- and lepton-multiplets reside in various twisted sectors. As a result we have only one non-vanishing Yukawa coupling at the trilinear level consistent with gauge-top-Yukawa unification [17].<sup>3</sup> This is a direct consequence of the fact that both the Higgs multiplets and the top multiplets “live” in the bulk (untwisted sector), while other particles are localized at fixed points or fixed tori in the extra dimensions. As we shall see, this particular configuration has important consequences for the soft mass terms of  $(\tilde{t}_L, \tilde{b}_L)$ - and  $\tilde{t}_R$ -squarks as well as for the soft Higgs masses. Fields in the untwisted sector descend from a torus compactification of extra dimensions. Torus compactification in itself would yield  $N = 4$  supersymmetry in  $d = 4$  and the untwisted sector of orbifold compactification feels remnants of this extended supersymmetry, most clearly seen in the framework of “no-scale” models [19]. In the models under consideration this gives a suppression to the soft masses of  $(\tilde{t}_L, \tilde{b}_L)$  and  $\tilde{t}_R$  not shared by the others squarks and sleptons. We thus obtain the pattern of soft terms with a two step hierarchy: gauginos, Higgses and stops at the TeV scale, all other sfermions at the multi-TeV scale of the order of the gravitino mass. A large Yukawa coupling for the top quark requires special geometric properties of extra dimensions which reflect themselves in the pattern of soft scalar masses. In upshot, the soft masses of the top-multiplet are so light because the mass of the top quark is so large.

Let us now discuss the mechanism of SUSY breakdown in more detail. The models of the Minilandscape show a specific pattern of gauge group in the hidden sector [20] with SUSY breakdown via gaugino condensates [21]. Moduli stabilization can proceed along the lines of [22]. This could take care of the  $U$ - and  $T$ -moduli of the models, but not the dilaton  $S$ . We thus remain with a “run-away” dilaton and a positive “vacuum energy” for finite  $S$ . The vacuum energy has to be adjusted to zero. This can be done with a scalar matter field  $X$  (in the untwisted sector) in a “down-lifting mechanism” as described in [10]. This adjusts the vacuum energy and fixes the vacuum expectation value of the dilaton  $S$ . A mirage picture of mixed dilaton-anomaly mediation emerges.

Such settings in which supersymmetry is dominantly broken by matter fields have been studied in [15]. The relevant Kähler potential reads

$$K = -3 \ln(T + \bar{T}) + X\bar{X} + Q_\alpha \bar{Q}_\alpha (T + \bar{T})^{n_\alpha} [1 + \xi_\alpha X\bar{X} + \mathcal{O}(|X|^4)], \quad (2)$$

where  $X$  denotes a “hidden” matter field, the  $Q_\alpha$  are the observable fields with “modular weights”  $n_\alpha$ . The general formulae [23] for the soft masses have been specialized to the case that supersymmetry is dominantly broken by  $X$  with  $F^X \neq 0$  and  $\langle X \rangle \approx 0$  [15]. Following [10], we define the quantity

$$Q := \frac{16\pi^2}{m_{3/2}} \frac{F^S}{S_0 + \bar{S}_0}, \quad (3)$$

<sup>3</sup> Other Yukawa couplings are suppressed as in the framework of the Froggatt-Nielsen mechanism [18].

where  $S_0 \in \mathbb{R}$  is the VEV of the dilaton. The soft supersymmetry breaking parameters are then [10]

$$M_a = \frac{m_{3/2}}{16\pi^2} [\varrho + b_a g_a^2], \quad (4a)$$

$$A_{\alpha\beta\delta} = \frac{m_{3/2}}{16\pi^2} [-\varrho + (\gamma_\alpha + \gamma_\beta + \gamma_\delta)], \quad (4b)$$

$$m_\alpha^2 = \frac{m_{3/2}^2}{(16\pi^2)^2} [\varrho^2 \xi_\alpha - \dot{\gamma}_\alpha + 2\varrho(S_0 + \bar{S}_0) \partial_S \gamma_\alpha + (1 - 3\xi_\alpha)(16\pi^2)^2]. \quad (4c)$$

Here  $b_a$  denote the usual MSSM  $\beta$ -function coefficients,  $\gamma_\alpha$  the standard anomalous dimensions and the derivative of  $\gamma_i$  with respect to  $S$  is given by  $(S_0 + \bar{S}_0) \partial_S \gamma_i = -\gamma_i$ .<sup>4</sup>

