Light Z' in heterotic string standardlike models

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The discovery of the Higgs boson at the LHC supports the hypothesis that the Standard Model provides an effective parametrization of all subatomic experimental data up to the Planck scale. String theory, which provides a viable perturbative approach to quantum gravity, requires for its consistency the existence of additional gauge symmetries beyond the Standard Model. The construction of heterotic string models with a viable light Z' is, however, highly constrained. We outline the construction of standardlike heterotic string models that allow for an additional Abelian gauge symmetry that may remain unbroken down to low scales. We present a string inspired model, consistent with the string constraints.

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I. INTRODUCTION

String theory provides a predictive framework for exploring unification of the gravitational and gauge interactions. The consistency of string theory dictates that it must accommodate a specific number of degrees of freedom to produce an anomaly free and finite framework. Some of these degrees of freedom give rise to the gauge symmetries that we may identify with those of the subatomic gauge interactions, whereas the others do not produce an observable manifestation in contemporary experiments. This is both a theoretical challenge and a technological one, since the hierarchy of the gravitational and gauge interactions implies that the additional degrees of freedom required by string theory are interacting extremely weakly with its observable segments.

The methodology to explore the string unification of gravity and the gauge interactions entails the construction of string models that reproduce the observed subatomic matter and interactions. Indeed, numerous quasirealistic models have been constructed by using target-space and world sheet techniques [1]. To date all these models possess $N = 1$ spacetime supersymmetry, which stabilizes the constructions and provides a better fit to the experimental data in some scenarios. However, the question of supersymmetry breaking is an open issue and it may well be that it is not manifested within reach of contemporary experiments. The main problem in that case will be to construct viable string models in which supersymmetry is broken at a higher scale, which is not outside the realm of possibilities. The subatomic data are encoded in the Standard Model of particle physics, and therefore the realistic string constructions aim to reproduce the minimal supersymmetric Standard Model. The Standard Model data provide hints that the matter states and gauge bosons originate from representations of larger symmetry groups. Most appealing in this context is the embedding of the Standard Model matter states in the three **16** spinorial representations of an $SO(10)$ gauge group. This structure is reproduced perturbatively in the heterotic string.

The gauge content of the Standard Model consists of the three group sectors that correspond to the strong, electroweak and weak hypercharge interactions. These correspond to a rank-4 group, whereas the heterotic string in four dimensions may give rise to a rank-22 group. While the Standard Model states in heterotic string models are typically neutral under 8 of these degrees of freedom, they are charged with respect to the others. The possible observation of an additional gauge degree of freedom at contemporary experiments will provide evidence for the additional degrees of freedom predicted by string theory.

The existence of additional $U(1)$ gauge symmetries in string theory has indeed been of interest since the observation that string theory is free of gauge and gravitational anomalies [2]. Indeed, extra Z' string inspired models occupy a substantial number of studies that utilize effective field theory constructions to explore their phenomenological implications [3–6]. However, quite surprisingly, the construction of quasirealistic world sheet heterotic string models that accommodate an extra $U(1)$ gauge symmetry in the observable sector, which may remain unbroken at low scales, has proven to be an arduous task for a variety of phenomenological constraints. In fact, to date there does not exist a single quasirealistic exact string solution that accommodates an extra $U(1)$ gauge symmetry that remains viable down to low scales. The problem stems from the fact that in many string constructions the extra family universal $U(1)$'s, that are typically discussed in string inspired models, are anomalous, and cannot remain unbroken down to low scales.

On the other hand, models that give rise to anomaly free family universal extra $U(1)$ symmetries cannot accommodate the low scale gauge coupling data [7]. The primary reason is that the charge assignment of the Standard Model

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states under these anomaly free $U(1)$'s does not admit an E_6 embedding, which emerges as a necessary ingredient to accommodate the gauge coupling data. In [7] we discussed the world sheet construction of extra anomaly free Z' models that do admit an E_6 embedding. The observable gauge symmetry at the string level in the model of [7] is $SO(6) \times SO(4) \times U(1)$, which is broken to $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{Z'}$, with the $U(1)_{Z'}$ being anomaly free and admits an E_6 embedding.

