4D GUT (and SM) MODEL BUILDING FROM INTERSECTING D-BRANES

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ABSTRACT

We provide a general overview of the current state of the art in three generation model building proposals - using intersecting D-brane toroidal compactifications of IIA string theories - which have, only, the SM at low energy. In this context, we focus on these model building directions, where natural non-supersymmetric constructions based on $SU(4)_C \times SU(2)_L \times SU(2)_R$, SU(5) and flipped SU(5) GUT groups, have at low energy only the Standard Model. In the flipped SU(5) GUTS, the special build up structure of the models accommodates naturally a see-saw mechanism and a new solution to the doublet-triplet splitting problem.
1 Introduction to SM D6/D5-brane model building with only the SM at Low Energy

In the last two years, constructions based on D-branes intersecting at angles -intersecting brane worlds (IBW’s) for short - received a lot of attention [1] - [22], as on these constructions, for the first time in string theory, it became possible \(^1\) to construct four dimensional non-supersymmetric intersecting D6-brane models that have only the SM gauge group and chiral spectrum - with right handed neutrinos \(\nu_R\)'s - at low energies [1, 2, 3]. The initial constructions of IBW’s exhibiting the SM at low energy, were based on a background of D6-branes intersecting at angles in 4D toroidal orientifolds [4] of [T-dual to models with magnetic deformations [5]. See also [16].] type IIA theory; possess broken supersymmetry on the bulk and on the ‘branes’, and exhibit proton stability as baryon number is a gauged symmetry. The primary common phenomenological characteristics of the four stack D6-models of [1] and the five and six SM’s of [2] and [3] respectively - emphasizing that there are no D6-brane models with only the SM at low energy using constructions with more than six stacks of D6-branes at the string scale \(M_s\) - are :

- the prediction of the existence of the SM chiral spectrum together with \(\nu_R\)'s,
- the conservation of lepton number - the models admit Dirac terms for the neutrinos - their masses appear as a result of the existence of particular Yukawa couplings associated with the breaking of the chiral symmetry.

Additionally, the SM’s of [2] and [3] exhibit a new phenomenon - not found in the SM’s of [1], namely the prediction of the existence of N=1 supersymmetric (SUSY) partners of \(\nu_R\)'s, the s\(\nu_R\)'s. Thus even though the models of [2, 3] are non-supersymmetric, they have particular N=1 SUSY partners, the s\(\nu_R\)'s, whose presence is necessary in order to break the extra beyond the hypercharge U(1)'s that survived massless the presence of the generalized Green-Schwarz mechanism, the latter cancelling the mixed U(1)-gauge anomalies \(^2\). Starting from a SM-like configuration at \(M_s\) and constructing a D-brane configuration that had only the SM at low energy, as in the models of [1, 2, 3], was not the only model building success story of IBW’s. For dimensional (4D) configurations with intersecting D5-branes and only the SM at low energy - wrapped on a background of type IIB compactifications on a \(T^4 \times C/Z_N\) - were also obtained in [7].

Moreover the first non-SUSY constructions of string GUTS which have only the SM at low en-

\(^1\)See also [23] for other reviews on the subject

\(^2\)We note that in these kind of constructions uncancelled NS tadpoles remain, whose cancellation in higher orders of perturbation theory remains an open issue. The NS tadpoles do not affect the low energy spectrum of the models but they rather imply the instability of the present models, in the present order of perturbation theory, in a flat background. Higher order corrections to NS tadpoles might be responsible for stabilizing these D-brane configurations.
ergy, were constructed in [8], based on the Pati-Salam structure $SU(4)_C \times SU(2)_L \times SU(2)_R$ at $M_s$.

2 Building the $SU(4)_C \times SU(2)_L \times SU(2)_R$ GUTS With Only The SM At Low Energy

Extensions of these GUTS with four, five and six stacks of D6-branes were also considered in [8, 14, 15].

