D-brane Standard Model

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Abstract: The minimal embedding of the Standard Model in type I string theory is described. The $SU(3)$ color and $SU(2)$ weak interactions arise from two different collections of branes. The correct prediction of the weak angle is obtained for a string scale of 6-8 TeV. Two Higgs doublets are necessary and proton stability is guaranteed. It predicts two massive vector bosons with masses at the TeV scale, as well as a new superweak interaction.

1 Introduction

String theory is the only known framework for quantizing gravity. If its fundamental scale is of the order of the Planck mass, stability of the hierarchy of the weak scale requires low energy supersymmetry. This framework fits nicely with the apparent unification of the gauge couplings in the minimal supersymmetric standard model. However, breaking supersymmetry at low energies is a hard problem, which in string perturbation theory implies a large extra dimension, \cite{1, 2, 3}. Recently, an alternative approach has been put forward \cite{4, 5} in which stabilization of the hierarchy is achieved without supersymmetry, by lowering the string scale down to a few TeV \cite{3, 4, 5, 6, 7}. A natural realization of this possibility is offered by weakly coupled type I string theory, where gauge interactions are described by open strings whose ends are confined on D-branes, while gravity is mediated by closed strings in the bulk \cite{5}. The observed hierarchy between the Planck and the weak scales is then accounted for by two or more large dimensions, transverse to our brane-world, with corresponding size varied from a millimeter to a fermi.

One of the main questions with such a low string scale is to understand the observed values of the low energy gauge couplings. One possibility is to have the three gauge group factors of the Standard Model arising from different collections of coinciding branes. This is unattractive since the three gauge couplings correspond in this case to different arbitrary parameters of the model. A second possibility is to maintain unification by imposing all the Standard Model gauge bosons to arise from the same collection of D-branes. The large difference in the actual values of gauge couplings could then be explained either by introducing power-law running from a few TeV to the weak scale \cite{5}, or by an effective
logarithmic evolution in the transverse space in the special case of two large dimensions [10]. However, no satisfactory model built along these lines has so far been presented.

A third possibility exists [11] which is alternative to unification but nevertheless maintains the prediction of the weak angle at low energies. Specifically, we consider the strong and electroweak interactions to arise from two different collections of coinciding branes, leading to two different gauge couplings, [7]. Assuming that the low energy spectrum of the (non-supersymmetric) Standard Model can be derived by a type I′ string vacuum, the normalization of the hypercharge is determined in terms of the two gauge couplings and leads naturally to the right value of $\sin^2 \theta_W$ for a string scale of the order of a few TeV. The electroweak gauge symmetry is broken by the vacuum expectation values of two Higgs doublets, which are both necessary in the present context to give masses to all quarks and leptons.

Another issue of this class of models with TeV string scale is to understand proton stability. In the model presented here, this is achieved by the conservation of the baryon number which turns out to be a perturbatively exact global symmetry, remnant of an anomalous $U(1)$ gauge symmetry broken by the Green-Schwarz mechanism. Specifically, the anomaly is canceled by shifting a corresponding axion field that gives mass to the $U(1)$ gauge boson.

As it turns out, some of the standard model fermions are fluctuations of strings ending in a different brane. This implies the presence of a new short range interaction due to the gauge bosons and/or scalars representing the fluctuations of the extra brane. Moreover, the two extra $U(1)$ gauge groups are anomalous and the associated gauge bosons become massive with masses of the order of the string scale. Their couplings to the standard model fields up to dimension five are fixed by charges and anomalies.

