Low Energy Supersymmetry from the Heterotic String Landscape

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We study possible correlations between properties of the observable and hidden sectors in heterotic string theory. Specifically, we analyze the case of the $\mathbb{Z}_6$-II orbifold compactification which produces a significant number of models with the spectrum of the supersymmetric standard model. We find that requiring realistic features does affect the hidden sector such that hidden sector gauge group factors SU(4) and SO(8) are favored. In the context of gaugino condensation, this implies low energy supersymmetry breaking.

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In the string theory landscape [1–5], the minimal supersymmetric standard model (MSSM) corresponds to a certain subset of vacua out of a huge variety. To obtain string theory predictions, one can first identify vacua with realistic properties, and then analyze their common features. In this Letter, we study possible implications of this approach for supersymmetry breaking. First, we look for models consistent with the MSSM at low energies, then we study common features of their hidden sectors which are responsible for supersymmetry breaking.

We find that requiring realistic features affects the hidden sector such that, in the context of gaugino condensation, low energy supersymmetry breaking is favored. Since high energy supersymmetry is usually required by consistency of string models, this correlation provides a top-down motivation for low energy supersymmetry, which is favored by phenomenological considerations such as the gauge hierarchy problem and electroweak symmetry breaking.

We base our study [6] on the orbifold compactifications [7,8] of the $E_8 \times E_8$ heterotic string [9]. Recent work on an orbifold GUT interpretation of heterotic models [10–12] has facilitated construction of realistic models. In particular, the $\mathbb{Z}_6$-II orbifold (see [12]) has been shown to produce many models with realistic features [6,13,14]. These include the gauge group and the matter content of the MSSM, gauge coupling unification and a heavy top quark. Such models are generated using the gauge shifts

$$V^{\mathrm{SO}(10),1} = (\tfrac{1}{3}, \tfrac{1}{2}, \tfrac{1}{2}, 0, 0, 0, 0, 0)(\tfrac{1}{3}, 0, 0, 0, 0, 0, 0, 0),$$
$$V^{\mathrm{SO}(10),2} = (\tfrac{1}{3}, \tfrac{1}{3}, \tfrac{1}{3}, 0, 0, 0, 0, 0)(\tfrac{1}{6}, \tfrac{1}{6}, 0, 0, 0, 0, 0, 0),$$

and

$$V^{E_6,1} = (\tfrac{1}{2}, \tfrac{1}{3}, \tfrac{1}{6}, 0, 0, 0, 0, 0)(0, 0, 0, 0, 0, 0, 0, 0),$$
$$V^{E_6,2} = (\tfrac{2}{3}, \tfrac{1}{3}, \tfrac{1}{3}, 0, 0, 0, 0, 0)(\tfrac{1}{6}, \tfrac{1}{6}, 0, 0, 0, 0, 0, 0).$$

These shifts are chosen due to their "local grand unified theory (GUT)" [13–16] properties. They lead to massless matter in the first twisted sector (T_1) forming a **16**-plet of SO(10) in the case of $V^{\mathrm{SO}(10),1}$, $V^{\mathrm{SO}(10),2}$, and **27**-plet of E_6 in the case of $V^{E_6,1}$, $V^{E_6,2}$. These states are invariant under the orbifold action and all appear in the low energy theory. Further, if we choose Wilson lines such that

$$G_{\mathrm{SM}} \subset \mathrm{SU}(5) \subset \mathrm{SO}(10) \quad \text{or} \quad E_6, \tag{1}$$

the hypercharge will be that of standard 4D GUTs. These features facilitate construction of realistic models.

We focus on models with one Wilson line of order 3 (W_3) and one Wilson line of order 2 (W_2), although we include all models with 2 Wilson lines in the statistics. These are the simplest constructions allowing for 3 MSSM matter families without chiral exotics. In this case, two matter generations have similar properties while the third family is different. Selection of realistic models proceeds as follows: (1) Generate Wilson lines W_3 and W_2. (2) Identify "inequivalent" models. (3) Select models with $G_{\mathrm{SM}} \subset \mathrm{SU}(5) \subset \mathrm{SO}(10)$. (4) Select models with net three $(\mathbf{3}, \mathbf{2})$. (5) Select models with nonanomalous $U(1)_Y \subset \mathrm{SU}(5)$. (6) Select models with net 3 SM families + Higgs bosons + vectorlike. (7) Select models with a heavy top. (8) Select models where exotics decouple and gauginos condense. Steps (1)–(7) are described in detail in Ref. [6]. At the last step, we select models in which the decoupling of the SM exotic states is possible without breaking the largest gauge group in the hidden sector. We find that all or almost all of the matter states charged under this group can be given large masses consistent with string selection rules, which allows for spontaneous supersymmetry breaking via gaugino condensation.

The models satisfying all of the above criteria we consider the "MSSM candidates." Our results are presented in Table I. More details can be found in [17]. We find it remarkable that out of $\mathcal{O}(10^4)$ inequivalent models,

TABLE I. Statistics of $\mathbb{Z}_6$-II orbifolds based on the shifts $V^{\mathrm{SO}(10),1}$, $V^{\mathrm{SO}(10),2}$, $V^{E_6,1}$, $V^{E_6,2}$ with two Wilson lines.

Criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$	$V^{E_6,1}$	$V^{E_6,2}$
(2) Inequivalent models with 2 WL	22 000	7800	680	1700
(3) SM gauge group $\subset$ SU(5) $\subset$ SO(10) (or E_6)	3563	1163	27	63
(4) 3 net $(\mathbf{3}, \mathbf{2})$	1170	492	3	32
(5) Nonanomalous $U(1)_Y \subset$ SU(5)	528	234	3	22
(6) Spectrum = 3 generations + vectorlike	128	90	3	2
(7) Heavy top	72	37	3	2
(8) Exotics decouple + gaugino condensation	47	25	3	2

$\mathcal{O}(10^2)$ pass all of our requirements. In this sense, the region of the heterotic landscape endowed with local SO(10) and E_6 GUTs is particularly "fertile" [6].

A comment is in order. We require that only the fields neutral under the SM and the largest hidden sector group factor develop vacuum expectation values (VEVs). In "generic" vacua, the hidden sector gauge group is broken by matter VEVs charged under this group. Similarly, the SM gauge group is broken by generic vacuum configurations. Clearly, most of the string landscape is not relevant to our physical world. It is only possible to obtain useful predictions from the landscape once certain criteria are imposed. Here we require that gaugino condensation be allowed so that supersymmetry can be broken. Since the largest hidden sector group factor would dominate supersymmetry (SUSY) breaking, we focus on vacua in which this factor is preserved by matter VEVs. Within the set of our promising models, we can now study predictions for the scale of supersymmetry breaking.

Our MSSM candidates have the necessary ingredients for supersymmetry breaking via gaugino condensation in the hidden sector [18–21]. In particular, they contain non-Abelian gauge groups with little or no matter. The corresponding gauge interactions become strong at some intermediate scale which can lead to spontaneous supersymmetry breakdown. The specifics depend on the moduli stabilization mechanism, but the main features such as the scale of supersymmetry breaking hold more generally. In particular, the gravitino mass is related to the gaugino condensation scale $\Lambda \equiv \langle \lambda\lambda \rangle^{1/3}$ by

$$m_{3/2} \sim \frac{\Lambda^3}{M_{\mathrm{Pl}}^2}, \tag{2}$$

while the proportionality constant is model dependent. As an example, below we consider a well-known mechanism based on nonperturbative corrections to the Kähler potential.

The gaugino condensation scale is given by the renormalization group (RG) invariant scale of the condensing gauge group,

$$\Lambda \sim M_{\mathrm{GUT}} \exp\left(-\frac{1}{2\beta}\frac{1}{g^2(M_{\mathrm{GUT}})}\right), \tag{3}$$

where β is the beta-function. Since $1/g^2 = \mathrm{Re}S$, this translates into a superpotential for the dilaton S, $W \sim \exp(-3S/2\beta)$. This simple superpotential suffers from the notorious "runaway" problem; i.e., the vacuum of this system is at $S \to \infty$. One possible way to avoid it is to amend the tree level Kähler potential by a nonperturbative correction, $K = -\ln(S + \bar{S}) + \Delta K_{\mathrm{np}}$. The form of this correction has been studied in Refs. [22,23]. With a favorable choice of the parameters, the dilaton can be stabilized at a realistic value $\mathrm{Re}S \approx 2$ while breaking supersymmetry,

$$F_S \sim \frac{\Lambda^3}{M_{\mathrm{Pl}}}. \tag{4}$$

The T moduli can be stabilized at the same time by including T dependence in the superpotential required by T duality [24,25]. In simple examples, the overall T modulus is stabilized at the self-dual point such that $F_T = 0$. This leads to dilaton dominated supersymmetry breaking. For $\Lambda \sim 10^{13}$ GeV, the gravitino mass lies in the TeV range which is favored by phenomenology. SUSY breaking is communicated to the observable sector by gravity [18].

Similar considerations apply to generic models where the scale of supersymmetry breaking is generated by dimensional transmutation via gaugino condensation, irrespective of the dilaton stabilization mechanism.

In Fig. 1, we display the frequency of occurrence of various gauge groups in the hidden sector (see [26] for a

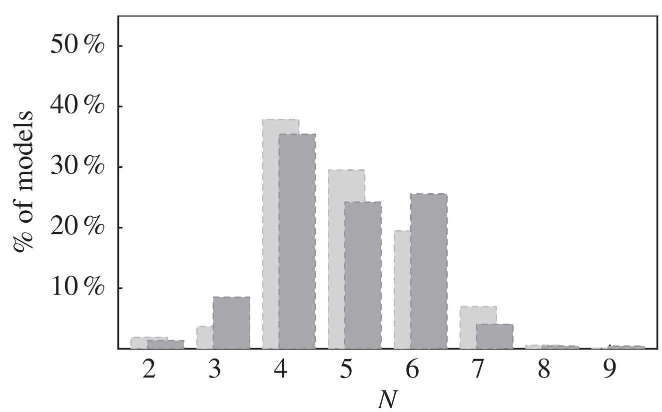

FIG. 1. Number of models vs the size of largest gauge group in the hidden sector. N labels SU(N), SO($2N$), E_N groups. The background corresponds to step 2, while the foreground corresponds to step 6.

