A D-brane inspired Trinification model

G.K. Leontaris

Theoretical Physics Division, Ioannina University, GR-45110 Ioannina, Greece

Abstract

A non-supersymmetric D-brane inspired model with $U(3)_C \times U(3)_L \times U(3)_R$ symmetry is analyzed. The gauge group is broken down to the Standard Model by $(1, 3, \bar{3})$, $(1, 3, 1)$ and $(1, 1, 3)$ Higgs vev's. Quark masses are obtained from tree-level couplings, while charged leptons receive masses from fourth order Yukawa terms, as a consequence of extra abelian symmetries, thus a natural quark-lepton hierarchy arises. Light Majorana neutrino masses are obtained through a see-saw type mechanism operative at the $SU(3)_R$ breaking scale of the order $M_R \geq 10^9$GeV.

1. Description of the Model

In this talk, I will describe a model based on the gauge symmetry $U(3)^3$[1] which contains as a subgroup the $SU(3)_C \times SU(3)_L \times SU(3)_R$ symmetry supplemented by three $U(1)$ factors and can be considered as a D-brane analogue of the trinification model proposed in [2, 3]. I give here a brief description how such a symmetry could arise in this context. A Dp-brane is an extended object in p-dimensions. In D-brane constructions[4]-[8] the basic ingredient is the brane stack, i.e., a certain number of parallel, almost coincident D-branes. A single D-brane carries a $U(1)$ gauge symmetry which is the result of the reduction of the ten-dimensional Yang-Mills theory. A stack of N parallel branes gives rise to a $U(N)$ gauge group. Chirality arises when they are wrapped on a torus [6], while in the case of intersecting branes chiral fermions sit in singular points in the transverse space. The compact space is usually taken to be a six-dimensional factorizable torus $T^6 = T^2 \times T^2 \times T^2$ while the number of fermion generations, are related to the two distinct numbers of brane wrappings around the two circles of the torus. Thus, for two stacks n_a, n_b, the gauge group is $U(n_a) \times U(n_b)$ while the fermions (which live in the intersections) belong to the bi-fundamental representations $(n_a, \bar{n}_b)$, or $(\bar{n}_a, n_b)$.

Thus, to construct the D-brane analogue of the trinification model, we consider three stacks of D-branes, each stack containing 3 parallel almost coincident branes giving rise to the gauge symmetry

$$U(3)_C \times U(3)_L \times U(3)_R \,.$$

The first $U(3)$ is related to $SU(3)$ color, the second involves the weak $SU(2)_L$ and the third is related to a possible intermediate $SU(2)_R$ gauge group. Since $U(3)$ is equivalent to $SU(3) \times U(1)$, our D-brane construction –in addition to the standard trinification gauge group– contains also three extra $U(1)$ abelian symmetries, thus the $U(3)^3$ gauge symmetry can be equivalently written

$$SU(3)_C \times SU(3)_L \times SU(3)_R \times U(1)_C \times U(1)_L \times U(1)_R \tag{1}$$

In the D-brane context, matter fields appear as open strings having both their ends attached to some of

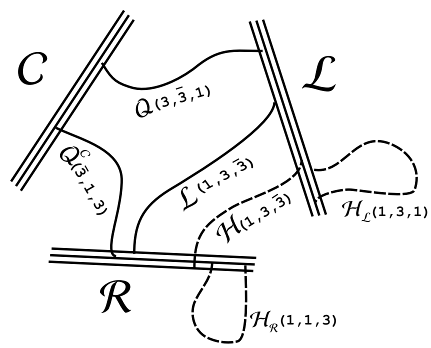

Figure 1: Schematic representation of a $U(3)_C \times U(3)_L \times U(3)_R$ D-brane configuration and the matter fields of the model.