2 Hypercharge embeddings and the weak angle

The gauge group closest to the $SU(3) \times SU(2) \times U(1)$ of the Standard Model one can hope to derive from type I′ string theory in the above context is $U(3) \times U(2) \times U(1)$. The first factor arises from three coincident D-branes (“color” branes). An open string with one end on them is a triplet under $SU(3)$ and carries the same $U(1)$ charge for all three components. Thus, the $U(1)$ factor of $U(3)$ has to be identified with gauged baryon number. Similarly, $U(2)$ arises from two coincident “weak” D-branes and the corresponding abelian factor is identified with gauged weak-doublet number. A priori, one might expect that $U(3) \times U(2)$ would be the minimal choice. However it turns out that one cannot give masses to both up and down quarks in that case. Therefore, at least one additional $U(1)$ factor corresponding to an extra D-brane (“$U(1)$” brane) is necessary in order to accommodate the Standard Model. In principle this $U(1)$ brane can be chosen to be independent of the other two collections with its own gauge coupling. To improve the predictability of the model, here we choose to put it on top of either the color or the weak D-branes. In either case, the model has two independent gauge couplings $g_3$ and $g_2$ corresponding, respectively, to the gauge groups $U(3)$ and $U(2)$. The $U(1)$ gauge coupling $g_1$ is equal to either $g_3$ or $g_2$.

Let us denote by $Q_3$, $Q_2$ and $Q_1$ the three $U(1)$ charges of $U(3) \times U(2) \times U(1)$, in a self explanatory notation. Under $SU(3) \times SU(2) \times U(1)_3 \times U(1)_2 \times U(1)_1$, the members of a family of quarks and leptons have the following quantum numbers:

\[ Q = (3, 2; 1, w, 0)_{1/6} \]
Here, we normalize all $U(N)$ generators according to $\text{Tr} T^a T^b = \delta^{ab}/2$, and measure the corresponding $U(1)_N$ charges with respect to the coupling $g_N/\sqrt{2N}$, with $g_N$ the $SU(N)$ coupling constant. Thus, the fundamental representation of $SU(N)$ has $U(1)_N$ charge unity. The values of the $U(1)$ charges $x, y, z, w$ will be fixed below so that they lead to the right hypercharges, shown for completeness as subscripts.

The quark doublet $Q$ corresponds necessarily to a massless excitation of an open string with its two ends on the two different collections of branes. The $Q_2$ charge $w$ can be either $+1$ or $-1$ depending on whether $Q$ transforms as a 2 or a $\bar{2}$ under $U(2)$. The antiquark $u^c$ corresponds to fluctuations of an open string with one end on the color branes and the other on the $U(1)$ brane for $x = \pm 1$, or on other branes in the bulk for $x = 0$. Ditto for $d^c$. Similarly, the lepton doublet $L$ arises from an open string with one end on the weak branes and the other on the $U(1)$ brane for $z = \pm 1$, or in the bulk for $z = 0$. Finally, $l^c$ corresponds necessarily to an open string with one end on the $U(1)$ brane and the other in the bulk. We defined its $Q_1 = 1$.

The weak hypercharge $Y$ is a linear combination of the three $U(1)$'s:

$$Y = c_1 Q_1 + c_2 Q_2 + c_3 Q_3. \quad (2)$$

$c_1 = 1$ is fixed by the charges of $l^c$ in eq. $(1)$, while for the remaining two coefficients and the unknown charges $x, y, z, w$, we obtain four possibilities:

$$c_2 = -\frac{1}{2}, \quad c_3 = -\frac{1}{3}; \quad x = -1, \ y = 0, \ z = 0, \ w = -1$$

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$$c_2 = -\frac{1}{2}, \quad c_3 = \frac{2}{3}; \quad x = 0, \ y = 1, \ z = 0, \ w = 1$$

$$c_2 = \frac{1}{2}, \quad c_3 = \frac{2}{3}; \quad x = 0, \ y = 1, \ z = -1, \ w = -1 \quad (3)$$

Orientifold models realizing the $c_3 = -1/3$ embedding in the supersymmetric case with intermediate string scale $M_s \sim 10^{11}$ GeV have been described in $[13]$. To compute the weak angle $\sin^2 \theta_W$, we use from eq. $(2)$ that the hypercharge coupling $g_Y$ is given by $[3]$:}

$$\frac{1}{g_Y^2} = \frac{2}{g_1^2} + \frac{4c_2^2}{g_2^2} + \frac{6c_3^2}{g_3^2}, \quad (4)$$

with $g_1 = g_2$ or $g_1 = g_3$ at the string scale. On the other hand, with the generator normalizations employed above, the weak $SU(2)$ gauge coupling is $g_2$. Thus,

$$\sin^2 \theta_W \equiv \frac{g_Y^2}{g_2^2 + g_Y^2} = \frac{1}{1 + 4c_2^2 + 2g_2^2/g_1^2 + 6c_3^2g_2^2/g_3^2}, \quad (5)$$