In this paper we discuss the world sheet construction in standardlike models, i.e. in which the observable gauge symmetry is broken at the string level to $SU(3)_C \times SU(2)_W \times U(1)_{B-L} \times U(1)_{T_{3_R}} \times U(1)_\zeta$. In both of these cases the symmetry is broken to $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{Z'}$, by the vacuum expectation value (VEV) of the Standard Model singlet in the **16** representation of $SO(10)$. We use the tools of the free fermionic formulation for our analysis, which for the gauge degrees of freedom of the heterotic string is entirely equivalent to a free bosonic description [8].

II. ADDITIONAL $U(1)$'S IN HETEROTIC STRING MODELS

The heterotic string models in the free fermionic formulation [9] produce some of the most realistic string models constructed to date. The quasirealistic models correspond to $Z_2 \times Z_2$ orbifold compactifications, at special points in the moduli space, with discrete Wilson lines [10]. They lead to a rich space of three generation models charged under a subgroup of $SO(10)$. In the free fermionic formulation all the degrees of freedom needed to cancel the conformal world sheet anomaly are represented in terms of free fermions propagating on the string world sheet. For example, a set of eight complex fermions give rise to the Cartan generators of the observable gauge group and are denoted by $\{\bar{\psi}^{1,\ldots,5}, \bar{\eta}^{1,2,3}\}$. Under parallel transport around the noncontractible loops of the world sheet torus, these fermions pick up a phase. The phases of the world sheet fermions, constrained by modular invariance, then make up our boundary condition basis vectors which, in addition to the associated one-loop generalized Gliozzi-Scherk-Olive (GGSO) coefficients, describe the heterotic string models in the free fermionic formulation fully [9].

The basis vectors span a finite additive group, Ξ, consisting of the sectors, α, from which the physical states are obtained by acting on the vacuum with bosonic and fermionic oscillators and by applying the GGSO projections.

For a sector consisting of periodic complex fermions only, the vacuum is a spinor, $|\pm\rangle$, representing the Clifford algebra of the corresponding zero modes, f_0 and f_0^*, which have fermion number $F(f) = 0, -1$ respectively. In addition, the Cartan subalgebra of our rank-22 group is $U(1)^{22}$, generated by the right-moving currents, $\bar{f}\bar{f}^*$. For each complex fermion, f, the $U(1)$ charges correspond to

$$Q(f) = \frac{1}{2}\alpha(f) + F(f). \tag{2.1}$$

The representation (2.1) shows that $Q(f)$ is identical to the world sheet fermion numbers, $F(f)$, for world sheet fermions with Neveu-Schwarz boundary conditions, $\alpha(f) = 0$, and is $F(f) + \frac{1}{2}$ for those with Ramond boundary conditions, $\alpha(f) = 1$. The charges for the $|\pm\rangle$ spinor vacua are $\pm\frac{1}{2}$.

The boundary conditions of the set of eight complex world sheet fermions that give rise to the Cartan generators of the observable gauge group, with $\bar{\psi}^{1,\ldots,5}$ generating the $SO(10)$ group and $\bar{\eta}^{1,2,3}$ generating three $U(1)$ symmetries, denoted by $U(1)_{1,2,3}$, will be the focus of our discussion in this paper. The vector bosons contributing to the four-dimensional observable gauge group are charged with respect to these Cartan generators, and arise from the untwisted sector, as well as from twisted sectors, i.e. sectors that contain periodic fermions.

The early three generation free fermionic models were Nanopoulos-Antoniadis-Hagelin-Ellis (NAHE)-based models [11] with more recent methods for the systematic classification of free fermionic models developed in [12–14]. In NAHE-based models [15–19] the first set of five basis vectors, $\{\mathbf{1}, S, b_1, b_2, b_3\}$, is fixed. The addition of b_1, b_2 and b_3 breaks the $N = 4$ spacetime SUSY, generated by S, to $N = 1$ and the respective sectors correspond to the three twisted sectors of the $Z_2 \times Z_2$ orbifold. At this stage, the gauge symmetry is $SO(10) \times SO(6)^3 \times E_8$ with the hidden E_8 being generated by $\{\bar{\phi}^{1,\ldots,8}\}$. Adding the basis vector $x \equiv \{\bar{\psi}^{1,\ldots,5}, \bar{\eta}^{1,2,3}\} \equiv 1$ produces the extended NAHE basis set [20] with the resulting gauge symmetry being $E_6 \times U(1)^2 \times SO(4)^3 \times E_8$, where the linear combination $J_\zeta = \bar{\eta}^{1*}\bar{\eta}^1 + \bar{\eta}^{2*}\bar{\eta}^2 + \bar{\eta}^{3*}\bar{\eta}^3$ generates the $U(1)$ charges in the decomposition of $E_6 \to SO(10) \times U(1)$. As we discuss below the vector x plays a crucial role in generating a viable light Z' in free fermionic models.