the brane stacks. For example, strings with endpoints attached on two different 3-brane stacks belong to the $(3, \bar{3})$ or $(\bar{3}, 3)$ multiplets of the corresponding gauge group factors. The possible representations which arise in this scenario should be appropriate to accommodate the standard model particles and Higgs fields. As such candidates we choose the open strings that appear in figure 1. Under the decomposition (1) these lead to the following matter representations

$$\mathcal{Q} = (3, \bar{3}, 1)_{(+1,-1,\ 0)} \tag{2}$$

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

$$\mathcal{L} = (1, 3, \bar{3})_{(\ 0,+1,-1)} \tag{4}$$

Here, we adopt a notation where the three first numbers refer to the color, left and right $SU(3)$ gauge groups, while the three indices correspond to the three $U(1)_{C,L,R}$ symmetries respectively. It turns out that these three representations suffice to accommodate all the fermions of the Standard Model. In particular, the representation (2) includes the left-handed quark doublets $q = (u, d)^T$ and an additional colored triplet D with SM-quantum numbers as those of the down quark, while representation (3) contains the right-handed partners of (2). Finally (4) involves the lepton doublet, the right-handed electron and its corresponding neutrino, two additional $SU(2)_L$ doublets and another neutral state, which was given the name neutreto [2]. For a single family, we write the following assignment

$$(3,\bar{3},1) = \begin{pmatrix} u_r & d_r & D_r \\ u_g & d_g & D_g \\ u_b & d_b & D_b \end{pmatrix},\ (\bar{3},1,3) = \begin{pmatrix} u_r^c & u_g^c & u_b^c \\ d_r^c & d_g^c & d_b^c \\ D_r^c & D_g^c & D_b^c \end{pmatrix},\ (1,3,\bar{3}) = \begin{pmatrix} E^{c0} & E^- & e \\ E^{c+} & E^0 & \nu \\ e^c & \nu^{c+} & \nu^{c-} \end{pmatrix}. \quad (5)$$

The Higgs multiplets responsible for the symmetry breaking down to the Standard Model fall into two categories: One of them is accommodated in the same representation as the lepton fields,

$$\mathcal{H}_a = (1,3,\bar{3})_{(\ 0,+1,-1)},\ a = 1,2 \quad (6)$$

Two more scalar fields are required to eliminate additional Z' bosons and provide with masses the extra states:

$$\mathcal{H}_{\mathcal{L}} = (1,3,1)_{(0,-2,0)} \quad (7)$$

$$\mathcal{H}_{\mathcal{R}} = (1,1,3)_{(0,0,-2)} \quad (8)$$

This second class of representations arise from strings having both their endpoints on the left and right brane-stacks respectively (see figure 1). The decomposition of the $SU(3)^3$ representations is assumed with respect to [1]

$$SU(3)_C \times SU(3)_L \times SU(3)_R \supseteqq SU(3)_C \times [SU(2)_L \times U(1)_{L'}] \times [U(1)_{R'} \times U(1)_\Omega] \quad (9)$$

while, employing the usual hypercharge embedding $Y = -\frac{1}{6}X_{L'} + \frac{1}{3}X_{R'}$ where $X_{L'}$ and $X_{R'}$ represent the $U(1)_{L'}$ and $U(1)_{R'}$ generators respectively, the transformations of the fermion fields under $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\Omega$ are as follows (here we have suppressed the $U(1)_{C,L,R}$ indices):

$$\begin{aligned} \mathcal{Q} &= q_{(0)} + D_{(0)} \\ \mathcal{Q}^c &= d^c_{(+1)} + u^c_{(0)} + D^c_{(+1)} \\ \mathcal{L} &= \ell^+_{(+1)} + \ell^-_{(-1)} + \ell^c{}_{(0)} + \nu^{c+}_{(+1)} + \nu^-_{(-1)} + e^c_{(0)} \\ \mathcal{H} &= h^{d+}_{(+1)} + h^{d-}_{(-1)} + h^u{}_{(0)} + e^c_{H\,(0)} + \nu^{c+}_{H\ (+1)} + \nu^{c-}_{H\ (-1)}, \end{aligned} \quad (10)$$

where the indeces $(0), (\pm 1)$ refer to the 'charges' with respect to $U(1)_\Omega$.

