PHENOMENOLOGY OF D-BRANE MODELS *

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Standard Model: although successful, it is not the final theory (gravity not unified, fermion mass hierarchy not explained, etc)

Attempts to solve these problems involve:

1) Early extensions of SM:

Grand Unified Theories (GUTs) , SUSY GUTs, etc.

Predictions:

- unification of couplings at $M_S \sim 10^{15} - 10^{16}\mathrm{GeV}$,
- See-saw Neutrino masses compatible with experiments, etc

Shortcomings:

- New undetermined parameters (scalar masses etc,), proton decay,...

2) Recent Attempts: String and D-brane models.

In particular, Intersecting D-Branes offer a promising framework for Model Building.

New interesting features:

- Possibility of low M_S (thus, no need of SUSY)
- Baryon number conservation due to extra $U(1)$'s
- Split SUSY spectrum in certain cases
- Calculability (gauge and Yukawa couplings, # generations ...)

D-brane Constructions

Basic Ingredient in D-brane model building: A stack of N parallel (almost coincident) D-branes (brane stack) gives rise to a $U(N)$ gauge symmetry. (a single D-brane carries a $U(1)$ symmetry.)

Matter: Strings stretched between brane stacks. Thus: A string stretched between N_a, N_b Brane stacks gives rise to $(N_a, \bar{N}_b)$-irrep.

Compact space: $T^6 = T^2 \times T^2 \times T^2$

Chirality: Arises when branes are wrapped around the torus. A simple example of a D-brane wrapping around the two radii of a T^2 is shown below:

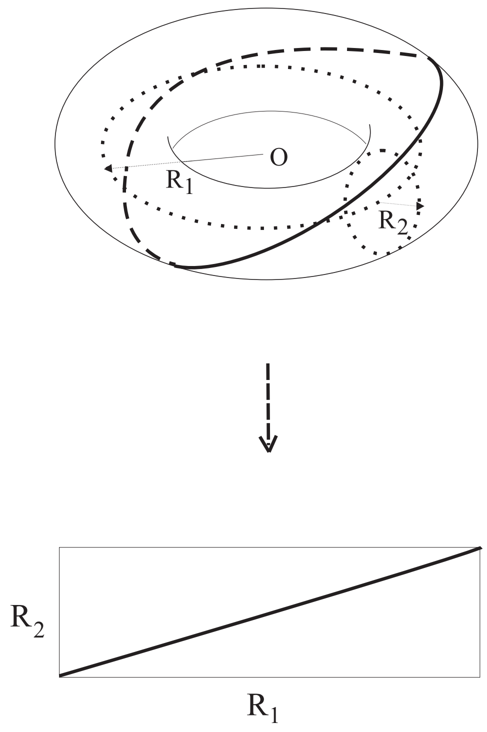


Figure 1: Representation of a $(1, 1)$ D-brane wrapping on a T^2 torus.

Fermion Generations. If (n_a^i, m_a^i) are the wrapping numbers of the $\mathrm{D}6_a$ brane around the i^{th} torus, the number of generations equals the number of intersections:

$$I_{ab} \quad = \quad \prod_{i=1}^{3} (n_a^i m_b^i - n_b^i m_a^i) \tag{1}$$

Gauge couplings g_a

$$\frac{4\pi^2}{g_a^2} \quad = \quad \frac{M_S}{\lambda_{II}} \ell_{m_a n_a} \tag{2}$$

$M_S =$ string scale
$\lambda_{II} =$ type-II string coupling
$\ell_{mn} = 2\pi \sqrt{n^2 R_1^2 + m^2 R_2^2 + 2nmR_1 R_2 \cos\theta}$

Yukawa couplings λ_{ijk} ($A_{ijk} =$ world-sheet area)

$$\lambda_{ijk} \quad = \quad e^{-\frac{R_1 R_2}{\alpha'} A_{ijk}} \tag{3}$$

MODEL BUILDING

Observe that D-brane constructions generate $U(N)$ symmetries:

$$U(n) \quad \rightarrow SU(n) \times U(1) \tag{4}$$

therefore:

• if we wish to generate previous successful models in the context of D-branes, in addition to the old gauge symmetries we expect several $U(1)$ factors.