The next stage in constructing NAHE-based models involves adding basis vectors to the NAHE set. These additional vectors reduce the number of chiral generations to three and simultaneously break the four-dimensional gauge group. The visible $SO(10)$ gauge symmetry is broken to one of its maximal subgroups:

(1)

    (i) $SU(5) \times U(1)$ (FSU5) [15];

    (ii) $SU(3) \times SU(2) \times U(1)^2$ (SLM) [16];

    (iii) $SO(6) \times SO(4)$ (PS) [17];

(2)

    (i) $SU(3) \times U(1) \times SU(2)^2$ (LRS) [18];

    (ii) $SU(4) \times SU(2) \times U(1)$ (SU421) [19].

The difference between the models in case I and those in case II is the anomalous $U(1)_A$ symmetry that arises [22]. In case I, the $U(1)_{1,2,3}$ and their linear combination,

$$U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3, \tag{2.2}$$

are anomalous, whereas in the models of case II they are anomaly free. This can be seen from the different symmetry

breaking patterns: in the first case, $E_8 \times E_8$, generated by the basis set $\{\mathbf{1}, S, \zeta, x\}$, breaks to $SO(16) \times SO(16)$ due to the choice of GGSO phases. Implementing b_1 and b_2 then breaks $SO(16) \times SO(16) \rightarrow SO(10) \times U(1)^3 \times SO(16)$. We may also achieve this by breaking $E_8 \times E_8 \rightarrow E_6 \times U(1)^2 \times E_8$ via the addition of b_1 and b_2 as an initial step. The gauge symmetry is then reduced to $SO(10) \times U(1)_\zeta \times U(1)^2 \times SO(16)$ by GGSO projections that are equivalent to Wilson line breaking (e.g. [21]). The $U(1)_\zeta$ becomes anomalous because of the E_6 breaking to $SO(10) \times U(1)_\zeta$ and the GGSO projections removing states that would populate the 27 representation [22]. On the other hand, the models in case II are constructed from vacua with an $E_7 \times E_7$ gauge symmetry. These models circumvent the E_6 embedding; hence $U(1)_\zeta$ may remain anomaly free. Only having the MSSM states survive to low scales produces an $SU(2)^2 \times U(1)_\zeta$ mixed anomaly, which necessitates the existence of additional doublets in the spectrum [6]. However, the charges of the additional doublets not possessing the E_6 embedding leads to disagreement with the experimental gauge coupling data at the electroweak scale [7]. By contrast, if the charges do admit an E_6 embedding, the well-known cancellation between the additional doublets and triplets in the renormalization group equation solutions $\sin^2\theta_W(M_Z)$ and $\alpha_s(M_Z)$ [7] facilitates the compatibility with the gauge coupling data [7]. We note that in both cases the relevant combination is the identical combination of world sheet currents given by $U(1)_\zeta$ in (2.2).

We remark that the string models produce several additional $U(1)$'s in the observable sector that may *a priori* give rise to a low scale Z'. Two of those are the two combinations of $U(1)_{1,2,3}$, which are orthogonal to $U(1)_\zeta$. However, these are, in general, family nonuniversal and/or anomalous in the string models. Additionally, the models contain the combination,[1] $U(1)_C - U(1)_L$, which is embedded in $SO(10)$, and is orthogonal to the weak hypercharge [4]. Here Q_C and Q_L are given in terms of the world sheet charges by

$$Q_C = Q(\bar{\psi}^1) + Q(\bar{\psi}^2) + Q(\bar{\psi}^3) \quad \text{and}$$
$$Q_L = Q(\bar{\psi}^4) + Q(\bar{\psi}^5). \tag{2.3}$$

However, this $U(1)$ combination has to be broken at a high scale to produce sufficient suppression of m_{ν_τ}. The reason is the underlying $SO(10)$ symmetry at the string level, which dictates that the τ-neutrino Yukawa coupling is equal to that of the top quark. Hence, to produce a sufficiently suppressed mass term for ν_τ requires a relatively high seesaw scale, which is induced by the VEV of the Standard Model singlet in the **16** representation of $SO(10)$ [23].

