Concrete semi-realistic string/M theory constructions often predict the existence of new physics at the TeV scale, which may be different in character from the bottom-up ideas that are motivated by specific problems of the standard model. I describe two examples, heterotic and open string, of such constructions. The latter has a particularly interesting strongly-coupled quasi-hidden sector, which may lead to composite states at low energy and dynamical supersymmetry breaking. General issues, such as grand unification versus direct compactification, additional $U(1)$'s, gauge symmetries and other exotics, and flat directions are discussed.

1 Unification: from the Top Down

Most studies of possible new physics at the TeV scale are of the bottom-up type, motivated by attempts to solve problems or explain arbitrary features of the standard model. However, there could also be new physics that survives as a TeV-scale remnant of an underlying theory, e.g., at the Planck scale, that does not directly address problems of the standard model but which could provide an important probe of the underlying unification or dynamics.

The string/M theory paradigm is both ambitious and promising. It holds out a real possibility of eventually providing a complete and consistent description of all phenomena up to the Planck scale. Nevertheless, realization of these goals is held up by a number of significant obstacles. These include the need to explore the many realms of perturbative and non-perturbative M theory, the wide variety of possible compactifications, and the difficulties of stabilizing the dilaton and moduli and finding a satisfactory scheme for supersymmetry breaking. Accounting for the vanishing or incredibly tiny cosmological constant, $\Lambda_{\text{cosm}}$, appears to be especially intractable.

Significant progress may have to await formal and mathematical developments in our understanding of M theory, but it is important to carry out detailed studies of specific constructions in parallel. These could suggest new TeV-scale physics, suggest promising new directions for the exploration of M theory, allow the development of computational techniques, and generally help us understand the range of issues and possibilities.

It is unlikely that anyone will find a fully realistic construction in the near future, so most studies have emphasized specific features, such as the possibility that the fundamental scale $M_{\text{fund}}$ is much smaller than $M_{\text{pl}}$ (large extra dimensions), possibilities for supersymmetry breaking and an acceptable $\Lambda_{\text{cosm}}$, and models with dynamical dilaton/moduli stabilization. I will concentrate on studies carried out with M. Cvetič and others (and closely related work) of constructions leading to semi-realistic four-dimensional gauge...
theories containing the MSSM and for which $M_{\text{fund}} \sim M_{\text{pl}}$.

2 To GUT or Not To GUT

One basic question is whether (a) the underlying string theory first compactifies to an effective four-dimensional grand unified theory (GUT) and that at a lower scale the GUT is broken to the MSSM (plus possible additional gauge factors), or (b) whether the string theory compactifies directly to the MSSM (plus extensions) without the intermediate GUT stage\(^a\). In the latter case the traditional forms of gauge and Yukawa unification are typically lost, though they may still survive in some modified or partial form.

Traditional GUTs have several major successes. These include the approximate success of gauge unification\(^{14}\), the elegant explanation for the quantum numbers of the 15 members of each fermion family; a natural home for the GUT seesaw model\(^{15}\), which yields the right general scale for neutrino masses and can incorporate the leptogenesis scenario for the baryon asymmetry\(^{16}\), and a correct prediction for the $b$ to $\tau$ mass ratio. On the other hand, the simplest versions of the GUT seesaw lead to small neutrino mixings, comparable to those in the quark sector, contrary to observations; other fermion mass relations (involving the first two families) are not correct unless one complicates the model with higher-dimensional Higgs multiplets (and typically additional family symmetries); simple models may be excluded by the non-observation of proton decay; there are serious hierarchy problems, including the Higgs doublet-triplet splitting problem; one must explain the existence of an additional (GUT breaking) scale; and the simplest heterotic string models do not have the large (adjoint and other) Higgs representations required for the fermion spectrum and GUT breaking. For these reasons, one should keep an open mind as to whether a separate four-dimensional GUT stage is really necessary.

3 Direct Compactification

Direct compactifications are constructions in which the string theory compactifies directly to a four-dimensional theory including the MSSM, i.e., including the $SU(3) \times SU(2) \times U(1)$ gauge group, 3 families, and softly broken $N = 1$ supersymmetry.