• Several of those $U(1)$'s carry anomalies which are canceled by a generalized Green-Schwartz mechanism

• Some of them are related to global symmetries of SM.

• the anomaly-free combinations could in principle participate in the hypercharge

EXAMPLES OF MODEL BUILDING

A)The Standard Model: Assume the existence of N extra $U(1)$ abelian branes. The SM D-brane analogue is:

$$G = U(3)_C \times U(2)_L \times U(1)^N \tag{5}$$

Here is an example of the SM model spectrum for $N = 1$ (Antoniadis and Dimopoulos Nucl.Phys.B715:120-140,2005):

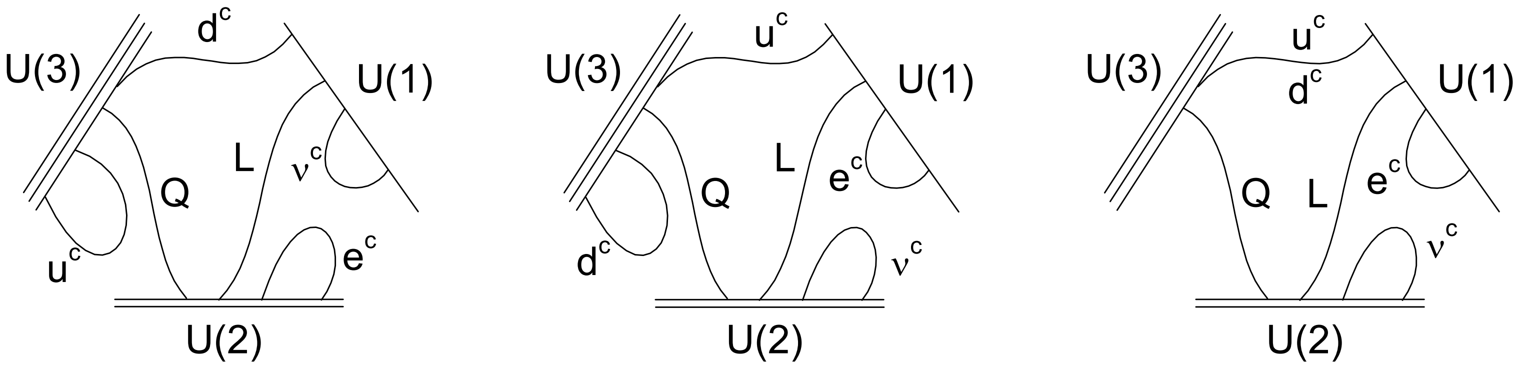


Figure 2: SM configurations with only one extra abelian brane.

The most general hypercharge gauge coupling condition is

$$\frac{1}{g_Y^2} = \frac{6{k_3}^2}{g_3^2} + \frac{4{k_2}^2}{g_2^2} + 2\sum_{i=1}^{N} \frac{{k_i'}^2}{{g_i'}^2} \tag{6}$$

The requirement to obtain the correct $U(1)_Y$ charges for the SM spectrum determines the coefficients $k_{2,3}, k_i'$.

• $k_{2,3}$ are due to the contributions of the abelian factors of $U(3)_C \to SU(3)_C \times U(1)_C$ and $U(2)_L \to SU(2)_L \times U(1)_L$

• k_i' are due to the abelian factors (the $U(1)$ branes).

• For $N = 1, 2, 3$ abelian branes the results for $k_{2,3}, k_i'$ are shown in the table below: (D.V. Gioutsos, GKL and A. Psallidas, Phys.Rev.D74:075007,2006 (hep-ph/0605187))

N		$\lvert k_3\rvert$	$\lvert k_2\rvert$	$\lvert k_1'\rvert$	$\lvert k_2'\rvert$	$\lvert k_3'\rvert$
1	a_1	$\frac{1}{3}$	$\frac{1}{2}$	0	–	–
	b_1	$\frac{1}{6}$	0	$\frac{1}{2}$	–	–
2	a_2	$\frac{1}{6}$	0	$\frac{1}{2}$	$\frac{1}{2}$	–
	b_2	$\frac{2}{3}$	$\frac{1}{2}$	1	0	–
	c_2	$\frac{1}{3}$	$\frac{1}{2}$	0	1	–
3	a_3	$\frac{1}{6}$	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	b_3	$\frac{1}{3}$	$\frac{1}{2}$	0	1	1
	c_3	$\frac{2}{3}$	$\frac{1}{2}$	1	0	0

Table 1: Simplest hypercharge embeddings for the $N = 1, 2, 3$ brane configurations.