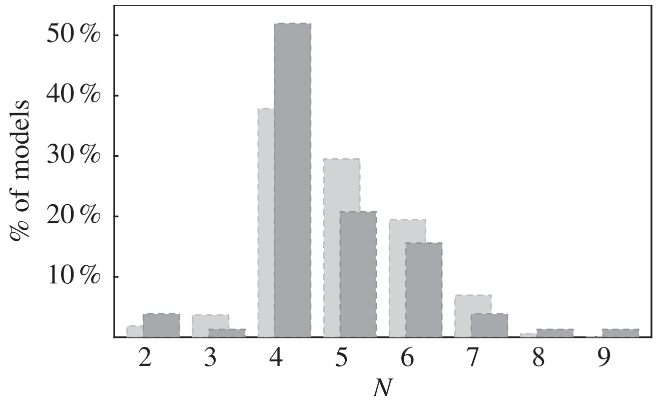

FIG. 2. As in Fig. 1 but with models of step 8 in the foreground.

related study). The preferred size (N) of the gauge groups depends on the conditions imposed on the spectrum. When all inequivalent models with 2 Wilson lines are considered, $N = 4$, 5, 6 appear with similar likelihood and $N = 4$ is somewhat preferred. If we require the massless spectrum to be the MSSM + vectorlike matter, the fractions of models with $N = 4$, 5, 6 become even closer. However, if we further require a heavy top quark and the decoupling of exotics at order 8, $N = 4$ is clearly preferred (Fig. 2). In this case, SU(4) and SO(8) groups provide the dominant contribution. Since all or almost all matter charged under these groups is decoupled, this leads to gaugino condensation at an intermediate scale. (We note that before step 8, gaugino condensation does not occur in many cases due to the presence of hidden sector matter.)

Possible scales of gaugino condensation are shown in Fig. 3. These are obtained from Eq. (3) by computing the beta-functions for each case and using $g^2(M_{\rm GUT}) \simeq 1/2$.

The correlation between the observable and hidden sectors is a result of the fact that modular invariance constrains the gauge shifts and Wilson lines in the two sectors. Moreover, the gauge shifts and Wilson lines determine the massless spectrum via the masslessness equations and the GSO projection.

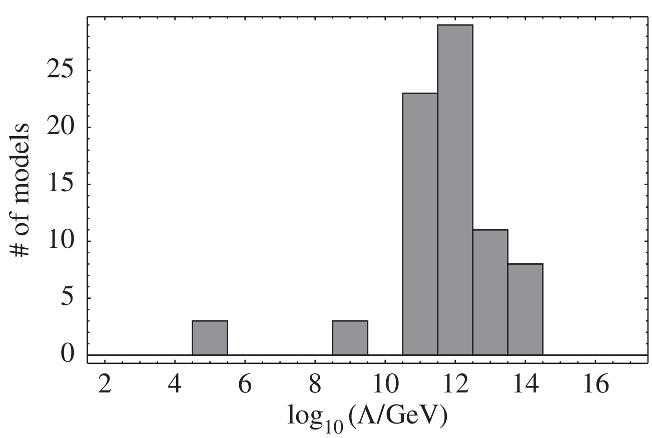

FIG. 3. Number of models vs scale of gaugino condensation.

We see that among the promising models, intermediate scale supersymmetry breaking is preferred. The underlying reason is that realistic spectra require complicated Wilson lines, which break the hidden sector gauge group. The surviving gauge factors are not too big (unlike in Calabi-Yau compactifications with the standard embedding), nor too small.

There are significant uncertainties in the estimation of the supersymmetry breaking scale. First, the identification of $\langle\lambda\lambda\rangle^{1/3}$ with the RG invariant scale is not precise. A factor of a few uncertainty in this relation leads to 2 orders of magnitude uncertainty in $m_{3/2}$. Also, there could be significant string threshold corrections which can affect the estimate. Thus, the resulting "prediction" for the superpartner masses should be understood within 2–3 orders of magnitude.

To conclude, we have considered a class of $\mathbb{Z}_6$-II orbifolds with 2 Wilson lines and SO(10) and E_6 local GUT structures. The choice of 2 Wilson lines is motivated by the apparent similarity of the first two fermion generations, while the local GUT structures are motivated by the quantum numbers of the SM families. We have found that requiring realistic features in this set of models is correlated with the supersymmetry breaking scale such that, in the context of gaugino condensation, low energy supersymmetry is favored.

It would be interesting to extend these results to Calabi-Yau compactifications of the heterotic string which also produce promising models [27,28].

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