Such models often involve additional surviving gauge factors. These often include quasi-hidden non-abelian groups, which may be candidates for dynamical supersymmetry breaking. A truly hidden sector would mean that no fields transform nontrivially under both the MSSM and the hidden groups. However, in the specific constructions we have examined there are a few (mixed) chiral supermultiplets which transform under both sectors and connect them.

\(^a\)Grand unification could still exist in higher dimensions\(^{13}\)
In addition, there are frequently additional (non-anomalous) $U(1)'$ factors and associated $Z'$ gauge bosons, often with family non-universal couplings which lead to flavor changing neutral currents (FCNC)\cite{17}. Both the ordinary and quasi-hidden sector particles often carry $U(1)'$ charges. There may be additional non-abelian groups in the ordinary sector as well.

Another common feature are new exotic chiral supermultiplets, such as new standard model singlets (which may, however, carry $U(1)'$ charges), quarks or leptons with non-standard $SU(2) \times U(1)$ assignments (e.g., left-handed singlets and/or right-handed doublets), and extra Higgs doublets. The particles which communicate between the gauge sectors are typically fractionally charged (e.g., electric charge of $\pm 1/2$). Constructions sometimes violate $R$-parity, e.g., through Higgs/lepton mixing.

\section{Two Examples}

In this section I describe detailed investigations of the low energy consequences of two concrete constructions. Neither is fully realistic, but each predicts possible types of new-TeV scale physics.

\subsection{A Heterotic Example}

Most of the effort in the last decade was on perturbative heterotic constructions\cite{12}. Such models involve an anomalous $U(1)_A$ symmetry, implying a constant Fayet-Iliopoulos contribution to the $U(1)_A$ $D$ term. This must be cancelled by string-scale VEVs for some of the fields in the effective four-dimensional theory to avoid string-scale supersymmetry breaking. A systematic procedure was developed in\cite{3} to classify all of the non-abelian singlet directions that are $F$-flat and $D$-flat with respect to all of the gauge factors. The large VEVs break some of the gauge symmetries and give string-scale masses to some of the particles, modifying the effective four-dimensional theory from its initial apparent form and requiring that the interactions of the residual massless fields be recomputed (vacuum restabilization)\cite{3}.

The restabilization was worked out for a number of examples in\cite{4,5,6}. In particular, a detailed analysis was made\cite{4} of the flat directions involving non-abelian singlets and their consequences for a construction, CHL5, due originally to Chaudhuri, Hockney, and Lykken\cite{2}. Before restabilization, CHL5 has the gauge group

\[\{SU(3)_C \times SU(2)_L\}_{\text{obs}} \times \{SU(4)_2 \times SU(2)_2\}_{\text{hid}} \times U(1)_A \times U(1)'\] \hfill (1)

where the subscripts refer to the observable and quasi-hidden sector gauge groups, respectively. There are six non-anomalous $U(1)$ factors. In addition

\footnote{There are often anomalous $U(1)'$ factors as well, typically broken near the string scale.}
to the MSSM fields, the particle content consists of
\[6(1, 2, 1, 1)(\text{extra } H, L) + [(3, 1, 1, 1) + (\bar{3}, 1, 1, 1)](\text{exotic } D)\]
\[+ 4(1, 2, 1, 2)(\text{mixed}) + 42(1, 1, 1, 1)(\text{NA singlets})\]
\[+ [2(1, 1, 4, 1) + 10(1, 1, \bar{4}, 1) + 8(1, 1, 1, 2) + 5(1, 1, 4, 2)\]
\[+ (1, 1, 4, 2) + 8(1, 1, 6, 1) + 3(1, 1, 1, 3)](\text{hidden})\] (2)

The only satisfactory hypercharge definition is
\[Y = \frac{1}{96}(-8Q_2 - 3Q_3 - 8Q_4 - Q_5 + Q_6),\] (3)

which has Kač-Moody level 11/3, to be compared with the minimal value 5/3.

Some features of representative flat directions after restabilization are

- There is always at least one extra \(Z'\) at the TeV (or possibly an intermediate) scale, with non-family-universal couplings, leading to flavor changing neutral currents.