One of the characteristics of string derived models is the appearance of anomalous $U(1)$ symmetries. Unlike the heterotic string case where only one abelian factor is anomalous, in type I string theory, many anomalous abelian factors can be present and their cancellation is achieved through a generalized Green–Schwarz mechanism [18] providing masses to the corresponding anomalous gauge bosons. In the model under consideration, it is easy to see that the only one anomaly-free $U(1)$ combination, is

$$U(1)_{\mathcal{Z}'} = U(1)_C + U(1)_L + U(1)_R \quad (11)$$

All states represented from strings having their ends attached on two different brane stacks, i.e. $\mathcal{Q}, \mathcal{Q}^c, \mathcal{L}$ and $\mathcal{H}$, have zero "charge" under $\mathcal{Z}'$. States represented by strings having both their ends attached to the same brane stack, as is the case of $\mathcal{H}_{\mathcal{L}}$ and $\mathcal{H}_{\mathcal{R}}$, are "charged" under $U(1)_{\mathcal{Z}'}$. Under the standard hypercharge definition, $\mathcal{H}_{\mathcal{L}}$, $\mathcal{H}_{\mathcal{R}}$ are fractionally charged with $Q_{\mathcal{H}_{\mathcal{L}}} = (\pm 1/3, \pm 2/3)$ and $Q_{\mathcal{H}_{\mathcal{R}}} = (\pm 1/3, \pm 2/3)$. The standard hypercharge is embedded in $SU(3)_L \times SU(3)_R$, however, it could also include the anomaly-free $U(1)_{\mathcal{Z}}$, so that $Y' = Y + x\mathcal{Z}$. This is possible since, as explained above, the fermion and standard Higgs multiplets carry zero $U(1)_{\mathcal{Z}}$ charge, therefore, their hypercharge is not affected. On the contrary, the fractionally charged states $\mathcal{H}_{\mathcal{L},\mathcal{R}}$ will receive a $U(1)_{\mathcal{Z}}$-contribution in their hypercharge. Choosing an appropriate value for coefficient x, the representations $\mathcal{H_L} = (1,3,1)$ and $\mathcal{H_R} = (1,1,3)$ obtain integral charges like those of the standard model Higgs and lepton fields.

The standard hypercharge is embedded in $SU(3)_L \times SU(3)_R$, however, it could also include the anomaly-free $U(1)_{\mathcal{Z}'}$, so that $Y' = Y + x\mathcal{Z}'$. This is possible since the fermion and standard Higgs multiplets carry zero $U(1)_{\mathcal{Z}'}$ charge, therefore, their hypercharge is not affected. On the contrary, the fractionally charged states $\mathcal{H_{L,R}}$ will receive a $U(1)_{\mathcal{Z}'}$-contribution in their hypercharge. Choosing $x = \frac{1}{6}$, the representations $\mathcal{H_L} = (1,3,1)$ and $\mathcal{H_R} = (1,1,3)$ obtain integral charges like those of the standard model Higgs and lepton fields. In particular, the embedding

$$Y' \;=\; Y + \frac{1}{6}\mathcal{Z}' \;\equiv\; -\frac{1}{6}X_L + \frac{1}{3}X_R + \frac{1}{6}\mathcal{Z}' \tag{12}$$

leaves all the representations containing the SM spectrum unchanged, while for the $\mathcal{H_{L,R}}$ scalar fields it yields

$$\mathcal{H_L} \;=\; (1,3,1) = \hat{h}_L^+\left(1,2;-\frac{1}{2},0\right) + \hat{\nu}_{\mathcal{H_L}}\,(1,1;1,0) \tag{13}$$

$$\mathcal{H_R} \;=\; (1,1,3) = \hat{e}^c_H(1,1;1,0) + \hat{\nu}^{c+}_{\mathcal{H_R}}(1,1;0,1) + \hat{\nu}^{c-}_{\mathcal{H_R}}(1,1;0,-1) \tag{14}$$