A detailed analysis of various phenomenological issues of the above models has been carried out, for the non-supersymmetric as well as the split-supersymmetric cases: The analysis shows that for models where the $U(1)$ branes are aligned to $SU(3)$ or $SU(2)$ branes:

•With respect to the predictions of the string scale, there are three classes of viable models: (N is the number of abelian branes)

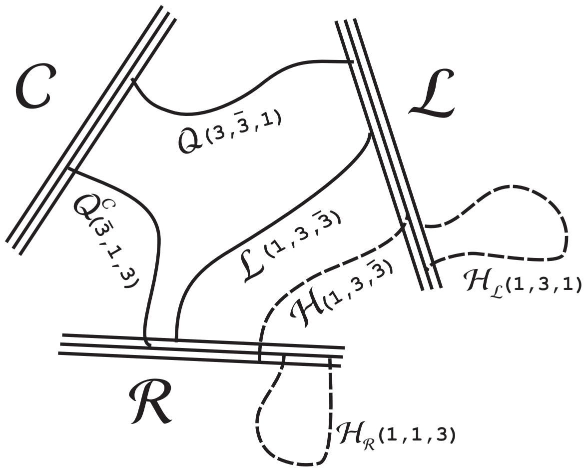
1: There are $N = 1, 3$ models with string scale $M_S \sim 10^{16}$ GeV.

2: There are $N = 2$ models with $M_S \sim 10^{7-8}$ GeV;
In addition, the condition $m_b^0 = m_\tau^0$ at M_S is fulfilled.

3: There are $N = 3$ models with M_S as low as a few TeV.

B)The "Trinification" Model:

To generate this group one needs three stacks of D-branes, each stack containing 3 parallel almost coincident branes. (GKL and J. Rizos, Phys.Lett.B632:710-716,2006 (hep-ph/0510230))



The gauge symmetry is $U(3)_C \times U(3)_L \times U(3)_R$, or:

$$SU(3)_c \times SU(3)_L \times SU(3)_R \times U(1)_C \times U(1)_L \times U(1)_R \qquad (7)$$

The abelian $U(1)_{C,L,R}$ factors have mixed anomalies with the non-abelian $SU(3)^3$. The anomaly free combination,

$$U(1)_{\mathcal{Z}'} = U(1)_C + U(1)_L + U(1)_R$$

allows the possibility of (re)defining the hypercharge

$$Y = -\frac{1}{6}X_{L'} + \frac{1}{3}X_{R'} + \frac{1}{6}\mathcal{Z}' \tag{8}$$

where $-\frac{1}{6}X_{L'} + \frac{1}{3}X_{R'}$ is the standard definition of $SU(3)^3$, and $X_{L'}, X_{R'}, \mathcal{Z}'$ generators of the appropriate $U(1)$ factors.

Spectrum

Fermion and Higgs states obtained from strings attached to two different branes (see figure above) with their quantum numbers:

$$\mathcal{Q} \quad = \quad (3, \bar{3}, 1)_{(+1,-1,\ \ 0)} \tag{9}$$

$$\mathcal{Q}^c \quad = \quad (\bar{3}, 1, 3)_{(-1,\ \ 0,+1)} \tag{10}$$

$$\mathcal{L} \quad = \quad (1, 3, \bar{3})_{(\ \ 0,+1,-1)} \tag{11}$$

$$\mathcal{H} \quad = \quad (1, 3, \bar{3})_{(\ \ 0,+1,-1)} \tag{12}$$

Higgs states from strings with both ends on the same 3-stack

$$\mathcal{H}_{\mathcal{L}} \quad = \quad (1, 3, 1)_{(0,-2,0)} \tag{13}$$

$$\mathcal{H}_{\mathcal{R}} \quad = \quad (1, 1, 3)_{(0,0,-2)} \tag{14}$$

Due to the additional $U(1)$ symmetries, at tree-level only one Yukawa coupling is allowed

$$\lambda^{ij}_{Q,1}\, \mathcal{Q}_i\, \mathcal{Q}^c_j\, \mathcal{H}_a, \quad a = 1, 2 \tag{15}$$

It can provide quark masses as well masses for the extra triplets.