$\text{A study of hypercharge embeddings in gauge groups obtained from M-branes was considered in Ref. [12]. In the context of Type I groundstates such embeddings were considered in [3].}$

$\text{The gauge couplings } g_{2,3} \text{ are determined at the tree-level by the string coupling and other moduli, like radii of longitudinal dimensions. In higher orders, they also receive string threshold corrections.}$
which for \( g_1 = g_2 \) reduces to:

\[
\sin^2 \theta_W(M_s) = \frac{1}{4 + 6c_3^2g_2^2(M_s)/g_3^2(M_s)},
\]

(6)

while for \( g_1 = g_3 \) it becomes:

\[
\sin^2 \theta_W(M_s) = \frac{1}{2 + 2(1 + 3c_3^2)g_2^2(M_s)/g_3^2(M_s)}.
\]

(7)

We now show that the above predictions agree with the experimental value for \( \sin^2 \theta_W \) for a string scale in the region of a few TeV. For this comparison, we use the evolution of gauge couplings from the weak scale \( M_Z \) as determined by the one-loop beta-functions of the Standard Model with three families of quarks and leptons and one Higgs doublet,

\[
\frac{1}{\alpha_i(M_s)} = \frac{1}{\alpha_i(M_Z)} - \frac{b_i}{2\pi} \ln \frac{M_s}{M_Z}; \quad i = 3, 2, Y
\]

(8)

where \( \alpha_i = g_i^2/4\pi \) and \( b_3 = -7, b_2 = -19/6, b_Y = 41/6 \). We also use the measured values of the couplings at the \( Z \) pole \( \alpha_3(M_Z) = 0.118 \pm 0.003, \alpha_2(M_Z) = 0.0338, \alpha_Y(M_Z) = 0.01014 \) (with the errors in \( \alpha_{2,Y} \) less than 1%).

In order to compare the theoretical relations for the two cases (6) and (7) with the experimental value of \( \sin^2 \theta_W = g_Y^2/(g_2^2 + g_Y^2) \) at \( M_s \), we plot in Fig. 1 the corresponding curves as functions of \( M_s \). The solid line is the experimental curve. The dashed line

![Figure 1: The experimental value of \( \sin^2 \theta_W \) (thick curve), together with the theoretical predictions (6) with \( c_3 = -1/3 \) (dashed line) and (7) with \( c_3 = 2/3 \) (dotted-dashed), are plotted as functions of the string scale \( M_s \).](image-url)
to the function (7) for $c_3 = 2/3$. Thus, the second case, where the $U(1)$ brane is on top of the color branes, is compatible with low energy data for $M_s \sim 6 - 8$ TeV and $g_s \simeq 0.9$. This selects the last two possibilities of charge assignments in Eq. (3). The curve corresponding to $g_1 = g_3$ and $c_3 = -1/3$ gives for $M_s$ few thousand TeV. This value is too high to protect the hierarchy. The other case, where the $U(1)$ brane is on top of the weak branes, is not interesting either. For $c_3 = 2/3$, the corresponding curve does not intersect the experimental one at all and is not shown in the Fig. 1, while the case of $c_3 = -1/3$ leads to $M_s$ of a few hundred GeV and is excluded experimentally. In the sequel we shall restrict ourselves to the last two possibilities of Eq. (3).