where the transformation properties and the quantum numbers of $\mathcal{H_{L,R}}$ are written here with respect to the symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\Omega$. Thus, under (12) the multiplet $\mathcal{H_L}$ contains a standard Higgs doublet $\hat{h}_L$ and a neutral singlet $\hat{\nu}_{\mathcal{H_L}}$. The $\mathcal{H_R}$ representation is decomposed into a charged singlet $\hat{e}_{\mathcal{H_R}}$ and the two neutral components $\hat{\nu}^+_{\mathcal{H_R}}$, $\hat{\nu}^-_{\mathcal{H_R}}$ which will play a crucial role to the formation of heavy mass terms for the additional lepton doublets and the breaking of the extra $U(1)_{\mathcal{Z}'}$. Indeed, since $\mathcal{H}_{1,2}$ Higgs fields do not carry any charge under $U(1)_{\mathcal{Z}'}$, the latter remains unbroken. Thus, to break this remnant abelian factor, we need to assume non-zero vevs for the $\mathcal{H_L}$ and/or $\mathcal{H_R}$ field.

2. The string scale

We first start our discussion assuming unification of all couplings at M_S. The reduction of the $SU(3)^3 \times U(1)^3$ to the SM is in general associated with three different scales corresponding to the the $SU(3)_R$, $SU(3)_L$ and $U(1)_{\mathcal{Z}'}$ symmetry breaking. We will assume here for simplicity that the $SU(3)_{L,R}$ and $U(1)_{\mathcal{Z}'}$ symmetries break simultaneously at a common scale M_R, hence the model is characterized only by two large scales, the string/brane scale M_S, and the scale M_R. Using the one-loop renormalization group equations, we eliminate the string coupling and obtain the following formulae for the scales M_R, M_S:

$$M_R \;=\; M_Z \times \exp\left[2\pi\frac{6\,x/a_Y + 3\,y/a_2 + z/a_3}{6x\,b_Y + 3y\,b_2 + z\,b_3}\right] \tag{15}$$

$$M_S \;=\; M_R \times \exp\left[2\pi\frac{6(b_3-b_2)/a_Y + (6b_Y - 13b_3)/a_2 + (13b_2 - 6b_Y)/a_3}{6x\,b_Y + 3y\,b_2 + z\,b_3}\right]. \tag{16}$$

Here $x = b_L - b_C$, $y = 4b_C - b_L - 3b_R$ and $z = b_C - 10b_L + 9b_R$, with $b_C = -11 + 2\,n_g$, $b_{L,R} = -11 + 2\,n_g + \frac{1}{12}(3\,n_{\hat{H}} + 1)$, where $n_{\hat{H}}$ the number of the Higgs fields $\mathcal{H_{L,R}}$ which in our case is taken to be $n_{\hat{H}} = 2$, while $\alpha_{3,2,Y}$ are the SM couplings at M_Z. In the present model, the spectrum implies $b_L = b_R$. We then find that $y = 4x$ and $z = -9x$, thus as can be checked from (15), at the one-loop approximation the M_R scale does not depend on $b_{L,R,C}$ beta functions and can be expressed only in terms of the low energy parameters as follows

$$M_R \;=\; M_Z \times \exp\left[\frac{6/a_Y - 12/a_2 - 1/a_3}{6b_Y - 12b_2 - b_3}\right] \approx 1.7\times 10^9 GeV \tag{17}$$

Thus, M_R in this case (i.e. $b_L = b_R$) is independent of the physics at the String scale. On the contrary, M_S, as expected, strongly depends on the $SU(3)^3$ beta functions. If we adopt the heterotic string scale $M_S \sim 4\times 10^{17}$ GeV as its highest value, this implies that $b_{L,R} \geq -\frac{3}{2}$. Such values for the $b_{L,R}$ beta