A light Z' in heterotic string models must therefore be a linear combination of $U(1)_C$, $U(1)_L$ and $U(1)_\zeta$. Thus, the

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[1] $U(1)_C = 3/2U(1)_{B-L}$ and $U(1)_L = 2U(1)_{T_{3_R}}$ are used in free fermionic models.

$U(1)_\zeta$ symmetry, given by (2.2), must be anomaly free. Furthermore, the gauge coupling data dictate that the charges of the light states must admit an E_6 embedding. The task then is to obtain an anomaly free $U(1)_\zeta$, which admits an E_6 embedding of the charges. However, as we noted above, in the quasirealistic NAHE-based free fermionic models [15–19], $U(1)_\zeta$ is either anomalous or does not admit an E_6 embedding.

We look for potential candidates in the space of symmetric orbifolds classified in [13]. These models, generically, admit an anomalous $U(1)_\zeta$ due to its E_6 embedding. However, a subset of these models may allow for an anomaly free $U(1)_\zeta$: the self-dual models under the spinor-vector duality of [24]. The spinor-vector duality exchanges vectorial **10** representations of $SO(10)$ with spinorial **16** representations in the twisted sectors. The self-dual models are those with an equal number of spinorial and vectorial representations. E_6 is broken when these states arise from different twisted sectors. A self-dual, three generation model with unbroken $SO(10)$ symmetry was presented in [13], whereas such a model with a broken $SO(10)$ symmetry has not yet been constructed.

Another way to construct potential candidate models with an anomaly free $U(1)_\zeta$ is by following an alternative symmetry breaking pattern to $E_6 \rightarrow SO(10) \times U(1)_\zeta$. Previously this was accomplished by projecting out the enhancing gauge bosons originating in the x sector, i.e. those transforming in the **128** of $SO(16)$ that enhance $SO(16) \rightarrow E_8$. Here we may build models that keep these enhancing gauge bosons but project out some of the $SO(10)$ gauge bosons. This will break E_6 to a different subgroup, as shown, for example, in the three generation $SU(6) \times SU(2)$ models of [14]. The Standard Model generations are then embedded in the $(\mathbf{15}, \mathbf{1})$ and $(\mathbf{6}, \mathbf{2})$ representations of $SU(6) \times SU(2)$, i.e. all the states in the **27** of E_6 are retained in the spectrum. The recipe, therefore, for constructing heterotic string models with anomaly free $U(1)_\zeta$ is to retain the states arising from the x-basis vector. In this case the untwisted gauge symmetry is enhanced by the spacetime vector bosons arising from x. At the same time the twisted matter states from a given sector $\alpha \in \Xi$ are complemented by the states from the sector $\alpha + x$ to form complete E_6 representations, decomposed under the unbroken gauge symmetry at the string scale.

III. STANDARDLIKE MODELS WITH LIGHT Z'

In [7] we discussed the construction of Pati-Salam heterotic string models with an anomaly free $U(1)_{Z'}$, along the lines outlined at the end of Sec. II. In this section we articulate the construction of standardlike heterotic string models with an anomaly free $U(1)_{Z'}$. The low scale Z' in the string models is a combination of the Cartan generators, $U(1)_{1,2,3}$, that are generated by the right-moving complex

world sheet fermions $\bar{\eta}^{1,2,3}$, together with a $U(1)$ symmetry, which is embedded in the $SO(10)$ and is orthogonal to the weak hypercharge.

The vector bosons that generate the four-dimensional gauge group in the free fermionic models arise from three sectors: the untwisted sector; the sector x; and the sector $\zeta = 1 + b_1 + b_2 + b_3 = \{\bar{\phi}^{1,\dots,8}\} \equiv 1$. The basis set $\{1, S, x, \zeta\}$ results in a four-dimensional model with $N = 4$ spacetime supersymmetry. This model will have, at a generic point in the compactified space, either $E_8 \times E_8$ or $SO(16) \times SO(16)$ gauge symmetry depending on the GGSO phase $c\binom{x}{\zeta} = \pm 1$. In the $E_8 \times E_8$ case, the generators of the observable E_8 originate in the untwisted and in the x sectors, with the adjoint of $SO(16)$ coming from the

untwisted sector and the enhancing gauge bosons, transforming in the **128**, originating in the x sector.