From the general solution (3) and the requirement that the Higgs doublet has hypercharge $1/2$, one finds the following possible assignments for it, in the notation of Eq. (1):

$$c_2 = -\frac{1}{2} : \begin{array}{c} H \ (1, 2; 0, 1, 1)_{1/2} \\ H' \ (1, 2; 0, -1, 0)_{1/2} \end{array}$$

$$c_2 = \frac{1}{2} : \begin{array}{c} \tilde{H} \ (1, 2; 0, -1, 1)_{1/2} \\ \tilde{H}' \ (1, 2; 0, 1, 0)_{1/2} \end{array}$$

It is straightforward to check that the allowed (trilinear) Yukawa terms are:

$$c_2 = -\frac{1}{2} : \ H' Q u_c , \ H^\dagger L l_c , \ H^\dagger Q d_c$$

$$c_2 = \frac{1}{2} : \ \tilde{H}' Q u_c , \ \tilde{H}^\dagger L l_c , \ \tilde{H}^\dagger Q d_c$$

Thus, two Higgs doublets are in each case necessary and sufficient to give masses to all quarks and leptons. Let us point out that the presence of the second Higgs doublet changes very little the curves of Fig. 1 and consequently our previous conclusions about $M_s$ and $\sin^2 \theta_W$.

A few important comments are now in order:

(i) The spectrum we assumed in Eq. (1) does not contain right-handed neutrinos on the branes. They could in principle arise from open strings in the bulk. Their interactions with the particles on the branes would then be suppressed by the large volume of the transverse space [14]. More specifically, conservation of the three $U(1)$ charges allow for the following Yukawa couplings involving the right-handed neutrino $\nu_R$:

$$c_2 = -\frac{1}{2} : \ H' L \nu_L ; \ c_2 = \frac{1}{2} : \ \tilde{H} L \nu_R$$

These couplings lead to Dirac type neutrino masses between $\nu_L$ from $L$ and the zero mode of $\nu_R$, which is naturally suppressed by the volume of the bulk.

(ii) Implicit in the above was our assumption of three generations (1) of quarks and lepton in the light spectrum. They can arise, for example, from an orbifold action along the lines of the model described in Ref. [13].

(iii) From Eq. (7) and Fig. 1, we find the ratio of the $SU(2)$ and $SU(3)$ gauge couplings at the string scale to be $\alpha_2/\alpha_3 \sim 0.4$. This ratio can be arranged by an appropriate choice of the relevant moduli. For instance, one may choose the color and $U(1)$ branes to be D3 branes while the weak branes to be D7 branes. Then the ratio of couplings above can be explained by choosing the volume of the four compact dimensions of the seven branes to be $V_4 = 2.5$ in string units. This being larger than one is consistent with the picture above. Moreover it predicts an interesting spectrum of KK states for the Standard model, different from the naive that have appeared hitherto: The only Standard Model particles
that have KK descendants are the W bosons as well as the hypercharge gauge boson. However since the hypercharge is a linear combination of the three U(1)’s the massive U(1) gauge bosons couple not to hypercharge but to doublet number.

Another possibility would be to move slightly off the orientifold point which may be necessary also for other reasons (see discussion towards the end of the paper).

(iv) Finally, it should be stressed that there are some alternative assignments that may work and these are discussed further in [11].

3 The fate of $U(1)$’s and proton stability

The model under discussion has three $U(1)$ gauge interactions corresponding to the generators $Q_1, Q_2, Q_3$. From the previous analysis, the hypercharge was shown to be either one of the two linear combinations:

$$Y = Q_1 \mp \frac{1}{2} Q_2 + \frac{2}{3} Q_3.$$  (14)

It is easy to see that the remaining two $U(1)$ combinations orthogonal to $Y$ are anomalous. In particular there are mixed anomalies with the SU(2) and SU(3) gauge groups of the Standard Model.

These anomalies are canceled by two axions coming from the closed string sector, via the standard Green-Schwarz mechanism [14]. The mixed anomalies with the non-anomalous hypercharge are also canceled by dimension five Chern-Simmons type of interactions [14]. The presence of such interactions has so far escaped attention in the context of string theory.

An important property of the above Green-Schwarz anomaly cancellation mechanism is that the two $U(1)$ gauge bosons $A$ and $A'$ acquire masses leaving behind the corresponding global symmetries [14]. This is in contrast to what would had happened in the case of an ordinary Higgs mechanism. These global symmetries remain exact to all orders in type I string perturbation theory around the orientifold vacuum.

