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A mini-landscape of exact MSSM spectra in heterotic orbifolds

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Abstract

We explore a "fertile patch" of the heterotic landscape based on a $\mathbb{Z}_6$-II orbifold with SO(10) and E_6 local GUT structures. We search for models allowing for the exact MSSM spectrum. Our result is that of order 100 out of a total 3×10^4 inequivalent models satisfy this requirement.

1. Introduction

Although there are only a few consistent 10D string theories, there is a huge number of 4D string compactifications [1,2]. This leads to the picture that string theory has a vast landscape of vacua [3]. The (supersymmetric) standard model (SM) corresponds to one or more possible vacua which *a priori* might not be better than others. To obtain predictions from string theory one can employ the following strategy: First seek vacua that are consistent with observations and then study their properties. Optimistically, one might hope to identify certain features common to all realistic vacua, which would lead to predictions. Even if this is not the case, one might still be able to assign probabilities to certain features, allowing one to exclude certain patches of the landscape on a statistical basis. However, realistic vacua are very rare. For instance, in the context of orientifolds of Gepner models, the fraction of models with the chiral matter content of the standard model is about 10^{-14} [4,5]. The probability of getting something close to the MSSM in the context of intersecting D-branes in an orientifold background is 10^{-9} [6,7], even if one allows for chiral exotics. In this study, we show that certain patches of the heterotic landscape are more "fertile" in the sense that the analogous probabilities are at the percent level.

We base our model scan on the heterotic $E_8 \times E_8$ string [8,9] compactified on an orbifold [10–16]. Our study is motivated by recent work on an orbifold GUT interpretation of heterotic string models [17–19]. We focus on the $\mathbb{Z}_6$-II orbifold, which is described in detail in [17,19,20]. The search strategy is based on the concept of "local GUTs" [20–23] which inherits certain features of standard grand unification [24–26]. Local GUTs are specific to certain points in the compact space, while the 4D gauge symmetry is that of the SM. If matter fields are localized at such points, they form a complete GUT representation. This applies, in particular, to a **16**-plet of a local SO(10), which comprises one generation of the SM matter plus a right-handed neutrino [26,27],

$$\mathbf{16} = (\mathbf{3},\mathbf{2})_{1/6} + (\bar{\mathbf{3}},\mathbf{1})_{-2/3} + (\bar{\mathbf{3}},\mathbf{1})_{1/3} + (\mathbf{1},\mathbf{2})_{-1/2} + (\mathbf{1},\mathbf{1})_{1} + (\mathbf{1},\mathbf{1})_{0}, \tag{1}$$

where representations with respect to $SU(3)_C \times SU(2)_L$ are shown in parentheses and the subscript denotes hypercharge. On the other hand, bulk fields are partially projected out and form incomplete GUT multiplets. This offers an intuitive explanation for the

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observed multiplet structure of the SM [20–23]. This framework is consistent with MSSM gauge coupling unification as long as the SM gauge group is embedded in a simple local GUT $G_{\rm local} \supseteq {\rm SU}(5)$, which leads to the standard hypercharge normalization.

We find that the above search strategy, as opposed to a random scan, is successful and a considerable fraction of the models with SO(10) and E_6 local GUT structures pass our criteria. Out of about 3×10^4 inequivalent models which involve 2 Wilson lines, $\mathcal{O}(100)$ are phenomenologically attractive and can serve as an ultraviolet completion of the MSSM.

2. MSSM search strategy: Local GUTs

It is well known that with a suitable choice of Wilson lines it is not difficult to obtain the SM gauge group up to U(1) factors. The real challenge is to get the correct matter spectrum and the GUT hypercharge normalization. To this end, we base our strategy on the concept of local GUTs. An orbifold model is defined by the orbifold twist, the torus lattice and the gauge embedding of the orbifold action, i.e. the gauge shift V and the Wilson lines W_n. We consider only the gauge shifts V which allow for a local SO(10) or E_6 structure. That is, V are such that the left-moving momenta p (we use the standard notation, for details see e.g. [18–20]) satisfying

$$p \cdot V = 0 \bmod 1, \qquad p^2 = 2 \tag{2}$$

are roots of SO(10) or E_6 (up to extra group factors). Furthermore, the massless states of the first twisted sector T_1 are required to contain **16**-plets of SO(10) at the fixed points with SO(10) symmetry or **27**-plets of E_6 at the fixed points with E_6 symmetry.