Spacetime supersymmetry is broken to $N = 1$ by the addition of the basis vectors b_1 and b_2. This also reduces the observable gauge symmetry from $E_8 \to E_6 \times U(1)^2$ or $SO(16) \to SO(10) \times U(1)^3$. The gauge symmetry can be reduced even further by additional vectors. With the exception of the model in [14], the quasirealistic free fermionic models follow the second symmetry breaking pattern; i.e. the vector bosons arising from the x sector are, in all these models, projected out.

We consider the symmetry breaking pattern in the observable sector induced by the following boundary condition assignments in three consecutive basis vectors:

$$1. \, b\{\bar{\psi}^{1,\dots,5},\bar{\eta}^{1,2,3}\} = \{1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1\} \Rightarrow SO(6) \times SO(4) \tag{3.1}$$

$$2. \, b\{\bar{\psi}^{1,\dots,5},\bar{\eta}^{1,2,3}\} = \{1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 1 \quad 1\} \Rightarrow SO(4) \times SO(2) \times SO(2) \times SO(2) \tag{3.2}$$

$$3. \, b\{\bar{\psi}^{1,\dots,5},\bar{\eta}^{1,2,3}\} = \left\{\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\right\} \Rightarrow SU(2) \times U(1) \times U(1) \times U(1) \times U(1), \tag{3.3}$$

where on the right-hand side we display the breaking pattern of the untwisted $SO(10)$ generators, induced by the consecutive basis vectors, and we omitted the common factor of $U(1)^3$ corresponding to $\bar{\eta}^{1,2,3}$. We consider here only the models with symmetric boundary conditions for the set of real fermions $\{y, \omega | \bar{y}, \bar{\omega}\}^{1,\dots,6}$. The boundary condition assignments for $\bar{\eta}^{1,2,3}$ are fixed by the modular invariance constraints on $N_{ij}(v_i \cdot b_j) = 0 \mod 4$, whereas the modular invariance constraints on the three additional basis vectors are fixed by the boundary conditions of the world sheet fermions $\{\bar{\phi}^{1,\dots,8}\}$, which produce the Cartan generators of the hidden sector gauge group.

We denote the three vectors that extend the NAHE set by α, β and γ. Each of these vectors then incorporates one of the boundary condition assignments given in (3.1), (3.2) and (3.3), respectively. The vector x may then arise as, for example, the vector 2γ, or as a separate basis vector. The requirement is, however, that the vector bosons arising from the x sector are retained in the spectrum.

The untwisted gauge symmetry arising from the untwisted vector bosons after implementation of the GGSO projections of the basis vectors α, β and γ is

$$SU(2) \times U(1)_C \times U(1)_{\bar{\psi}^3} \times U(1)_{\bar{\psi}^4} \times U(1)_{\bar{\psi}^5}$$
$$\times U(1)_{\bar{\eta}^1} \times U(1)_{\bar{\eta}^2} \times U(1)_{\bar{\eta}^3}, \tag{3.4}$$

where $Q_C = Q(\bar{\psi}^1) + Q(\bar{\psi}^2)$ and we denoted in (3.4) the world sheet fermions that generate each $U(1)$ symmetry. The inclusion of the spacetime vector bosons that survive

the GGSO projections from the x sector then enhances the untwisted gauge symmetry to

$$SU(3)_C \times SU(2)_L \times U(1)_{C'} \times U(1)_{4'}$$
$$\times U(1)_{5'} \times U(1)_{1''} \times U(1)_{2''}, \tag{3.5}$$

where

$$U(1)_{3'} = U(1)_{\bar{\psi}^3} + U(1)_{\bar{\psi}^4} + U(1)_{\bar{\psi}^5} - U(1)_\zeta; \tag{3.6}$$

$$U(1)_{2'} = U(1)_C + U(1)_{\bar{\psi}^3} + U(1)_{\bar{\psi}^4}$$
$$+ U(1)_{\bar{\psi}^5} + U(1)_\zeta; \tag{3.7}$$

$$U(1)_{C'} = 3U(1)_C - U(1)_{\bar{\psi}^3} - U(1)_{\bar{\psi}^4}$$
$$- U(1)_{\bar{\psi}^5} - U(1)_\zeta; \tag{3.8}$$

$$U(1)_{4'} = U(1)_{\bar{\psi}^4} - U(1)_{\bar{\psi}^5}; \tag{3.9}$$

$$U(1)_{5'} = 2U(1)_{\bar{\psi}^3} - U(1)_{\bar{\psi}^4} - U(1)_{\bar{\psi}^5}; \tag{3.10}$$

$$U(1)_{1''} = U(1)_{\bar{\eta}^1} - U(1)_{\bar{\eta}^2}; \tag{3.11}$$

$$U(1)_{2''} = U(1)_{\bar{\eta}^1} + U(1)_{\bar{\eta}^2} - 2U(1)_{\bar{\eta}^3}. \tag{3.12}$$