- There is a quasi-hidden sector involving the SU(4) \(\times\) SU(2) group. However, a few mixed multiplets and \(U(1)'\) factors connect the sectors. The non-abelian groups are not asymptotically free, so they are not a candidate for fractional charge confinement, supersymmetry breaking by gaugino condensation, or dilaton/moduli stabilization.

- There are many exotics, including a charge \(-1/3\) \(D_{L,R}\) quark, additional Higgs/lepton doublets, non-abelian singlets, and charge \(\pm1/2\) particles (the mixed and some of the hidden sector states). In most cases the fermions are massless or unacceptably light. There are extra Higgs doublets, with trilinear couplings to singlets that can generate non-standard off-diagonal effective \(\mu\) terms, but not enough such couplings to be realistic.

- The higher Kač-Moody embedding of hypercharge and the exotics modify the gauge unification. Using \(\alpha_s(M_Z)\) as input, one predicts \((\sin^2 \theta_W, g_2) \sim (0.16, 0.48)\), which disagree with (but are not too far from) the experimental values (0.23, 0.65).

- The primitive Yukawa couplings at the string scale \(M_s\) are not arbitrary, but are related to the gauge coupling \(g\) as \(g, g/\sqrt{2},\) or 0. However, after restabilization some couplings, originally due to higher dimensional operators, may be smaller, of order \(gv/M_s\), where \(v \sim (10^{-1} - 10^{-2})M_s\) is the scale of VEVs involved in the restabilization. The CHL5 model implies \(t - b\) universality, consistent with the data for large \(\tan \beta\), as well as \(\tau - \mu\) universality. The latter is unphysical and is a clear defect of the construction. There is also a noncanonical \(b - \tau\) relation, a semi-realistic \(d\)-quark texture, and no obvious mechanism for a \(\nu\) seesaw, except possibly associated with intermediate scale \(U(1)'\) breaking.
• One of the flat directions involves \( R_P, L \) and \( B \) violation.

• When additional but ad hoc phenomenological soft supersymmetry breaking terms at the string scale are assumed\(^4\), one finds that a large \( M_{Z'} \) of order 1 TeV is possible, the sparticles are typically heavier than in the MSSM (because the \( Z' \) mass is set by the SUSY-breaking scale, with the smaller electroweak scale due to cancellations), and there is a richer Higgs, neutralino, and chargino spectrum than in the MSSM\(^{15}\).

4.2 An Intersecting Brane (Open String) Example

As an open string example, consider the intersecting \( D \) brane construction of Cvetić, Shiu, and Uranga\(^7\), based on a \( Z_2 \times Z_2 \) Type IIA orientifold with three 2-tori. It is chiral, with an odd number of families for one tilted 2-torus. There are stacks of D6 branes wrapped on each \( T^2 \), and the model is \( N = 1 \) supersymmetric for specific angle conditions. The phenomenology of the construction was considered in detail in\(^8\),\(^9\),\(^12\).

The gauge group for the four dimensional effective theory is

\[
SU(3) \times SU(2) \times Sp(2)_B \times Sp(2)_A \times Sp(4) \times U(1)^5,
\]

where the quasi hidden sector group \( Sp(2)_B \times Sp(2)_A \times Sp(4) \) is asymptotically free, allowing the possibility of charge confinement, dilaton/moduli stabilization, and dynamical supersymmetry breaking\(^\text{12}\). Two of the \( U(1) \) factors are anomalous. Their gauge bosons acquire string-scale masses, but their symmetries restrict the Yukawa couplings. There are three surviving non-anomalous \( U(1) \)'s, i.e., \( Q_8 \pm Q_8' \) and \( B - L = Q_3/3 - Q_1 \), where \( Q_8, Q_8' \) are remnants of an underlying \( Sp(8) \) symmetry, and \( Q_{3,1} \) are related to an underlying Pati-Salam type \( U(4) \). The weak hypercharge is

\[
Y = \frac{B - L}{2} + \frac{1}{2}(Q_8 + Q_8').
\]

Unfortunately, there is no simple mechanism to break the two extra \( U(1)' \) symmetries.