So, as long as we stay at the orientifold point, all three charges $Q_1, Q_2, Q_3$ are conserved and since $Q_3$ is the baryon number, proton stability is guaranteed.

To break the electroweak symmetry, the Higgs doublets in Eq. (9) or (10) should acquire non-zero VEV’s. Since the model is non-supersymmetric, this may be achieved radiatively [16]. From Eqs. (11) and (12), to generate masses for all quarks and leptons, it is necessary for both Higgses to get non-zero VEV’s. The baryon number conservation remains intact because both Higgses have vanishing $Q_3$. However, the linear combination which does not contain $Q_3$, will be broken spontaneously, as follows from their quantum numbers in Eqs. (9) and (11). This leads to an unwanted massless Goldstone boson of the Peccei-Quinn type. The way out is to break this global symmetry explicitly, by moving away from the orientifold point along the direction of the associated modulus so that baryon number remains conserved. Instanton effects in that case will generate the appropriate symmetry breaking couplings in the potential.

4 A fifth force?

As is obvious from the previous discussion in order to explain the ratio of the strong to the weak coupling we must assume that the U(2) gauge group arises from a D7 brane with four compact directions, with radii $R_i$, $i = 1, 2, 3, 4$ and $R_1 R_2 R_3 R_4 \sim 2.5$ and $R_i \geq 1$.
in string units. The other interactions arise from D3 branes. By looking again on the charge assignments of open strings that represent the fermions, it is obvious that the $\bar{U}$ and the electron singlet (as well as one of the Higgses) must terminate in an extra set of branes different from the one described above. In general, the gauge group of such a brane will be $U(n)$ for some $n \geq 1$. The $U(1)$ factor is necessarily anomalous. It is easy to check that it has mixed anomalies with the $SU(3)$ of color. Thus, this gauge boson will acquire a mass $M = gM_s$ where $g$ is the gauge coupling of the anomalous $U(1)$. If such an extra set consists of D3 branes, or D7 branes parallel to the U(2) branes, then this implies the existence of a new force among u-quarks and electrons with the same strength as the strong or the weak force. The non-abelian piece $SU(n)$, if there, must be broken completely at the string scale, otherwise it would be incompatible with data. The $U(1)$ is broken by the anomaly and the associated gauge boson has a mass of the order of TeV.

The alternative possibility is that the branes are D7 branes intersecting the U(2) branes along the 1,2 directions, the effective gauge coupling is $g^2 = (4\pi\alpha_{\text{strong}})^{-1} \frac{M_s^2}{M_p^2} \sim 5 \times 10^{-31}$, and the mass of the anomalous gauge boson is $M = gM_s \sim 5 \times 10^{-3} \text{eV}$ which corresponds to a range of $40 \mu$m. This is currently allowed by "fifth force" data but is probably excluded by supernova physics due to the large cross section for producing such gauge bosons. The gauge boson above would be the only particle with low lying KK excitations quantized in units of $8 \times 10^{-3} \text{eV}$. Low-lying KK states coming from the bulk have masses also quantized in units of $8 \times 10^{-3} \text{eV}$ and are thus of the same order as the masses described above.

In conclusion, we presented a particular embedding of the Standard Model in a non-supersymmetric D-brane configuration of type I/I’ string theory. The strong and electroweak couplings are not unified because strong and weak interactions live on different branes. Nevertheless, $\sin^2 \theta_W$ is naturally predicted to have the right value for a string scale of the order of a few TeV. The model contains two Higgs doublets needed to give masses to all quarks and leptons, and preserves baryon number as a (perturbatively) exact global symmetry. The model satisfies the main phenomenological requirements for a viable low energy theory and its explicit derivation from string theory deserves further study.

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4There is an alternative possibility, [11], where the electron singlet is a string with both end on the weak brane. In this case the experimental constraints are weaker, since only the $\bar{u}$-quark feels the fifth force.