$U(1)_{3'}$ and $U(1)_{2'}$ are the combinations that are embedded in $SU(3)_C$ and $SU(2)_L$, respectively, and $U(1)_\zeta$ is given by (2.2). The observable matter representations in the free

TABLE I. High scale spectrum and $SU(3)_C \times SU(2)_L \times U(1)_{C''} \times U(1)_{4'} \times U(1)_{\zeta'}$ quantum numbers, with $i = 1, 2, 3$ for the three light generations. The charges are displayed in the normalization used in free fermionic heterotic string models.

Field	$SU(3)_C$	$\times SU(2)_L$	$U(1)_{C''}$	$U(1)_{4'}$	$U(1)_{\zeta'}$
Q_L^i	3	2	$+\frac{1}{2}$	0	$\frac{1}{2}$
u_L^i	$\bar{3}$	1	$-\frac{1}{2}$	-1	$\frac{1}{2}$
d_L^i	$\bar{3}$	1	$-\frac{1}{2}$	$+1$	$\frac{1}{2}$
e_L^i	1	1	$+\frac{3}{2}$	$+1$	$\frac{1}{2}$
L_L^i	1	2	$-\frac{3}{2}$	0	$\frac{1}{2}$
N_L^i	1	1	$+\frac{3}{2}$	-1	$\frac{1}{2}$
D^i	3	1	-1	0	-1
$\bar{D}^i$	$\bar{3}$	1	$+1$	0	-1
$\bar{H}^i$	1	2	0	$+1$	-1
H^i	1	2	0	-1	-1
S^i	1	1	0	0	$+2$

fermionic models arise from the sectors b_j, which produce states in the spinorial **16** representation of $SO(10)$, decomposed under the unbroken untwisted gauge group, and the sectors $b_j + x$, which produce states in the **10** + **1** representations of $SO(10)$ that are decomposed similarly. Under the rotation of the Cartan generators displayed in (3.6)–(3.12), the states from these sectors combine to form representations of the enhanced gauge group in (3.5). We can make a further rotation on the $U(1)$ generators by taking

$$U(1)_{C''} = \frac{1}{4} U(1)_{C'} - \frac{1}{2} U(1)_{5'}; \quad (3.13)$$

$$U(1)_{\zeta'} = \frac{1}{4} U(1)_{C'} + \frac{1}{2} U(1)_{5'}. \quad (3.14)$$

This reproduces the charge assignments in the **27** representation of E_6, which are displayed in Table I. Additionally, the model contains pairs of heavy Higgs states

$$\mathcal{N} + \bar{\mathcal{N}} = \left(1, 1, \frac{3}{2}, -1, \frac{1}{2}\right) + \left(1, 1, -\frac{3}{2}, +1, -\frac{1}{2}\right) \quad (3.15)$$

that are needed to break the gauge symmetry to $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Z'}$, where the $U(1)_Y$ and $U(1)_{Z'}$ combinations are given by

$$U(1)_Y = \frac{1}{3} U(1)_{C''} + \frac{1}{2} U(1)_{4'}, \quad (3.16)$$

$$U(1)_{Z'} = \frac{1}{3} U(1)_{C''} - \frac{1}{3} U(1)_{4'} - \frac{5}{3} U(1)_{\zeta'}. \quad (3.17)$$

The model also contains a pair of vectorlike light Higgs states that are needed to obtain agreement with the gauge coupling data at the electroweak scale,
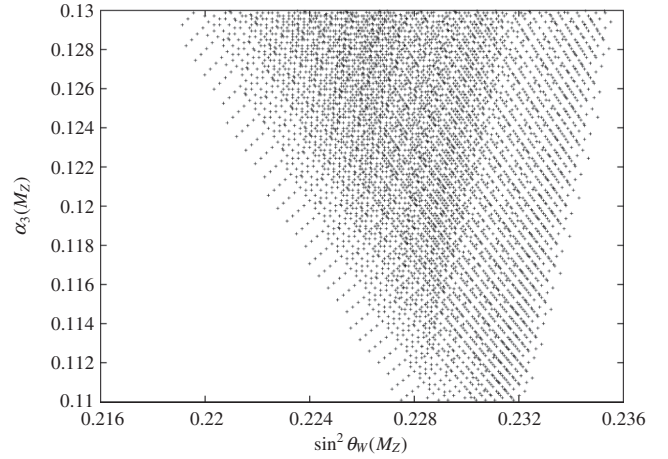