The chiral states associated with strings localized at intersecting branes include three complete standard model families, although only two of the left-handed families have Higgs Yukawa couplings. There are actually four families of right-handed fields (i.e., left-handed \( \bar{u}, \bar{d}, \bar{e}, \bar{\nu} \)). These have non-universal \( Q_8 - Q_8' \) charges, leading in general to flavor changing neutral currents, e.g., in \( B_s \rightarrow \mu^+\mu^- \), \( B_d \rightarrow \phi K_S \), or \( \tau^+ \rightarrow \mu^+ e^+ e^- \).

There are several exotics that are charged under both the ordinary and quasi-hidden sectors. These include states that transform as \((3, 1, 2, 1, 1)\) and \((1, 1, 2, 1, 1)\) under \( SU(3) \times SU(2) \times Sp(2)_B \times Sp(2)_A \times Sp(4) \). These are candidates to be the exotic \((SU(2)\text{-singlet})\) left-handed partners of the extra family of right-handed particles. Unfortunately, they have the wrong electric
charges, $Q_{EM} = Y = 1/6$ and $-1/2$, respectively, and there is no alternative successful definition of $Y$ that can remedy the problem. There is also an exotic $(1, 2, 1, 1, 4)$ with $Q_{EM} = \pm 1/2$. Fortunately, these fractionally-charged states may disappear from the spectrum due to charge confinement in the quasi-hidden sector, to be replaced with composite states to form the missing exotic left-handed family (see Section 5.6).

The particular construction actually has 24 Higgs doublet candidates (12 $u$-type and 12 $d$-type). While additional doublets are a real possibility at the TeV scale, 24 is excessive, leading to much of the difficulties with the low energy gauge couplings. There are no candidates for chiral singlets that could generate an effective $\mu$ term. The Yukawa interactions are discussed in 9.

The spectrum also includes two localized singlets, two localized $SU(2)$ triplets, and a number of unlocalized chiral singlets and adjoints. There is no simple mechanism for giving the latter states masses (a generic problem for such constructions.) There are also a number of non-chiral states, which, however, generically have string-scale masses.

The intersecting brane model does not have canonical gauge unification, because each gauge factor is associated with a different stack of branes\(^c\). In particular, the boundary conditions on the couplings at the string scale depend both on the dilaton $S$, and also (in a non-universal way) on a modulus $\chi$, defined as the ratio of the two radii of the first two-torus (the ratios for the other two-tori are related by the supersymmetry condition). The gauge couplings at low energy were computed in 8 as functions of the modulus and dilaton, and the absolute values were given in terms of the predicted stabilized values of $S$ and $\chi$ in 12. The predicted standard model gauge couplings are unrealistically small, i.e., $(\alpha^{-1}, \alpha^{-1}, \sin^2 \theta_W) = (52.2, 525, 0.29)$, respectively, to be compared with the experimental values $\sim (8.5, 128, 0.23)$. The failure is due both to the non-canonical boundary conditions and the contributions of the extra Higgs doublets and other exotics to the running.

5 Things to Watch For

Let me now describe examples of types of new physics which could emerge in specific constructions.

5.1 Gauge Unification?

As described in Section 2, the MSSM is consistent with the gauge unification expected in simple four-dimensional grand unified theories or simple perturbative heterotic string constructions. In particular, using the precisely known values of $\alpha$ and the $\Lambda_{MSS}$ weak angle $\tilde{s}_Z^2$ (both evaluated at $M_Z$) and assuming

\(^c\) Variant constructions yield a grand unified group and canonical gauge boundary conditions 7.
gauge unification, one can predict $\alpha_s(M_Z) \sim 0.130 \pm 0.010$ and the unification scale $M_G \sim 3 \times 10^{16}$ GeV\(^{14}\). The $\alpha_s(M_Z)$ prediction agrees within 10% with the experimental value of $\sim 0.12$, with the discrepancy possibly due to threshold corrections or higher dimensional operators. There is no prediction for $M_G$ in a GUT, but one expects $M_G \sim 5 \times 10^{17}$ GeV in the simple heterotic case. This is within 10% when properly measured in $\ln M_G$. It is easy to find corrections to the simple heterotic predictions, e.g., new exotic particles typically yield $O(1)$ corrections to both $\alpha_s(M_Z)$ and $\ln M_G$. The difficulty is in understanding why the discrepancies are not larger.