An important feature of the scalar masses  $m_\alpha$  is that they are generically of the order  $m_{3/2}$ , unless  $\xi_\alpha = 1/3$ . Untwisted matter fields  $Q_\alpha^{\text{ut}}$  can lead to a situation with  $\xi_\alpha = 1/3$ . Of course, in specific models we do not expect that  $\xi_\alpha$  for untwisted matter fields, denoted by  $\xi_3$  from now on, is exactly equal to  $1/3$ , but we still expect that generically untwisted sector fields will have a value of  $\xi_\alpha$  closer to  $1/3$  than twisted matter fields, resulting in a hierarchy between the respective soft mass terms. In this study we base our discussion on the Kähler potential with one so-called overall Kähler modulus  $T$  (cf. Eq. (11) in [24])

$$K = -3 \ln \left[ T + \bar{T} - \frac{1}{3} (Q_\alpha^{\text{ut}} \bar{Q}_\alpha^{\text{ut}} + \tilde{X} \bar{\tilde{X}}) \right], \quad (5)$$

where  $\tilde{X}$  is the not yet canonically normalized field breaking supersymmetry. This Kähler potential describes untwisted fields  $Q_\alpha^{\text{ut}}$  and  $\tilde{X}$ , but not twisted sector fields for which a different Kähler potential is required. We can bring the above Kähler potential to the form in Eq. (2).<sup>5</sup>

$$K = -3 \ln(T + \bar{T}) + X\bar{X} + \frac{Q_\alpha^{\text{ut}} \bar{Q}_\alpha^{\text{ut}}}{(T + \bar{T})} \left[ 1 + \frac{1}{3} X\bar{X} + \mathcal{O}(|X|^4) \right], \quad (6)$$

where we went to canonically normalized hidden sector matter fields ( $X = \tilde{X}/(T + \bar{T})^{1/2}$ ). If we assume that supersymmetry is dominantly broken by an  $F$ -term VEV of  $X$ , we get from (4) soft masses for  $Q_\alpha^{\text{ut}}$  which are highly suppressed against  $m_{3/2}$ .<sup>6</sup> As mentioned above, for twisted sector matter fields the Kähler potential is different from (5) and one obtains  $\xi_\alpha$  values, denoted by  $\xi_f$  from now onwards, for such fields which differ from  $1/3$ . In particular, given the Kähler potential (5), we see that

$$m_\alpha \sim \begin{cases} \frac{m_{3/2}}{16\pi^2} & \text{for } Q_\alpha^{\text{ut}}, \\ m_{3/2} & \text{otherwise.} \end{cases} \quad (7)$$

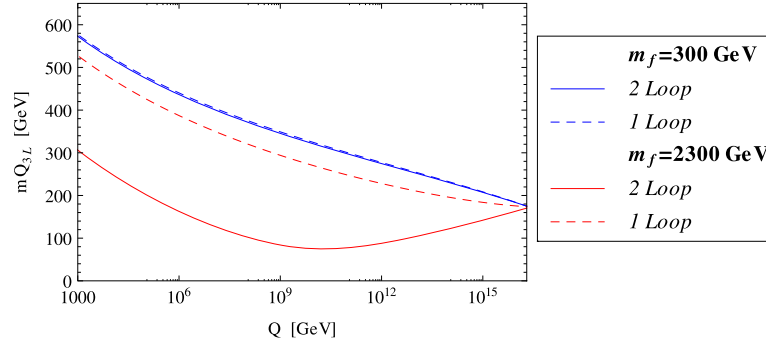
As mentioned before, in the explicit heterotic string models  $(t_L, b_L)$ ,  $t_R$  and  $H_{u,d}$  are in the untwisted sector while the other MSSM fields are not.<sup>7</sup> Taking into account that the gaugino masses are suppressed against  $m_{3/2}$  by a factor  $\log(M_{\text{Planck}}/m_{3/2})$ , we then

<sup>4</sup> We assume that the holomorphic Yukawa couplings do not depend on the dilaton.

<sup>5</sup> Note that the Kähler potential in Minilandscape models can deviate from the Kähler potential in Eq. (5), but leaving the coupling between  $X$  and  $Q_\alpha^{\text{ut}}$  distinct from the coupling to the twisted sector fields. An explicit Kähler potential can only be given in a detailed construction of the SUSY breaking field  $X$ , which is beyond the scope of this Letter, and we consider the Kähler potential for one overall modulus, allowing for deviations from  $\xi_3 = 1/3$  in due course.

<sup>6</sup> Observe that it is important that the field  $X$  itself is an untwisted sector field.