FIG. 1. Solutions of the gauge coupling RGEs in the presence of an additional $U(1)$ symmetry with E_6 embedding [26], assuming string unification between $2 \cdot 10^{16} \leq \mu \leq 5.27 \cdot 10^{17}$ GeV and $0 < \alpha_{\text{string}} \leq 0.1$. The phenomenologically viable region corresponds to $M_{\text{string}} \sim 2 \cdot 10^{16}$ GeV within this range of α_{string}.

$$h + \bar{h} = (1, 2, 0, -1, +1) + (1, 2, 0, +1, -1). \quad (3.18)$$

The vectorlike nature of the additional electroweak doublet pair is required because of anomaly cancellation. In Fig. 1 we demonstrate that this spectrum, assuming unification of the couplings at the heterotic string scale, is in agreement with $\sin^2\theta_W(M_Z)$ and $\alpha_3(M_Z)$.

The superpotential of the model contains the following terms:

$$Qu\bar{H} + QdH + LeH + LN\bar{H} \quad (3.19)$$

$$+ H\bar{H}S + D\bar{D}S \quad (3.20)$$

$$+ QQD + ud\bar{D} + dND + ueD + QL\bar{D} \quad (3.21)$$

$$+ Qu\bar{h} + LN\bar{h} + h\bar{h}\phi, \quad (3.22)$$

where ϕ stands for generic E_6 singlet fields arising in the string models and generation indices have been suppressed. The superpotential contains couplings of the electroweak doublets appearing in Table I, as well as of the additional pair of electroweak doublets in (3.18). The identification of the electroweak Higgs doublets requires a detailed analysis of the renormalization group evolution of the fermion and scalar couplings. Some of the couplings appearing in (3.22) should be suppressed by additional discrete symmetries [25] to ensure proton longevity. Light neutrino masses are generated in the model by the nonrenormalizable terms $NN\bar{\mathcal{N}}\bar{\mathcal{N}}$, which generate heavy Majorana masses for the right-handed neutrinos due to the VEV of the heavy Higgs states appearing in (3.15). We note that the existence of an extra Z' at low scale necessitates the existence of the

additional matter states at the low scale to guarantee that the spectrum is anomaly free.

IV. CONCLUSIONS

The Standard Model of particle physics provides a parametrization for subatomic experimental data, which is in agreement with all observations to date. The recent discovery of the Higgs boson by the ATLAS and CMS experiments [27] at the LHC provides further evidence for the validity of the Standard Model up to the Planck scale. Additional support for this possibility stems from matter gauge charges, proton longevity, the suppression of neutrinos' masses, and logarithmic evolution of the Standard Model parameters in the gauge and matter sectors. Preservation of the logarithmic running in the scalar sector of the Standard Model mandates its augmentation with a new symmetry, with supersymmetry being a phenomenologically viable possibility. Ultimately, we would like to calculate the parameters of the Standard Model from a fundamental theory. String theory provides a consistent framework to pursue this endeavor within a perturbatively finite theory of quantum gravity.

A remarkable feature of string theory is that its consistency mandates the existence of additional gauge degrees of freedom. Many of these extra degrees of freedom are expected to be broken at a high scale or be hidden from the Standard Model states. Remarkably, however, while the construction of quasirealistic standardlike heterotic string models has been achieved, the construction of such models with a light Z' has proven to be an arduous task.

In this paper we explored the construction of heterotic string standardlike models with a viable Z' within the free fermionic formulation. The key in this construction is to maintain in the spectrum the spacetime vector bosons from the x sector that enhance the gauge symmetry arising from the untwisted sector. The result is that all the matter states from the **27** of E_6, decomposed under the final gauge group, are retained in the spectrum. Concrete string models that realize this enhancement are the $SU(6) \times SU(2)$ heterotic string models of [14]. The outcome is that the family universal $U(1)_\zeta$ combination in (2.2) is anomaly free and agreement with the gauge coupling data at the electroweak scale is facilitated. The search for heterotic string standard like models that realize this construction is currently underway.

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