The basic features found in these intersecting D6-brane models can be classified as follows:
- The models even though they have overall N=0 SUSY, possess N=1 SUSY subsectors which are necessary in order to create a Majorana mass term for $\nu_R$’s.
- Extra branes are needed to cancel RR tadpoles. The presence of these branes creates extra matter singlets, transforming under both the visible SM gauge group and the extra D6-brane gauge group that may be used to break the extra U(1)’s, beyond hypercharge, surviving massless the presence of the generalized Green-Schwarz mechanism. Their presence is also used to make massive the exotic fermions, seen for example in the bottom part of table (1), taken from [15]. The fermion spectrum of table (1) is consistent with the calculation of RR tadpoles. The RR tadpoles get cancelled with the introduction of extra U(1) branes, $h^i$, that transform under the both the extra U(1) gauge group and the rest of the intersecting D6-branes of table (1). The existence of N=1 SUSY at the intersections $dd^*, dh, dh^*, eh, eh^*$, creates the singlets $s_R^b, \kappa_3^b, \kappa_4^b, \kappa_5^b, \kappa_6^b$ respectively, that contribute to the mass of the ‘light’ fermions $\chi^1_L, \chi^2_L$. All fermions of table (1) receive a mass of order $M_s$; the only exception being the light masses of $\chi^1_L, \chi^2_L$, weak fermion doublets. Lets us discuss the latter issue in more detail.

\[ \begin{array}{|c|c|c|c|c|c|c|c|} \hline \text{Fields} & \text{Intersection} & SU(4)_C \times SU(2)_L \times SU(2)_R & Q_a & Q_b & Q_c & Q_d & Q_s \\ \hline F_L & I_{abc} = 3 & 3 \times (4, 2, 1) & 1 & 1 & 0 & 0 & 0 \\ F_R & I_{abc} = -3 & 3 \times (\bar{3}, 1, 2) & -1 & 0 & 1 & 0 & 0 \\ \chi_L^1 & I_{abc} = -8 & 8 \times (1, \bar{3}, 1) & 0 & -1 & 0 & -1 & 0 \\ \chi_R^1 & I_{abc} = -8 & 8 \times (1, 1, 2) & 0 & 1 & 0 & 0 & 0 \\ \chi_L^2 & I_{abc} = -4 & 4 \times (1, \bar{3}, 1) & 0 & -1 & 0 & 0 & 1 \\ \chi_R^2 & I_{abc} = -4 & 4 \times (1, 1, 2) & 0 & 1 & 0 & 0 & 0 \\ \omega_L & I_{a} & 6\beta^2 \times (6, 1, 1) & 2 & 0 & 0 & 0 & 0 \\ y_R & I_{a} & 6\beta^2 \times (10, 1, 1) & -2 & 0 & 0 & 0 & 0 \\ s_R^b & I_{a} & 16\beta^2 \times (1, 1, 1) & 0 & 0 & 2 & 0 & 0 \\ s_R^b & I_{a} & 8\beta^2 \times (1, 1, 1) & 0 & 0 & 0 & 0 & -2 \\ \hline \end{array} \]

Table 1: Fermionic spectrum of the $SU(4)_C \times SU(2)_L \times SU(2)_R$, PS-II class of models together with $U(1)$ charges. We note that at energies of order $M_\gamma$ only the Standard model survives.

3These models were also based on the intersecting D6-backgrounds of [4].
The left handed fermions $\chi^1_L$ receive a contribution to their mass from the coupling

$$\langle h_2 \rangle \langle h_2 \rangle \langle \bar{F} R \rangle \langle H_1 \rangle \langle \bar{s}_B \rangle \langle h_2 \rangle \langle h_2 \rangle \langle \bar{F} H_1 \rangle \langle \bar{s}^1_B \rangle \sim (1, 2, 1)(1, 2, 1)$$

(2.1)

and from another coupling, of the same order as (2.1), also contributing to the mass of the $\chi^1_L$ fermion as

$$\langle h_2 \rangle \langle h_2 \rangle \langle \bar{F} R \rangle \langle H_1 \rangle \langle \bar{\kappa}^B \rangle \langle \bar{s}^2_B \rangle \langle \bar{F} H_1 \rangle \langle \bar{s}^2_B \rangle \sim (1, 2, 1)(1, 2, 1)$$

(2.2)

The left handed fermions $\chi^2_L$ receive a non-zero mass from the coupling

$$\langle h_2 \rangle \langle h_2 \rangle \langle \bar{F} R \rangle \langle H_1 \rangle \langle \bar{s}^2_B \rangle \langle \bar{s}^1_B \rangle \langle h_2 \rangle \langle h_2 \rangle \langle \bar{F} H_1 \rangle \langle \bar{s}^2_B \rangle \sim (1, 2, 1)(1, 2, 1)$$

(2.3)

and the coupling

$$\langle h_2 \rangle \langle h_2 \rangle \langle \bar{F} R \rangle \langle H_1 \rangle \langle \bar{\kappa}^B \rangle \langle \bar{s}^2_B \rangle \langle \bar{F} H_1 \rangle \langle \bar{\kappa}^B \rangle \sim (1, 2, 1)(1, 2, 1)$$