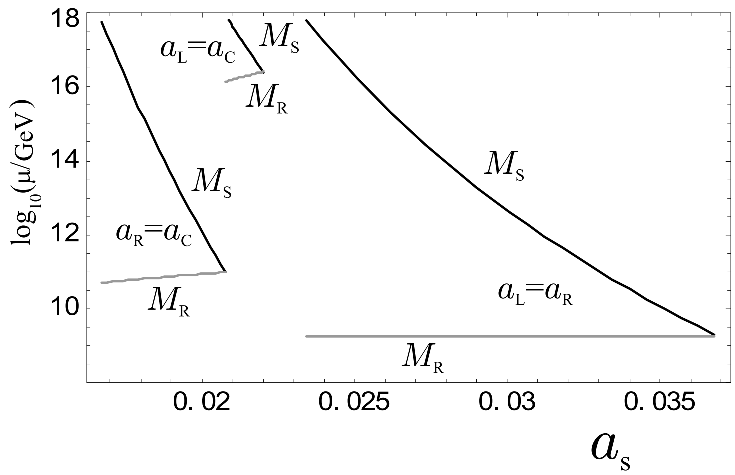

Figure 2: The string scale M_S, and $SU(3)_R$ breaking scale M_R as functions of the common coupling a for (i) $\alpha_L = \alpha_R = a_S$, (ii) $\alpha_L = \alpha_C = a_S$ and (iii) $\alpha_C = \alpha_R = a_S$. In all cases, we let M_S is truncated at 10^{18}GeV. In case (i) the M_R scale is constant $M_R \approx 1.7 \times 10^9 GeV$. In the remaining two cases, we find that M_R lowers as M_S attains higher values.

functions are obtained for a large number of Higgs fields and other matter multiplets which are usually present in a String spectrum.

In a D-brane realization of the proposed model, the three $U(3)$ gauge factors originate from 3-brane stacks that span different directions of the higher dimensional space. As a consequence, the corresponding gauge couplings $\alpha_{C,L,R}$ are not necessarily equal at the string scale M_S. However, in certain constructions, at least two D-brane stacks can be superposed and the associated couplings are equal[5]. In this context, we examine three different cases (i) $\alpha_C = \alpha_L \equiv a_S$ (ii) and $\alpha_L = \alpha_R \equiv a_S$, (iii) $\alpha_C = \alpha_R \equiv a_S$ at M_S which correspond to superposing the left with the right, the color with the left and the color with the right $U(3)$ brane stacks.

Solving the RGEs for the three cases mentioned above we obtain M_R and M_S as a function of the common coupling a_S. The results are presented in Figure 2. The curves extend from the point $M_S = M_R$ to the Planck scale. The case in the right part of the graph corresponds to $\alpha_L = \alpha_R = a_S$. We observe that in this case, the M_R scale remains constant $M_R \sim 1.7 \times 10^9$ GeV, i.e., it is independent of the common gauge coupling a_S. The second case (in the middle of the graph) corresponds to the case $\alpha_L = \alpha_C = \alpha_S$. The identification of M_S, M_R scales occurs at the unification point $M_S = M_R \approx 2.3 \times 10^{16}$GeV. Finally, for $\alpha_R = \alpha_C$, we obtain $M_R = M_S \approx 2.3 \times 10^{11}$GeV.

2.1 The Symmetry breaking and fermion masses

To break the symmetry and provide with masses the various matter multiplets we assume two Higgs in $\mathcal{H} = (1, 3, \bar{3})$ and a pair $\mathcal{H_L} = (1, 3, 1)$, $\mathcal{H_R} = (1, 1, 3)$ with the following vevs:

$$\begin{aligned}
\mathcal{H}_1 &\rightarrow \langle h_1^u \rangle = u_1,\ \langle h_1^{d-} \rangle = u_2,\ \langle \nu_{H,\,1}^{c+} \rangle = U, \\
\mathcal{H}_2 &\rightarrow \langle h_2^u \rangle = v_1,\ \langle h^{d-}{}_2 \rangle = v_2,\ \langle h^{d+}{}_2 \rangle = v_3, \langle \nu^{c-}_{H\ 2} \rangle = V_1,\ \langle \nu^{c+}_{H\ 2} \rangle = V_2 \\
\mathcal{H_L} &\rightarrow \langle \hat{\nu}_{\mathcal{H_L}} \rangle \\
\mathcal{H_R} &\rightarrow \langle \hat{\nu}_{\mathcal{H_R}} \rangle
\end{aligned}$$

