Low Energy Supersymmetry from the Heterotic 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 \(\text{SU}(4)\) and \(\text{SO}(8)\) are favoured. In the context of gaugino condensation, this implies low energy supersymmetry breaking.

In the string theory landscape \([1, 2, 8, 4, 5]\), 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 favoured. 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 favoured by phenomenological considerations such as the gauge hierarchy problem and electroweak symmetry breaking.

We base our study \([3]\) on the orbifold compactifications \([8, 16]\) of the \(E_8\times E_8\) heterotic string \([8]\). Recent work on an orbifold GUT interpretation of heterotic models \([10, 11, 12]\) 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 \([8, 13, 16]\). 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

\[
V^{\text{SO}(10),1} = \left( \frac{1}{3}, \frac{2}{3}, \frac{1}{2}, 0, 0, 0, 0, 0 \right) \left( \frac{1}{3}, 0, 0, 0, 0, 0, 0 \right),
\]

\[
V^{\text{SO}(10),2} = \left( \frac{1}{3}, \frac{2}{3}, \frac{1}{2}, 0, 0, 0, 0, 0 \right) \left( \frac{1}{3}, \frac{1}{3}, 0, 0, 0, 0, 0 \right),
\]

and

\[
V^{E_6,1} = \left( \frac{1}{3}, \frac{1}{3}, \frac{1}{2}, 0, 0, 0, 0, 0 \right) \left( 0, 0, 0, 0, 0, 0 \right),
\]

\[
V^{E_6,2} = \left( \frac{1}{3}, \frac{1}{3}, \frac{1}{2}, 0, 0, 0, 0 \right) \left( \frac{1}{3}, \frac{1}{3}, 0, 0, 0, 0 \right).
\]

These shifts are chosen due to their “local grand unified theory (GUT)” \([13, 14, 15, 16]\) properties. They lead to massless matter in the first twisted sector \((T_{1})\) forming a \(16\)-plet of \(\text{SO}(10)\) in the case of \(V^{\text{SO}(10),1}\), \(V^{\text{SO}(10),2}\), 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

\[
G_{SM} \subset \text{SU}(5) \subset \text{SO}(10) \text{ or } E_6,
\]

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 \(G_{SM} \subset \text{SU}(5) \subset \text{SO}(10)\).
4. Select models with net three \((3, 2)\).
5. Select models with non–anomalous \(U(1)_Y \subset \text{SU}(5)\).
(6) Select models with net 3 SM families + Higgses + vector–like.

(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 $\mathcal{O}(10^5)$ inequivalent models, $\mathcal{O}(10^2)$ 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 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 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, 19, 20, 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 given by

$$m_{3/2} \approx \frac{\Lambda^3}{M_{Pl}^2},$$

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

The gaugino condensation scale $\Lambda \equiv (\lambda \lambda)^{1/3}$ is given by the renormalization group (RG) invariant scale of the condensing gauge group,

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

where $\beta$ is the beta–function. Since $1/g^2 = \text{Re}S$, this translates into a superpotential for the dilaton $S$, $W \sim \exp(-3S/2\beta)$. This simple superpotential suffers from the notorious “run–away” 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 non–perturbative correction, $K = -\ln(S + \bar{S}) + \Delta K_{\text{int}}$. The form of this correction has been studied in Refs. [22, 23]. With a favourable choice of the parameters, the dilaton can be stabilized at a realistic value $\text{Re}S \approx 2$ while breaking supersymmetry,

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

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 favoured by phenomenology. SUSY breaking is communicated to the observable sector by gravity [18].

![Figure 1](image.png)

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

In Fig. 1 we display the frequency of occurrence of various gauge groups in the hidden sector (see [26] for a 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 + vector–like 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
TABLE I: Statistics of $\mathbb{Z}_6$-II orbifolds based on the shifts $V_{SO(10),1}$, $V_{SO(10),2}$, $V_{E_6,1}$, $V_{E_6,2}$ with two Wilson lines.

<table>
<thead>
<tr>
<th>criterion</th>
<th>$V_{SO(10),1}$</th>
<th>$V_{SO(10),2}$</th>
<th>$V_{E_6,1}$</th>
<th>$V_{E_6,2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) inequiv. models with 2 WL</td>
<td>22,000</td>
<td>7,800</td>
<td>680</td>
<td>1,700</td>
</tr>
<tr>
<td>(3) SM gauge group $\subset$ SU(5) $\subset$ SO(10) (or $E_6$)</td>
<td>3563</td>
<td>1163</td>
<td>27</td>
<td>63</td>
</tr>
<tr>
<td>(4) 3 net (3, 2)</td>
<td>1170</td>
<td>492</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>(5) non–anomalous U(1)$_V$ $\subset$ SU(5)</td>
<td>528</td>
<td>234</td>
<td>3</td>
<td>22</td>
</tr>
<tr>
<td>(6) spectrum = 3 generations + vector-like</td>
<td>128</td>
<td>90</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>(7) heavy top</td>
<td>72</td>
<td>37</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>(8) exotics decouple + gaugino condensation</td>
<td>47</td>
<td>25</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

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

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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[17] www.th.physik.uni-bonn.de/nilles/Z6IIorbifold/.
[27] V. Braun et al., JHEP 05 (2006), 043.