Since these massless states from T_1 are automatically invariant under the orbifold action, they all survive in 4D and appear as complete GUT multiplets. In the case of SO(10), that gives one complete SM generation, while in the case of E_6 we have $\mathbf{27} = \mathbf{16} + \mathbf{10} + \mathbf{1}$ under SO(10). It is thus necessary to decouple all (or part) of the **10**-plets from the low energy theory.

The Wilson lines are chosen such that the standard model gauge group is embedded into the local GUT as

$$G_{\rm SM} \subset {\rm SU}(5) \subset {\rm SO}(10) \text{ or } E_6, \tag{3}$$

such that the hypercharge is that of standard GUTs and thus consistent with gauge coupling unification. The spectrum has certain features of traditional 4D GUTs, e.g. localized matter fields form complete GUT representations, yet there are important differences. In particular, interactions generally break GUT relations since different local GUTs are supported at different fixed points. Also, gauge coupling unification is due to the fact that the 10D (not 4D) theory is described by a single coupling.

Our model search is carried out in the $\mathbb{Z}_6$-II orbifold compactification of the heterotic $E_8 \times E_8$ string, which is described in detail in [19,20]. In this construction, there are 2 gauge shifts leading to a local SO(10) GUT [28],

$$\begin{aligned} V^{{\rm SO}(10),1} &= \left(\tfrac{1}{3}, \tfrac{1}{2}, \tfrac{1}{2}, 0, 0, 0, 0, 0\right) \quad \left(\tfrac{1}{3}, 0, 0, 0, 0, 0, 0, 0\right), \\ V^{{\rm SO}(10),2} &= \left(\tfrac{1}{3}, \tfrac{1}{3}, \tfrac{1}{3}, 0, 0, 0, 0, 0\right) \quad \left(\tfrac{1}{6}, \tfrac{1}{6}, 0, 0, 0, 0, 0, 0\right), \end{aligned} \tag{4}$$

and 2 shifts leading to a local E_6 GUT,

$$\begin{aligned} V^{E_6,1} &= \left(\tfrac{1}{2}, \tfrac{1}{3}, \tfrac{1}{6}, 0, 0, 0, 0, 0\right) \quad (0, 0, 0, 0, 0, 0, 0, 0), \\ V^{E_6,2} &= \left(\tfrac{2}{3}, \tfrac{1}{3}, \tfrac{1}{3}, 0, 0, 0, 0, 0\right) \quad \left(\tfrac{1}{6}, \tfrac{1}{6}, 0, 0, 0, 0, 0, 0\right). \end{aligned} \tag{5}$$

We will focus on these shifts and scan over possible Wilson lines to get the SM gauge group. The $\mathbb{Z}_6$-II orbifold allows for up to two Wilson lines of order 2 and for one Wilson line of order 3 (cf. [19,20,29]).

The next question is how to get 3 matter generations. The simplest possibility is to use 3 equivalent fixed points with **16**-plets [21] which appear in models with 2 Wilson lines of order 2. If the extra states are vectorlike and can be given large masses, the low energy spectrum will contain 3 matter families. However, this strategy fails since all such models contain chiral exotic states [20]. In the case of E_6, it does not work either since one cannot obtain $G_{\rm SM} \subset {\rm SU}(5) \subset {\rm SO}(10) \subset E_6$ with 2 Wilson lines of order 2.

The next-to-simplest possibility is to use 2 equivalent fixed points which give rise to 2 matter generations. The third generation would then have to come from other twisted or untwisted sectors. The appearance of the third family can be linked to the SM anomaly cancellation. Indeed, the untwisted sector contains part of a **16**-plet. Then the simplest options consistent with the SM anomaly cancellation are that the remaining matter either completes the **16**-plet or provides vector-like partners of the untwisted sector. In more complicated cases, additional **16**- or $\overline{\mathbf{16}}$-plets can appear. The localized **16**- and **27**-plets are true GUT multiplets, whereas the third or “bulk” generation only has the SM quantum numbers of an additional **16**-plet. We find that the above strategy is successful and one often gets net 3 families. The other massless states are often vector-like with respect to the SM gauge group and can be given large masses consistent with string selection rules.

In our MSSM search, we focus on models of this type (although we include all models with 2 Wilson lines in the statistics). These are realized when 1 Wilson line of order 3 and 1 Wilson line of order 2 are present. We require that the spectrum contain 3 matter families plus vector-like states. Furthermore, we discard models in which the SU(5) hypercharge is anomalous. Although a non-anomalous hypercharge could be defined, typically it would not have the GUT normalization and thus would not be consistent with gauge unification.