(2.4)

Thus assuming that the leading area Yukawa for the couplings is of order $O(1)$, e.g. associated areas going to zero, the masses of

$$\chi^1_L, \chi^2_L \sim \frac{2\nu^2}{M_s}$$

(2.5)

• As the particles $\chi^1_L, \chi^2_L$ are not observed at present, the fact that their mass may be between

$$100 \text{ GeV} \leq \chi^1_L, \chi^1_L \leq 2\nu = max\left\{\frac{2\nu^2}{M_s}\right\} = 492 \text{ GeV}$$

(2.6)

sends the string scale

$$M_s \leq 1.2 \text{ TeV}$$

(2.7)

This is a general feature of all the Pati-Salam models based on toroidal orientifolds; they predict the existence of light weak doublets with masses between 100 and $\nu = 492$ GeV. The latter result may be considered as a general prediction of all classes of models based on intersecting D6-brane Pati-Salam GUTS.

Another important property of these constructions is that the conditions for some intersections to respect N=1 supersymmetry and also needed to guarantee the existence of a Majorana mass term for $s\nu_R$’s:

• solve the orthogonality conditions for the extra - beyond hypercharge - $U(1)$’s to survive

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4 In (2.1) we have included the leading contribution of the worksheet area connecting the seven vertices. In the following for simplicity reasons we will set the leading contribution of the different couplings to one e.g. area tends to zero.

5 In this case the masses of $\chi^1_L, \chi^2_L$ are the sum of the contributions of (2.1, 2.2) and (2.3, 2.4) respectively

6 The reader may convince itself that the maximum value of $2\nu^2/M_s$ is $2\nu$.

7 The latter becoming massive from the use of extra singlets created by the presence of extra branes; the latter needed to satisfy the RR tadpoles.
massless the presence of a generalized Green-Schwarz mechanism describing the couplings of the U(1)’s to the RR two form fields.

The considerations we have just described [8], [14], [15] are quite generic and the same methodology applies easily to the construction of more general GUT gauge groups in the context of intersecting brane worlds.

We note that at present the only existing string GUT constructions, in the context of Intersecting D6-brane Models, that have only the SM at low energy, with complete cancellation of RR tadpoles, are:

a) the toroidal orientifold II Pati-Salam GUTS of [8, 14, 15] and

b) the constructions of flipped SU(5), and SU(5) GUTS of [20] described next.

3 The Construction of Flipped SU(5) (and SU(5)) GUTS with only the SM at Low Energy

Let us review the intersecting D6-branes constructions of the $Z_3$ orientifolds of [17]. The D6-branes involved satisfy the following RR tadpole conditions where $^8$

$$\sum_a N_a Z_a = 2.$$  

(3.3)

As it was noticed in [17] the simplest realization of an SU(5) GUT involves two stacks of D6-branes at the string scale $M_s$, the first one corresponding to a $U(5)$ gauge group while the second one to a U(1) gauge group. Its effective wrapping numbers are given by

$$(Y_a, Z_a) = (3, \frac{1}{2}), \quad (Y_b, Z_b) = (3, -\frac{1}{2}),$$

(3.4)

Under the decomposition $U(5) \subset SU(5) \times U(1)_a$, the models become effectively an $SU(5) \times U(1)_a \otimes U(1)_b$ GUT. One combination of U(1)’s become massive due to its coupling to a RR field, another one remains massless to low energies. The spectrum of this SU(5) GUT may be seen in the first seven columns (reading from the left) of table (2). At this stage the SU(5) models - have the correct chiral fermion content of an SU(5) GUT - and the extra U(1) surviving the presence of the Green-Schwarz mechanism, breaks by the use of a singlet field present. However, the electroweak 5-plets needed for electroweak symmetry breaking of the models are absent. Later on, attempts to construct a fully N=1 supersymmetric SU(5) models at $M_s$ in [19], produced 3G models that were not free of remaining massless exotic 15-plets. Also, later on in [18] it was noticed that if one leaves unbroken, and rescales, the

$^8$ The net number of bifundamental massless chiral fermions in the models is defined as

$$(\bar{N}_a, N_b)_L : I_{ab} = Z_a Y_b - Y_a Z_b$$

(3.1)

$$(N_a, \bar{N}_b)_L : I_{ab} = Z_a Y_b + Y_a Z_b$$

(3.2)
Table 2: Chiral Spectrum of a two intersecting D6-brane stacks in a three generation flipped SU(5) ⊗ U(1)_{mass} model. Note that the charges under the U(1)_{fl} gauge symmetry, when rescaled appropriately (and U(1)_{fl} gets broken) ‘converts’ the flipped SU(5) model to a three generation (3G) SU(5).