More generally, string constructions with direct compactification typically involve gauge unification, but usually modified in form from the MSSM. For example, the boundary conditions on the couplings may be modified due to higher Kač-Moody levels in the embeddings of the different gauge factors, or may depend on moduli in the open-string constructions. As mentioned, exotic multiplets may modify the runnings of the couplings. One possibility is to consider constructions with canonical boundary conditions and no new particles with standard model quantum numbers (there are no known fully realistic examples). An alternative is to insist on canonical boundary conditions and only allow exotics which form complete $SU(5)$ multiplets (which preserves gauge unification at one-loop). Finally, it is possible that there are cancellations between non-canonical boundary conditions and non-standard running, in which case the apparent success of the MSSM-type unification would be accidental\(^d\).

5.2 A TeV Scale $Z'$?

String constructions often involve extra non-anomalous $U(1)'$ gauge symmetries and associated $Z'$ gauge bosons in the effective four-dimensional theory\(^e\). In both supergravity\(^{22}\) and gauge-mediated\(^{23}\) supersymmetry breaking schemes, the radiative breaking of the electroweak symmetry often simultaneously leads to radiative breaking of the $U(1)'$ at the electroweak or TeV (i.e., soft supersymmetry breaking) scale unless the breaking occurs at an intermediate scale\(^{24}\) along an $F$ and $D$ flat direction.

The $U(1)'$ symmetry allows an elegant solution to the $\mu$ problem\(^{25}\). If the superpotential $W$ contains a term $W \sim hS\tilde{H}_u\tilde{H}_d$, where $\tilde{S}$ is the superfield for a standard model singlet that is charged under $U(1)'$, then the $U(1)'$ prevents an elementary $\mu$, while $\langle S \rangle \neq 0$ not only breaks the $U(1)'$, but also generates an effective $\mu_{\text{eff}} = h\langle S \rangle$. (This is similar to the next to minimal supersymmetric model (NMSSM)\(^{27}\) but without the domain wall problems

\(^d\)This is similar to the non-canonical unification assumed in other theoretical frameworks, such as large extra dimensions\(^{19}\) or de-construction\(^{20}\).

\(^e\)Grand unified theories also often yield extra $U(1)'$ factors, but in that case an extra fine tuning is required to obtain $M_{Z'} \ll M_{\text{GUT}}$. Theories of dynamical symmetry breaking also often lead to an extra $U(1)'$\(^{21}\).
that plague the latter. The discrete symmetry of the NMSSM is embedded in the $U(1)'$.

The experimental limits, both from precision and collider experiments, are model dependent, but typically one requires $M_{Z'} > (500-800) \text{ GeV}$ and a $Z - Z'$ mixing angle $|\delta| < \text{few} \times 10^{-3}$. Models with $M_{Z'} \gtrsim 10M_Z$ and small enough mixing can be obtained either by imposing a modest tuning on the parameters, or by breaking the $U(1)'$ along a nearly flat direction in a secluded sector. Anomaly free $U(1)'$ models consistent with canonical gauge unification have been constructed.

An extra TeV-scale $Z'$ is perhaps the best motivated new physics beyond supersymmetry. The existence of a $Z'$ could have a number of other implications. Constructions involving a low energy $U(1)'$ typically also involve new particles with exotic standard model quantum numbers (some of which may be quasi-stable). The string constructions often involve $Z'$ couplings that are not family universal, leading to flavor changing neutral current effects, especially for the third family. The Higgs sector of such models is more complicated than the MSSM, with a larger value allowed for the lightest scalar mass. In the secluded sector case there may be significant mixing between Higgs doublets and singlets. The constructions involving some tuning have a large supersymmetry breaking scale and a non-standard particle spectrum. The $U(1)'$ symmetry often prevents a traditional seesaw mechanism for the neutrino masses, but there are several other possibilities for both Dirac and Majorana masses. There may be new sources of CP violation. The $U(1)'$ models allow a strongly first order electroweak phase transition. Because of this and the new CP phases (which may occur at tree level in the scalar sector) they allow for electroweak baryogenesis without the stringent parameter constraints on the MSSM.

