Stringy Standard Models

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Introduction

In this talk we give a short overview of attempts to construct the Standard Model, or more precisely the MSSM within string theory. As a general disclaimer, the list of references provided is by no means complete and certainly does not reflect all approaches which have been taken. References to earlier important papers on similar material can be found in the included references.

Heterotic Models

Some reviews on model building in heterotic M-theory may be found in [1, 2]. We first recall that the strongly coupled limit of the heterotic $E_8 \times E_8$ theory is given by heterotic M-theory. There are two "end of the world" ten dimensional E_8 branes separated by an interval of length R_{11}. In order to construct semi-realistic models in four dimensions, we compactify six of the remaining dimensions on a Calabi-Yau threefold, X. Even though unification is expected to take place in a higher dimensional sense, the main idea is to organize all of the matter content into GUT multiplets of $SU(5)$, $Spin(10)$ or E_6. We turn on a suitable gauge field strength in an $SU(n) \times discrete$ subgroup of E_8 to break down to the gauge group of the Standard Model (G_{std}), with some additional possible $U(1)$ factors, and then further isolate the pieces which we would like to identify with the MSSM spectrum. In the above, the "*discrete*" piece of the field strength refers to a choice of discrete Wilson line when $\pi_1(X) \neq 0$. To achieve this breaking pattern we must find an appropriate holomorphic gauge bundle V_1 on the visible brane. Letting V_2 denote the gauge bundle on the hidden brane, at the level of cohomology, upon integrating over the interval the heterotic anomaly amounts to the condition:

$$c_2\left(V_1\right) + c_2(V_2) + \sum_i \left[W_i\right] = c_2\left(TX\right).$$

In the above equation, the $[W_i]$'s denote the contribution due to $M5$-branes wrapping curves in X. The massless spectrum of the theory now follows by analyzing the kernel of the six dimensional Dirac operator. This procedure is summarized in [3]. The number of generations minus the number of anti-generations is $c_3(V_1)/2$. An important model building constraint on V_1 is that we must require:

$$3 = N_{gen} = \left|\frac{1}{2}c_3(V_1)\right|.$$

Note that the index can only count the number of generations minus the number of anti-generations. This will generically lead to vector-like matter, so that we must either explicitly check that such pairs are lifted from the low energy spectrum, or construct V_1 so that no anti-generations are present.

In the limit where R_{11} tends to zero size, we recover the weakly coupled description. In this limit, it is most natural to consider the so-called standard embedding where the spin connection is embedded inside the gauge connection of the visible E_8 factor. Further details of this approach may be found in [4, 3]. In this case, it is natural to organize the matter content according to E_6 multiplets. So far, this approach has not yielded a spectrum identical with the MSSM spectrum. A further difficulty with this approach is that typically the perturbative limit makes a prediction for the value of Newton's constant G_N which is too large by a factor of about 400. This and other issues are discussed in greater detail in [5].

Returning to heterotic M-theory, we note that the presence of $M5$-branes allows us to relax the cohomological constraint on V_1. Making use of this fact, it has recently been shown in [6, 7] that besides the presence of moduli, one can achieve the exact spectrum of the MSSM. In what we shall call the $SU(5)$ model [6], the structure group of V_1 is $SU(5)$ so that the breaking pattern is $E_8 \to SU(5) \to G_{std}$. In the $Spin(10)$ model [7], the structure group is $SU(4)$ and the breaking pattern is $E_8 \to Spin(10) \to G_{std} \times U(1)_{B-L}$. In the $SU(5)$ model, the configuration is supersymmetric and satisfies the heterotic anomaly constraint. We note, however, that a generic point in vector bundle moduli space supports no Higgs up-Higgs down pairs. A single pair exists in a codimension two subspace of the vector bundle moduli space. In this model, right handed neutrinos are associated with the fermionic partners of the moduli. In the $Spin(10)$ model, there is an additional gauged $U(1)_{B-L}$, and the right handed neutrinos fit into the 16 representation of $Spin(10)$. We note that whereas stability has been e stablished in the $SU(5)$ models, at present this issue is less clear in the $Spin(10)$ model.

Type II Models with D-branes

In type II constructions with D-branes, the essential point is that the Standard Model can be described by a quiver gauge theory. Although we shall state the rules for building such quivers in type IIA language, all of these rules can be re-formulated purely in type IIB terms. To this end, we consider type IIA compactified on an orientifold of a Calabi-Yau threefold. D6-branes wrapping special Lagrangian submanifolds of the Calabi-Yau threefold will give rise to $U(n)$ type gauge theories. Further, the presence of O-planes allows more general $SO(n)$ and $Sp(n)$ type gauge groups when a D6-brane coincides with an O-plane. The chiral matter of the associated gauge theory is given by the intersection pairing between the various branes. Now let π_a denote a 3-cycle and π'_a its image under O-plane reflection, with similar notation for the 3-cycles π_b and π'_b. In our sign conventions, a stack of N_a D6-branes wrapping π_a and N_b D6-branes wrapping π_b will produce chiral matter in the $\left(\overline{N_a}, N_b\right)$ representation when $\pi_a \cap \pi_b$ is positive. We find chiral matter in the (N_a, N_b) representation when $\pi'_a \cap \pi_b$ is positive, and matter in the two index symmetric or anti-symmetric representation of $U(N_a)$ when the quantity $\left(\pi_a \cap \pi'_a \pm \pi_{O6} \cap \pi_a\right)/2$ is non-zero. In this formula, the $+$ sign (resp. $-$ sign) correlates with the anti-symmetric (resp. symmetric) representation. Detailed reviews on intersecting brane models for branes wrapping orbifolds of T^6 which cover many further aspects of such setups may be found in [8, 9, 10].

The most compact embedding of the standard model into a quiver gauge theory consistent with the abstract rules given above is given by the so-called "MQSM" constructed in [11]. We should caution that although this quiver is consistent with the above rules, it has not been realized as a D-brane configuration. This gauge theory is given by a three node quiver with gauge groups $U(3) \times Sp(1) \times U(1)$. Whereas one linear combination of $U(1)$ generators corresponds to hypercharge, the other is anomalous and is cancelled by a generalized Green-Schwarz mechanism. This is a general feature of such models. Indeed, the Stueckelberg mechanism will also cause some non-anomalous $U(1)$ gauge bosons to develop a mass due to the coupling on the d dimensional worldvolume:

$$\int C_{d-2} \wedge F$$

where F denotes the abelian field strength of the brane and C_{d-2} denotes the $d-2$ RR form. One can then expect a global $U(1)$ to persist in the theory which can be broken by gauge theory and stringy instanton effects.

Quiver gauge theories also naturally arise from D-brane probes of Calabi-Yau singularities. Recent constructions in type IIB string theory have shown that D3-brane probes of appropriate singularities can reproduce many of the expected features of MSSM-like quivers [12, 13, 14]. Locally, the singularity corresponds to a collapsed holomorphic surface inside of a non-compact Calabi-Yau threefold. Upon partially resolving this singularity, the probe brane splits up into a collection of D7-branes wrapping 4-cycles, D5-branes wrapping 2-cycles and D3-branes wrapping 0-cycles. These "fractional branes" then base the associated quiver gauge theory. An important feature of these models is that there exists a limit where the closed string modes decouple from the open string modes.

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