U(1) surviving massless the Green-Schwarz mechanism of the SU(5) GUT of [17], the rescaled U(1) becomes the flipped U(1) generator. However, the proposed 3G models lack the presence of GUT Higgses or electroweak pentaplets and were accompanied by extra exotic massless matter to low energies.

In [20] we have shown that it is possible to construct the first examples of string SU(5) and flipped SU(5) GUTS - where we identified the appropriate GUT and electroweak Higgses - which break to the SM at low energy. E.g. in the flipped SU(5) GUT, the fifteen fermions of the SM plus the right handed neutrino \( \nu_c \) belong to the

\[
F = 10_1 = (u, d, d^c, \nu^c), \quad f = \bar{5}_{-3} = (u^c, \nu, e), \quad l^c = 1_5 = e^c
\]

chiral multiplets. The GUT breaking Higgses may come from the ‘massive’ spectrum of the sector localizing the 10-plet (10^B_1 = (u_H, d_H, d^c_H, \nu^c_H)) fermions seen in table (2). The lowest order Higgs in this sector, let us call them \( H_1, H_2 \), have quantum numbers as those given in table (3). By looking at the last column of table (3), we realize that the Higgs \( H_1, H_2 \) are

Table 3: Flipped SU(5) ⊗ U^{fl} GUT symmetry breaking scalars.

| Intersection | GUT Higgses | repr. | \( Q_a \) | \( Q_b \) | \( Q^{fl} \) |
|--------------|-------------|-------|----------|----------|---------|
| \{a, O6\}    | \( H_1 \)   | 10    | 2        | 0        | 1       |
| \{a, O6\}    | \( H_2 \)   | \( 10 \) | -2       | 0        | -1      |

the GUT symmetry breaking Higgses of a standard flipped SU(5) GUT. By duplicating the analysis of section (3.1), one may conclude that what it appears in the effective theory as GUT breaking Higgs scalars, is the combination \( H^G = H_1 + H_2^* \). In a similar way the correct identification of the electroweak content [20] of the flipped SU(5) \( 5^B_{-2} = (D, h^-, h^0) \)-plet (and SU(5))GUTS made possible the existence of the see-saw mechanism which is generated by
the interaction
\[ L = \bar{Y}_L \nu L \cdot 10 \cdot \tilde{5} \cdot \bar{h}_4 + \bar{Y}_R \nu R \cdot \frac{1}{M_s} \cdot (10 \cdot \bar{\mathbf{T}}_B^B)(10 \cdot \mathbf{T}_B^B). \] (3.6)

Its standard version can be generated by choosing
\[ \langle h_4 \rangle = v, \quad \langle 10^B \rangle = M_s \] (3.7)
and generates small neutrino masses. In these constructions the baryon number is not a gauged symmetry, thus a high GUT scale of the order of the \(10^{16}\) GeV helps the theory to avoid gauge mediated proton decay modes like the [20]
\[ \sim \frac{1}{M_s^2} (\bar{u}_L^c u_L)(\bar{e}_R^c e_R), \sim \frac{1}{M_s^2} (\bar{d}_R^c u_R)(\bar{d}_L^c \nu_L). \] (3.8)

[In IBW’s proton decay by direct calculation of string amplitudes for SUSY SU(5) D-brane models was examined in [10].] Scalar mediated proton decay modes get suppressed by the existence of a new solution to the doublet-triplet splitting problem
\[ \frac{r}{M_s^2} (HHh)(\bar{F}\bar{F}\bar{h}) + m(h\bar{h})(\bar{H}H) + \kappa(\tilde{H}H)(\bar{H}H), \] (3.9)
that stabilizes the vev’s of the triplet scalars \(d^H, D\) [20]. This is the first example of a doublet-triplet splitting realization in IBW’s. The full solution of the gauge hierarchy problem, that is avoiding the existence of quadratic corrections to the electroweak Higgses remains an open issue in the present GUTS.

Recently the interest of model building in IBW’s has been focused in the construction of intersecting D6-brane models which localize the spectrum of MSSM at low energies [21], [22].

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