5.3 Exotics

Explicit constructions generally predict the existence of new exotic chiral supermultiplets in the effective four-dimensional theory. These can have interesting phenomenological consequences (and can significantly affect gauge unification). It is of course difficult to know to what extent these exotics should be viewed as defects of the particular constructions, and to what extent they are plausible candidates for new physics. One can always give the spin-0 exotic particles soft masses in the several hundred GeV range, but in many cases there is no satisfactory mechanism to give large masses to the fermions. In any case, the constructions we have studied in detail contain too many exotics.

Many kinds of exotics are encountered. For example, one frequently finds left-handed singlet or right-handed doublet quarks or leptons. These can be vectorlike, i.e., occurring as left and right handed pairs with the same
standard model quantum numbers. In this case the electroweak precision constraints are weak. Familiar examples include the vectorlike $SU(2)$-singlet charge $-1/3$ quark or the new left and right handed lepton doublets occurring in $E_6$ grand unified theories. Another possibility is for the $L$-singlet and $R$-doublet particles to form partial or complete mirror families, for which the precision constraints are strong. Models often have many new standard model singlets, which may however be charged under $U(1)'$ factors (see Section \ref{sec:SU(2)c}). There are also often additional Higgs doublets. The Higgs doublets and singlets may mix, leading to unusual Higgs spectra and couplings. There may also be mixing between Higgs and lepton doublets, a form of $R$-parity violation. There are usually particles that are standard model singlets that are charged under non-abelian quasi-hidden sector gauge groups. However, the standard model and hidden sectors are not totally decoupled: there are typically a few particles (often with fractional charges such as $\pm 1/2$) which couple to both sectors. The extra $U(1)'$ factors also may communicate between the sectors. The low energy theory is anomaly free, but because of the various types of exotics the anomaly cancellations may be complicated.

5.4 Flat directions

Flat directions are an important consideration in all supersymmetric theories. Consider, for example, a model with an additional $U(1)'$ which can be broken by two standard model singlets, $S_1$ and $S_2$. Let us further assume that there are no cubic (or quadratic) terms in the superpotential involving only the standard model singlets, i.e., the potential is $F$-flat at the renormalizable level\footnote{Such states may disappear from the spectrum if the hidden sector becomes strongly coupled (section \ref{sec:SU(2)c}). Otherwise, the lightest would be stable, with cosmological implications.}. The potential for $S_{1,2}$ is then

$$V(S_1, S_2) = m_1^2 |S_1|^2 + m_2^2 |S_2|^2 + \frac{g'Q'^2}{2} (|S_1|^2 - |S_2|^2)^2,$$  \hspace{1cm} (6)$$

where $m_i^2$ are the soft mass-squares evaluated at the electroweak scale, and I have assumed that $S_{1,2}$ have opposite signs for their $U(1)'$ charges (taken to be equal in magnitude for simplicity). $V$ is $F$ and $D$ flat along the direction $|S_1| = |S_2| \equiv |S|$. If $m_1^2 + m_2^2 > 0$ the flat direction will be irrelevant, and the breaking will be at or near the electroweak scale, where additional terms such as the $F$ terms associated with $W \sim hS_i H_u H_d$ will be important. On the other hand, for $m_1^2 + m_2^2 < 0$ the $S_i$ will acquire large expectation values along the flat direction at a scale intermediate between the electroweak and Planck scales. (The apparent runaway nature of the potential in (6) may be stabilized by loops (i.e., the running of the $m_i^2$) or by higher-dimensional terms in the superpotential \footnote{A variation is that there are cubic superpotential terms with small coefficients, leading to the possibility of $U(1)'$ breaking that is naturally at the TeV scale}. In the intermediate scale case, small Dirac
neutrino (or other fermion) masses may be generated by higher-dimensional terms such as
\[ W \sim \bar{H}_2 \bar{L}_L \nu_L \left( \frac{S}{M_{pl}} \right)^{P_D} \] (7)
in the superpotential, where \( P_D > 0 \). Possible cosmological implications of light Dirac neutrinos in \( U(1)' \) models are considered in 12.