<sup>7</sup> Note that for some models of the heterotic Minilandscape one also finds  $\tau_R$  in the untwisted sector. Here we restrict ourselves to models with  $\tau_R$  in the twisted sector and leave the phenomenological analysis of a  $\tau_R$  in the untwisted sector to future work.



**Fig. 1.** RGE running of  $m_{Q_{3L}}$  at the 1-loop and 2-loop level.

obtain the “natural SUSY” pattern from explicit model building in heterotic string theory. This pattern of soft masses is markedly different from the spectra in the CMSSM and leads to a specific pattern that can be tested at the LHC.

What are the specific properties of such a scheme? The main challenges come from a discussion of potential tachyonic instabilities. Remember that we are discussing a unified model originating from string theory at a very high scale ( $M_{\text{GUT}} \sim 10^{16}$  GeV) and we have to analyze the running of mass parameters from this high scale to the TeV scale. This is different from bottom-up approaches where we just assume a consistent spectrum at the TeV scale. We perform the running of mass parameters using the spectrum generator *Softsusy* [25]. In our analysis we will require the absence of tachyons at all scales.<sup>8</sup> In particular the small value of the stop mass is a potential source of instability since we obtain at the GUT scale<sup>9</sup>

$$m_{Q_{3L}}^2(M_{\text{GUT}}) \simeq \frac{m_{3/2}^2}{(16\pi^2)^2} (\xi_3 \varrho^2 - 3.7\varrho + 0.8 + (16\pi^2)^2 (1 - 3\xi_3)). \quad (8)$$

For  $\xi_3 = 1/3$  the absence of a tachyonic stop/sbottom mass at the GUT scale requires  $\varrho \gtrsim 10.9$  which corresponds to a mirage scale

$$M_{\text{MIR}} = M_{\text{GUT}} e^{-8\pi^2/\varrho} \gtrsim 10^{13} \text{ GeV}. \quad (9)$$

However, any small correction to  $\xi_3 = 1/3$  allows us to avoid tachyonic boundary conditions even for small  $\varrho$ . Such corrections may originate for example from small mixing of the bulk families with localized states or might be induced by sub-dominant mediation of supersymmetry breaking. In this case a lower mirage scale can be realized.

Besides the potential tachyonic boundary conditions, the large hierarchy among the scalar masses can lead to tachyonic stop/sbottom masses as a result of renormalization group running. In particular there exists a 2-loop contribution to the  $\beta$ -function of  $m_{Q_{3L}}^2$  which reads (see for example [27])

$$\beta^{2\text{-loop}} \simeq \frac{1}{(16\pi^2)^2} 48g_3^4 m_f^2, \quad (10)$$

where  $m_f^2 = (1 - 3\xi_f)m_{3/2}^2$  denotes the common mass of the scalar fields which are not in the untwisted sector.<sup>10</sup> Including the 1-loop

term  $\propto m_{\tilde{g}}^2$  we obtain

$$m_{Q_{3L}}^2(M_Z^2) \sim m_{Q_{3L}}^2 + 5m_{\tilde{g}}^2 \left(1 - \frac{(0.1m_f)^2}{m_{\tilde{g}}^2}\right), \quad (11)$$

where the quantities on the right-hand side are to be evaluated at the GUT scale. This suggests that the absence of tachyonic stops/sbottoms at the low scale requires  $m_f \lesssim 10m_{\tilde{g}}$  at the GUT scale. It turns out that the actual bound is slightly stronger as there exist sub-leading 1-loop terms  $\propto m_f^2$  which tend to decrease  $m_{Q_{3L}}^2$  further. The latter are, however, suppressed by small couplings and small numerical coefficients.

In Fig. 1 we show the full RGE running of  $m_{Q_{3L}}$  including sub-leading terms. As boundaries we have chosen a universal gaugino mass  $m_{1/2} = 300$  GeV,  $A = -m_{1/2}$  and  $m_t^2 = m_{1/2}^2/3$  for the untwisted fields. These conditions can be obtained from (4) in the limit of large  $\varrho$  and  $\xi_3 = 1/3$ . It can be seen that 2-loop effects are negligible for small  $m_f$ . However, with increasing  $m_f$  the term (10) becomes more important and eventually  $Q_{3L}$  becomes tachyonic.

Nevertheless we find in parameter scans of the heterotic “natural SUSY” scheme large regions of parameter space consistent with the following constraints:

- no tachyons (at all scales),
- correct electroweak symmetry breaking (EWSB),
- $115.5 \text{ GeV} < m_h < 127 \text{ GeV}$  (combined LHC and LEP bound on the Higgs mass [28]),
- LHC limits on the superpartner mass spectrum,
- no colored LSP.