The vevs $U, V_{1,2}$ and $\langle \hat{\nu}_{\mathcal{H_{L,R}}} \rangle$ are taken of the order M_R, while $u_{1,2}$ and $v_{1,2}$ are of the order of the electroweak scale.

Due to the existence of the additional $U(1)_{C,L,R}$ symmetries, only the following Yukawa coupling is present at the tree-level Yukawa potential

$$\lambda^{ij}_{Q,1}\, \mathcal{Q}_i\, \mathcal{Q}^c_j\, \mathcal{H}_a, \quad a = 1, 2 \tag{18}$$

providing up and down quark masses as well masses for the extra triplets. In particular, for the up quarks

$$m^{ij}_{uu^c} \;=\; \lambda^{ij}_{Q,1} u_1 + \lambda^{ij}_{Q,2} v_1 \tag{19}$$

For the down-type quarks d_i, d^c_j, D_i, D^c_j, we obtain a 6×6 down type quark matrix in flavor space, of the form

$$m_d \;=\; \begin{pmatrix} m_{dd^c} & M_{gd^c} \\ m_{dg^c} & M_{gg^c} \end{pmatrix} \tag{20}$$

where $m_{dd^c} = \lambda^{ij}_{Q,1}\, u_2 + \lambda^{ij}_{Q,2}\, v_2$ and $m_{dg^c} = \lambda^{ij}_{Q,2}\, v_3$ are 3×3 matrices with entries of the electroweak scale, while $M_{gd^c} = \lambda^{ij}_{Q,2}\, V_1$, $M_{gg^c} = \lambda^{ij}_{Q,1}\, U + \lambda^{ij}_{Q,2}\, V_2$ are of the order M_R. The diagonalization of the non-symmetric mass matrix (20) will lead to a light 3×3 mass matrix for the down quarks and a heavy analogue of the order of the $SU(3)_R$ breaking scale.

The extra $U(1)_{C,L,R}$ factors do not allow for a tree-level coupling for the lepton fields. The lowest order allowed leptonic Yukawa terms arise at fourth order. These are

$$\frac{f^{ab}_{ij}}{M_S}\,\mathcal{H}^\dagger_a\,\mathcal{H}^\dagger_b\,\mathcal{L}_i\,\mathcal{L}_j + \frac{\zeta_{ij}}{M_S}\,\mathcal{H}_{\mathcal{L}}\,\mathcal{H}^\dagger_{\mathcal{R}}\,\mathcal{L}_i\,\mathcal{L}_j \;\;\rightarrow\;\; \left(\alpha_{ij}\,\ell^+_i + \beta_{ij}\,\ell^-_i\right)\, e^c_j + \langle\hat{\nu}_{\mathcal{H}_{\mathcal{L}}}\rangle \left(\hat{\alpha}_{ij}\ell^+_i + \hat{\beta}_{ij}\ell^-_i\right)\,\ell^c_j \tag{21}$$

where f^{ab}_{ij}, ζ_{ij} are order one Yukawa couplings and

$$\begin{aligned} \alpha_{ij} &= \rho(f^{11}_{ij} u_1 + f^{21}_{ij} v_1) + \sigma(f^{22}_{ij} v_1 + f^{12}_{ij} u_1) \\ \beta_{ij} &= \xi\left(f^{22}_{ij} v_1 + f^{21}_{ij} u_1\right) \end{aligned} \tag{22}$$