5.5 Family Structure and the Fermion Spectrum

The family structure and fermion spectrum is perhaps the most mysterious feature of the standard model. Attempts to shed light on these issues in the framework of four-dimensional theories often invoke family symmetries and their breakings to restrict the form of the fermion mass matrices, often in conjunction with grand unification (generally extended to allow higher-dimensional Higgs representations). Bottom-up models involving extra dimensions greatly extend the possibilities for selection rules and family hierarchies.

String constructions allow another possibility, i.e., that string selection rules and differences in the embeddings for the three families (especially the third), rather than symmetries in the four-dimensional effective theory, may be the ultimate origin of the family structure. For example, selection rules in heterotic constructions may lead to the absence of couplings that are allowed by the symmetries of the effective four-dimensional field theory. It is possible that such stringy effects may ultimately explain the hierarchy of fermion masses and the pattern of their mixings (and possibly imply new flavor changing effects, e.g., from new \( Z' \) interactions). Unfortunately, no construction that is very realistic in this respect has yet emerged.

Some issues that string model builders should keep in mind include: the sources and magnitudes of CP-violating phases; possible resolutions of the strong CP problem, such as Peccei-Quinn symmetries; and possibilities in the superpotential or elsewhere for Majorana neutrino masses (in particular, whether terms leading to Majorana masses can be diagonal in neutrino flavor or only mix different families).

The effective low energy theory in string constructions may be of the WYSINWYG (what you see is not what you get) variety. For example, the number of families may be reduced from the apparent number in the compactification scheme by vacuum restabilization. On the other hand, more complicated symmetry breaking patterns may increase the number of families, or some low energy particles may be composite, as occurs in an intersecting brane construction.

\(^h\)Variations can yield comparable small Dirac and Majorana mass terms, as are needed to have mixing between ordinary and sterile neutrinos.

\(^i\)For example, a construction involving \( SU(6) \supset SU(2)^3 \) with a single 6-plet family could break to the diagonal \( SU(2) \) with three \( SU(2) \)-doublet families.
5.6 Asymptotic Freedom in the Quasi-Hidden Sector

An important issue is whether the quasi-hidden sector is asymptotically free, as is the case for the intersecting brane constructions in 7 (but not for the heterotic constructions in 4). An asymptotically free quasi-hidden sector is a candidate for supersymmetry breaking via gaugino condensation 13 at the scale at which the coupling becomes strong, as well as for dilaton/moduli stabilization. For example, the dilaton and shape moduli are stabilized in the intersection brane construction 12, leading to the interesting features of gaugino masses that are non-universal and which have large CP-violating phases. However, the model is not realistic in that there is a large negative cosmological constant and a large supersymmetry breaking scale around 10^{13} GeV. Further study of such constructions may be useful in motivating new patterns of soft supersymmetry breaking, even if the constructions are not fully realistic.

The strongly coupled groups may also lead to charge confinement and compositeness. For example, in the construction in 7 there are states with non-standard electric charge, such as 1/6 or ±1/2. These all carry nontrivial charges under the three quasi-hidden sector factors, and are presumably confined below the strong coupling scales. Standard anomaly matching conditions then require the existence of composite bound states, leading to the interesting feature that the low energy spectrum contains an exotic fourth family (all elements are SU(2)×U(1) singlets) in which the left-chiral components are composite and the right-chiral components elementary 5.

6 Conclusions

The Standard Model (extended to include neutrino masses) is extremely successful. Most aspects have been tested; in particular, precision electroweak data suggest that any underlying new physics should be of the decoupling type (i.e., the effects become smaller for larger mass scales), such as supersymmetry and unification. Nevertheless, the Standard Model is clearly incomplete: it involves too many free parameters, arbitrary features, and fine tunings. Superstring/M theory is an extremely promising theoretical direction, but testing it and picking from the large variety of vacua is extraordinarily challenging. We certainly need a vigorous program of bottom-up experimental and theoretical probes to test the SM (or MSSM) and search for alternatives or extensions. However, it is also important to carry out a major top-down program to attempt to connect M theory to experiment and suggest new TeV-scale physics that might not be motivated by bottom-up constructions. There may be much beyond the MSSM at the TeV scale.
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