In the considered scheme the superpartners of the first two generations become heavy. LHC constraints on gluinos, stops and sbottoms mainly arise from searches for jets + missing energy as well as searches for di-lepton signals (see for example [29,30]). Here – based on [30] – we will use the following estimates of the constraints

$$m_{\tilde{t}_1}, m_{\tilde{b}_1} > 250 \text{ GeV}, \quad m_{\tilde{g}} > 700 \text{ GeV}. \quad (12)$$

If gluinos and stop/sbottom are light the limits become slightly stronger, we assume

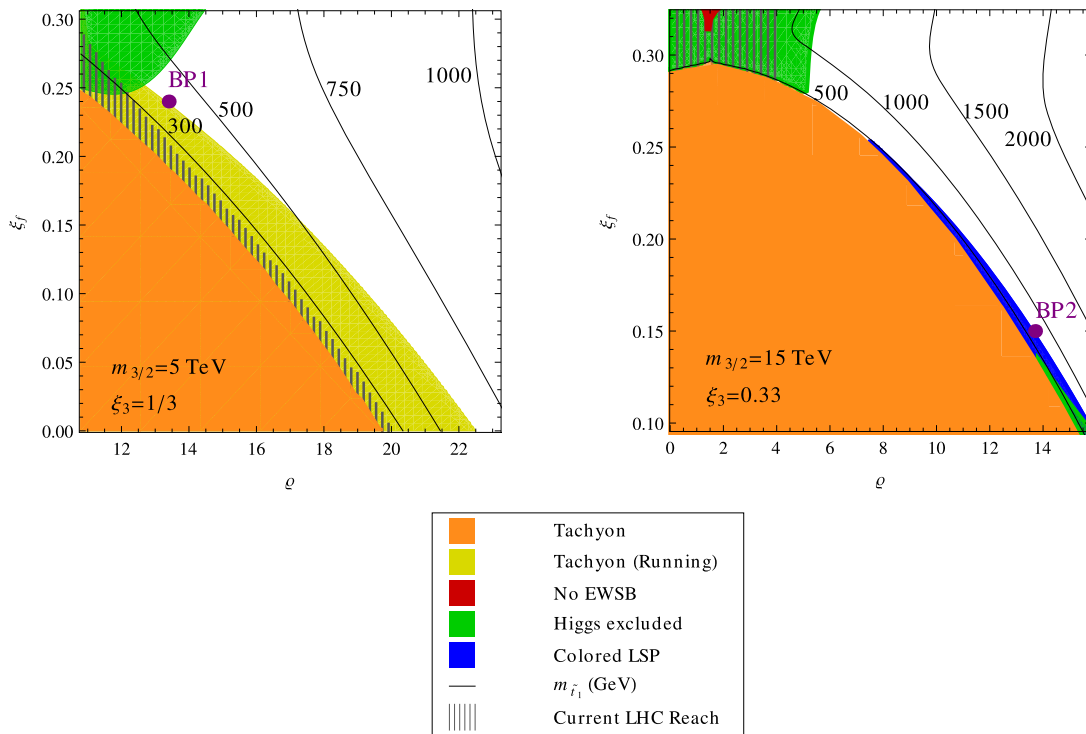
$$m_{\tilde{t}_1}, m_{\tilde{b}_1} > 250 \text{ GeV} + 0.5(1000 \text{ GeV} - m_{\tilde{g}}) \quad \text{for } m_{\tilde{g}} = 700\text{--}1000 \text{ GeV}. \quad (13)$$

This simple treatment is sufficient for our purposes as we will use the current LHC sensitivity only for illustration.

<sup>8</sup> We are aware that this assumption could be too strict [26], but we stick to it here for simplicity.

<sup>9</sup> This relation is sensitive to the Yukawa couplings at the GUT scale. It slightly changes for large  $\tan\beta$  where  $y_b$  becomes sizeable.

<sup>10</sup> Here we neglect subleading contributions from anomaly mediation.



**Fig. 2.** Parameter scans with different gravitino mass. On the left we assume that  $\xi_3 = 1/3$  is exact while on the right we assume that there are corrections giving  $\xi_3 = 0.33$ . The colored regions are excluded while the hatched regions indicate the current reach of the LHC (see text). The contours refer to  $m_{\tilde{t}_1}$ . The particle spectrum for the two benchmark points BP1 and BP2 is shown in Fig. 3. (Note that some information of the color coding might be lost in the B/W journal version but it can be found in the web version of this Letter.)