while $\hat{\alpha}_{ij} = \zeta_{ij}\frac{\langle\hat{\nu}^{c+*}_{\mathcal{H}_{\mathcal{R}}}\rangle}{M}, \hat{\beta}_{ij} = \zeta_{ij}\frac{\langle\hat{\nu}^{c-*}_{\mathcal{H}_{\mathcal{R}}}\rangle}{M}$ and $\rho = \frac{U}{M}, \sigma = \frac{V_2}{M}, \xi = \frac{V_1}{M}$. These terms provide with masses the charged leptons suppressed by a factor M_R/M_S compared to quark masses. Thus, a natural quark-lepton hierarchy arises in this model. All the remaining states (lepton like doublets and neutral singlets) obtain masses of the order M_R^2/M_S[1]. They further imply light Majorana masses for the three neutrino species through a see-saw mechanism. In particular, the neutrino mass matrix in the basis $\ell^+, \ell^-, \nu^{c+}, \nu^{c-}, \ell^c$ is

$$M_\nu \;\sim\; \frac{1}{M_S}\begin{pmatrix} m_W^2 & m_W^2 & m_W\, M_R & M_R^2 & M_R^2 \\ m_W^2 & m_W\, M_R & m_W\, M_R & m_W\, M_R & M_R^2 \\ m_W\, M_R & m_W\, M_R & M_R^2 & M_R^2 & 0 \\ m_W\, M_R & m_W\, M_R & M_R^2 & M_R^2 & 0 \\ M_R^2 & M_R^2 & 0 & 0 & 0 \end{pmatrix}$$

where we have assumed for simplicity common vevs $u_i = v_i = M_W, U = V_j = M_R$, where $i, j = 1, 2$. This is a see-saw type mass matrix. Three light neutrino species receive see-saw masses of the order m_W^2/M_S while the remaining states receive heavy masses of the order M_R^2/M_S. To obtain a light neutrino spectrum at the range of eV, the scale M_S should be of the order $M_S \sim 10^{13-15}$GeV. Interestingly, this is in accordance with the findings of the RGE analysis in section 3. In particular, M_S is found within the bounds of the cases $\alpha_L = \alpha_R$ and $\alpha_C = \alpha_R$ shown in figure 2. It is further compatible with the effective gravity scale in theories with large extra dimensions obtained in the context of Type I string models [6].

3. Conclusions

In this talk, we analyzed a $U(3)_C \times U(3)_L \times U(3)_R$ model which can be derived in the context of D-branes. Since $U(3) \rightarrow SU(3) \times U(1)$, this symmetry is equivalent to the standard $SU(3)^3$ trinification gauge group supplemented by three abelian factors $U(1)_{C,L,R}$. The main characteristic features of the model are:

• The three $U(1)$ factors define an unique anomaly-free combination $U(1)_{\mathcal{Z}'} = U(1)_C + U(1)_L + U(1)_R$ as well as two other anomalous combinations whose anomalies can be cancelled by a generalized Green-Schwarz mechanism.

• The Standard Model fermions are represented by strings attached to two different brane-stacks and belong to $(3, \bar{3}, 1) + (\bar{3}, 1, 3) + (1, 3, \bar{3})$ representations as is the case of the trinification model.

• The scalar sector contains Higgs fields in $(1, 3, \bar{3})$, as well as Higgs in (1,3,1) and (1,1,3) representations which can arise from strings whose both ends are attached on the same brane stack. The Higgs fields break the $SU(3)_L \times SU(3)_R$ part of the gauge symmetry down to $U(1)_{em}$; they further provide a natural quark-lepton hierarchy since quark masses are obtained from tree-level couplings, while, due to the extra $U(1)$ symmetries, charged leptons are allowed to receive masses from fourth order Yukawa terms.

• The $SU(3)_R$ breaking scale is found to be $M_R > 10^9$ GeV, while a string scale $M_S \sim 10^{13-15}$GeV is predicted which suppresses the light Majorana masses through a see-saw mechanism down to sub-eV range as required by neutrino physics.

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