The lowest order allowed leptonic Yukawa terms arise at fourth order

$$\frac{f^{ab}_{ij}}{M_S}\, \mathcal{H}^\dagger_a\, \mathcal{H}^\dagger_b\, \mathcal{L}_i\, \mathcal{L}_j + \frac{\zeta_{ij}}{M_S}\, \mathcal{H}_{\mathcal{L}}\, \mathcal{H}^\dagger_{\mathcal{R}}\, \mathcal{L}_i\, \mathcal{L}_j \tag{16}$$

where f^{ab}_{ij}, ζ_{ij} are order one Yukawa couplings. These terms imply:

• masses for charged leptons suppressed by a factor M_R/M_S compared to quark masses.

• light Majorana masses for the three neutrino species through a see saw mechanism.

• heavy masses for the extra states of the order M_R^2/M_S.

Gauge couplings and the string scale

In brane models, gauge couplings are not necessarily equal. They originate from gauge factors related to brane stacks that span different directions of the higher dimensional space. For simplicity assume the three particular cases:

- $a_L = a_R,\;\; a_L = a_C,\;\; a_C = a_R.$
- Assume that $SU(3)_{L,R}\, U(1)_{\mathcal{Z}'}$ symmetries break at M_R.
- Mass scales: M_S, M_R, M_W.

The M_S, M_R predictions for these three distinct cases are shown in the next table

case	M_R/GeV	M_S/GeV
$a_L = a_R$	1.7×10^9	$> 1.7 \times 10^9$
$a_L = a_C$	$< 2.3 \times 10^{16}$	$> 2.3 \times 10^{16}$
$a_C = a_R$	$< 2.3 \times 10^{11}$	$> 2.3 \times 10^{11}$

Table 2: Upper and lower bounds for $SU(3)_R$ breaking scale (M_R) and the corresponding String scale (M_S) for the three cases $a_L = a_C$, $a_R = a_C$ and $a_L = a_R$.

A FEW COMMENTS

• Several D-brane models are proposed in this talk as possible candidates to describe the physics of elementary particles, however to conclude whether some of them are relevant, further detailed analysis of their low energy consequences is necessary.

Some worth mentioning features are:

• SM D-brane variants predict a variety of sting scales. Depending on the brane orientations, M_S can range from a few TeV to $\sim 10^{17}$ GeV.

• On the contrary, the $U(3)^3$ model is characterized by relatively high unification scales larger than the intermediate $\sim 10^{10}$ and up to 10^{16} GeV.

Trying to understand the higher dimensional reality from the 4-dimensional "shadows" ...

{*Imagine prisoners who have been chained since childhood, deep inside a cave. Their heads are immobilized, so that their gaze is fixed on a wall. Behind the prisoners there is an enormous fire and between the prisoners and the fire there is a raised walkway along which animals, pants and other things are carried. Their shapes cast shadows on the wall which occupy prisoners attention. ... These shadows is the only reality they know, even though they are seeing merely shadows of higher dimensional objects.*}
(*adapted from Plato's "Republic", 5th Century BC*)

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Ανάπτυξη παντού. Ανάπτυξη για όλους.

ΥΠΟΥΡΓΕΙΟ ΕΘΝΙΚΗΣ ΠΑΙΔΕΙΑΣ ΚΑΙ ΘΡΗΣΚΕΥΜΑΤΩΝ
ΕΙΔΙΚΗ ΥΠΗΡΕΣΙΑ ΔΙΑΧΕΙΡΙΣΗΣ ΕΠΕΑΕΚ

ΕΥΡΩΠΑΪΚΗ ΕΝΩΣΗ
ΣΥΓΧΡΗΜΑΤΟΔΟΤΗΣΗ
ΕΥΡΩΠΑΪΚΟ ΚΟΙΝΩΝΙΚΟ ΤΑΜΕΙΟ

Η ΠΑΙΔΕΙΑ ΣΤΗΝ ΚΟΡΥΦΗ
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