In Fig. 2 we present two scans in the  $\rho$ - $\xi_f$ -plane for fixed gravitino mass and  $\xi_3$ .<sup>11</sup> Requiring the absence of tachyons substantially constrains the parameter space. For the case where  $\xi_3 = 1/3$  is exact, the region with  $\rho < 10.9$  is not shown as it generally yields a negative  $m_{Q_{3L}}^2$  at the GUT scale. Small values of  $\rho$  can, however, be accessed for  $\xi_3 \neq 1/3$  as shown for the case  $\xi_3 = 0.33$ . For low values of  $\xi_f$ , the hierarchy in the scalar sector grows which tends to decrease  $m_{Q_{3L}}^2$  through the RGE running. Both scans exhibit a sizeable region (orange in the web version) where this effect is so strong that tachyonic stops/sbottoms are obtained at the weak scale. In the yellow region (of the web version)  $m_{Q_{3L}}^2$  becomes negative at an intermediate scale, but – towards the low scale – turns positive again. As we require the absence of tachyons at all scales we also exclude this part of the parameter space. In the green region (of the web version) to the left of both scans, the Higgs boson mass is below its current limit of 115.5 GeV. In the scan to the right there exists also some parameter space with  $m_h > 127$  GeV in the lower right corner. As can be seen, the current LHC searches for superpartners have not yet reached the sensitivity to constrain the parameters in this scheme further.

The particle spectra for the two benchmark points indicated in Fig. 2 are visualized in Fig. 3. In both spectra there is a clear hierarchy: the gauginos, higgsinos and the scalars of the untwisted sector are significantly lighter than the other superpartners. The lightest scalars are  $\tilde{t}_1$  and  $\tilde{b}_1$  as their mass is decreased by the heavy scalars through the RGE running. Due to the mirage mediation the pattern of gaugino masses is compressed compared to the CMSSM. In both spectra the lightest superpartner is the bino.<sup>12</sup> The higgsinos are heavier as correct electroweak symmetry

breaking requires  $|\mu| \sim |m_{H_u}|$  at the weak scale and  $m_{H_u}$  receives a contribution  $\mathcal{O}(m_{\tilde{g}})$  from the RGE running. As the scale of supersymmetry breaking is unknown the overall scale of the spectrum cannot be determined.

Turning to the Higgs sector, we find that spectra with  $m_{\tilde{t}}, m_{\tilde{g}} \lesssim 1$  TeV yield  $m_h < 120$  GeV. Therefore, if the recent hints for  $m_h \sim 125$  GeV observed by ATLAS and CMS [28] are confirmed, this may suggest heavier stops and gluinos.

We see that the heterotic string as a UV completion of the MSSM leads to a pattern of soft terms that is compatible with all phenomenological constraints. The most relevant restrictions of the parameter space arise from the potential appearance of tachyonic instabilities. In fact, this is a situation to be faced in all top-down constructions where the stop masses are smaller than the masses of other squarks and sleptons. In the present Letter we have considered the case where tachyonic instabilities are absent from the large (GUT) scale to the weak scale. This might be too strong an assumption. Strictly speaking we would need this absence only at the weak scale, but such a situation would require a careful analysis of the cosmological evolution along the lines of reference [26]. This is beyond the scope of this Letter and will be subject of future research.

Apart from the heterotic string there are other constructions such as type II strings or M-theory that have been discussed in the present context. In the type IIB theory with uplifting a la KKLT [9] one finds a mirage scheme for gaugino masses [7] and heavy squarks and sleptons (including stops) [15]. Models based on the large volume scenario [31] could lead to a variety of patterns of soft breaking terms [32,33]. A similar situation can be found in F-theory [32], where gauge mediation has been conjectured to be the major source of supersymmetry breakdown [34]. Models based on M-theory [35] lead to a pattern similar to that of type IIB a la KKLT, with a compressed (mirage like) spectrum of gauginos and (ultra) heavy sfermions (see [36] and references

<sup>11</sup> In the scans we have set  $\text{sgn } \mu = +$  and  $\tan \beta = 10$ .

<sup>12</sup> The relic density of the binos can potentially match the dark matter density if there are stop co-annihilations.

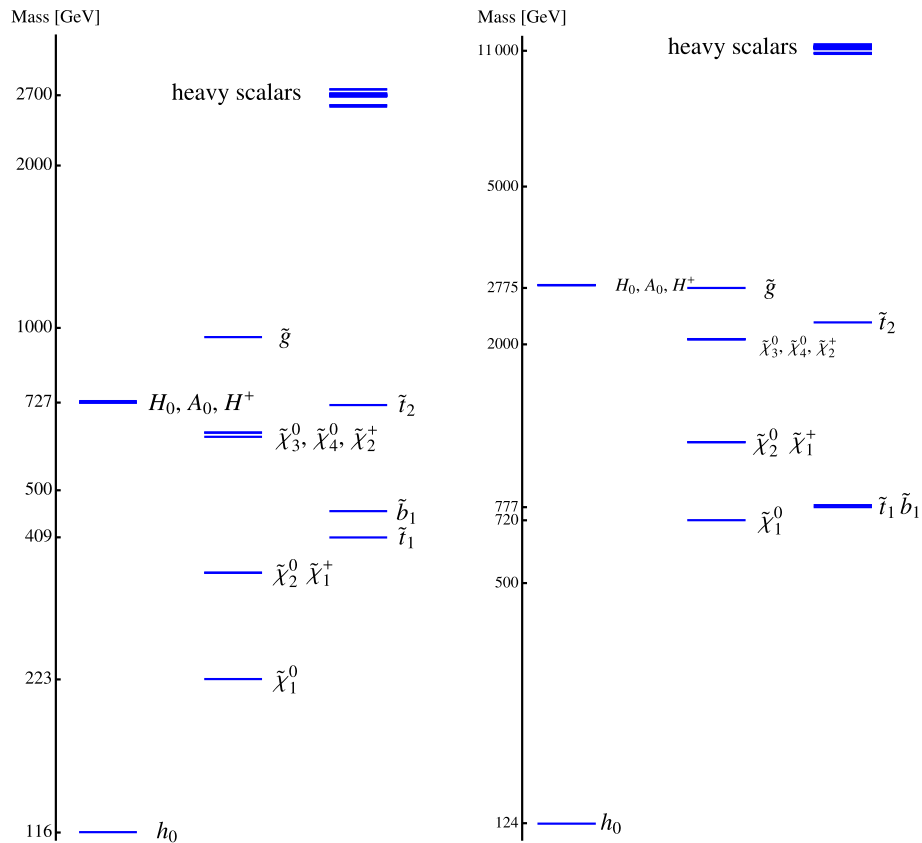


Fig. 3. Particle spectra for the benchmark points BP1 (left) and BP2 (right).

therein). In our spectrum of soft masses from the heterotic string, this hierarchy between the (heavy) scalar masses and the gluino mass cannot be arbitrarily large (i.e. there is no decoupling limit of the heavy scalars) due to the appearance of tachyonic light scalar masses for too large hierarchies. This hierarchy among the scalar masses due to the geometric separation of twisted and untwisted matter fields can be reduced in models with  $\xi_3 \neq 1/3$ , corresponding to less no-scale cancellations for the untwisted matter fields. Experiments at the LHC might be able to distinguish between the various schemes.

The heterotic pattern described here will be a serious challenge for SUSY searches at the LHC because of two reasons. First there is the compressed pattern of gaugino masses typical for the scheme of mirage mediation. It significantly reduces the ratio of gluino- to LSP-mass with important consequences for the properties of the gluino decay chain. Secondly, because of the light stops, this decay chain will predominantly include jets of heavy particles that are more difficult to identify experimentally. Our benchmark models in Fig. 3 show that the present reach of LHC does not yet restrict the parameter space.

The pattern has characteristic properties relating various types of soft terms but unfortunately cannot determine the overall scale of the SUSY breakdown. Here we have considered two benchmarks with small and large value of  $m_{3/2}$ , respectively. We can only hope that this overall scale is small enough to be within the reach of the LHC.

The theories considered here are the result of a string theory construction (including a consistent incorporation of gravity) as a UV completion of the MSSM. They reveal for the first time an explicit relation between MSSM constructions and the mechanism of SUSY breakdown and mediation from a top-down point of view. We see a profound connection between location of the fields in extra dimensions, the size of Yukawa couplings and the

pattern of soft mass terms. The top quark plays a very special role in this construction. The sector including the top quark and the Higgs-multiplets seem to be protected by a higher degree of ( $N = 4$  extended) supersymmetry in extra dimensions, with important consequences for the phenomenological prediction of the scheme. We are eagerly waiting for the LHC to test this picture in the not so distant future.

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