String Model Building and Their Phenomenological Consequences

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I. Introduction

- String theory could be the theory which correctly describes quantum gravity.
- String phenomenology goal: the SM or MSSM as low energy effective theory.
- The future model building is the string model building.

II. M-THEORY ON S^1/Z_2

M-theory on S^1/Z_2 is a 11-dimensional supergravity theory with two boundaries where the two E_8 Yang-Mills fields live on respectively.

Compactification:

- Keep 4-dimensional N=1 supersymmetry.
- Break the observable E_8 down to a smaller gauge group.

(A) Prediction: Newton's Constant

(i) Weakly coupled heterotic string theory:

$$L_{eff} = -\int d^{10}x\sqrt{g}e^{-2\phi}\left(\frac{4}{(\alpha')^4}R + \frac{1}{(\alpha')^3}\,\mathrm{tr}F^2 + \ldots\right) .$$

$$L_{eff} = -\int d^{4}x\sqrt{g}e^{-2\phi}V\left(\frac{4}{(\alpha')^4}R + \frac{1}{(\alpha')^3}\,\mathrm{tr}F^2 + \ldots\right) .$$

$$G_N = \frac{e^{2\phi}(\alpha')^4}{64\pi V}\,,\ \alpha_{GUT} = \frac{e^{2\phi}(\alpha')^3}{16\pi V}\,.$$

$$G_N = \frac{\alpha_{GUT}\alpha'}{4}\,.$$

The string scale can not be the GUT scale.

(ii) M-theory on S^1/Z_2

$$L_B = -\frac{1}{\kappa^2}\int_{M^{11}} d^{11}x\sqrt{g}\frac{1}{2}R - \sum_{i=1,2}\frac{1}{2\pi(4\pi\kappa^2)^{\frac{2}{3}}}\int_{M_i^{10}} d^{10}x\sqrt{g}\frac{1}{4}F^a_{AB}F^{aAB} .$$

$$8\pi\left[G_N^{(4)}\right]_W = \frac{\kappa^2}{2\pi\rho_p V_p}, \quad [\alpha_{\rm GUT}]_W = \frac{1}{2V_p f}(4\pi\kappa^2)^{2/3}$$

Convention: $8\pi G_N^{(d)} = M_d^{2-d} = \kappa_d^2$, $M_4 = M_{\rm Pl} = 2.4\times 10^{18}$ GeV, $M_{11} = \kappa^{-2/9}$.

The 11-dimensional Planck scale and the compactification scale of the Calabi-Yau manifold can be around the GUT scale, *i. e.*, it correctly predicts the Newton's constant.

(B) Compactification

A supergravity theory is described by the gauge kinetic function, Kähler potential, and superpotential.

At leading order, the gauge kinetic function, Kähler potential, and superpotential are related to the Witten *et al*'s previous results from the weakly-coupled heterotic string compactification via field transformation.

- Gauge kinetic function

$$Ref_{\alpha\beta} \;=\; f\, ReS\, \delta_{\alpha\beta}\;.$$

- Kähler potential

$$K \;=\; -\ln\left[S+\bar{S}\right]-3\ln\left[T+\bar{T}-2C^*_xC^x\right]\;.$$

- Superpotential

$$W = 8\sqrt{\frac{2}{3}}g_c\, d_{xyz}C^xC^yC^z\;.$$

T^6/Z_{12} orbifold compactification:

- Three families of the SM fermions, and the observable gauge symmetry is $U(1) \times U(1) \times E_6$.
- At the next to leading order, we can calculate the Kähler potential, superpotential, and gauge kinetic functions. Unlike the weakly coupled heterotic string theory, the next to the leading order corrections can be very large ($\mathcal{O}(1)$).
- We can calculate the supersymmetry breaking soft terms and show that the universality of the scalar masses will be violated, but the violation might be small.

- Gauge kinetic functions

$$
\begin{aligned}
f^{o}_{\alpha\beta} &= (S+\alpha_1 T_1 + \alpha_2 T_2 + \alpha_3 T_3)\, \delta_{\alpha\beta} \ , \\
f^{h}_{\alpha\beta} &= (S-\alpha_1 T_1 - \alpha_2 T_2 - \alpha_3 T_3)\, \delta_{\alpha\beta} \ ,
\end{aligned}
$$

- Kähler potential

$$
\begin{aligned}
K &= -\ln[S+\bar{S}] - \sum_{i=1}^{3} \ln[T_i + \bar{T}_i - 2C^{*}_{ia}C^{a}_{i}] \\
&\quad + \frac{2}{3}\frac{1}{S+\bar{S}}\Big(\sum_{j=1}^{3}\alpha_j(T_j+\bar{T}_j)\Big)\sum_{i=1}^{3}\Big(\frac{C^{*}_{ia}C^{a}_{i}}{T_i+\bar{T}_i}\Big) \ ,
\end{aligned}
$$

- Superpotential

$$
W = c g_c\, d_{xyz} C^x C^y C^z \ .
$$

(C) Model Building

GUTs can be realized naturally through the elegant E_8 breaking chain: $E_8 \supset E_6 \supset SO(10) \supset SU(5)$.

(1) SU(5) Model

- A Calabi–Yau threefold X with a $SU(5)$ holomorphic vector bundle $\mathcal{V}$.
- $\Pi_1(X) = Z_2$.
- $N_{\text{gen}} = \frac{1}{2} c_3(\mathcal{V}) = 3$.
- Anomaly cancellation: $c_2(\mathcal{V}) + c_2(\mathcal{V}') + [W] = c_2(TX)$.
- Natural doublet-triplet splitting.

Symmetry breaking:

$$E_8 \xrightarrow{\text{Bundle } \mathcal{V}} SU(5) \xrightarrow{\mathrm{Z}_2 \text{ Wilson line}} SU(3)_C \times SU(2)_L \times U(1)_Y \, .$$

$E_8 \supset SU(5) \times SU(5)$

$$\mathbf{248} = (\mathbf{24},\mathbf{1}) \oplus (\mathbf{1},\mathbf{24}) \oplus (\mathbf{5},\mathbf{10}) \oplus (\bar{\mathbf{5}},\overline{\mathbf{10}}) \oplus (\mathbf{10},\bar{\mathbf{5}}) \oplus (\overline{\mathbf{10}},\mathbf{5}) \, .$$

On the covering space $\widetilde{X}$ **(**$X = \widetilde{X}/Z_2$**)** with a $SU(5)$ holomorphic vector bundle $\widetilde{\mathcal{V}}$, we can calculate the numbers of fields:

$$n_{24} = H^1(\tilde{X}, \mathrm{ad}\widetilde{V}) = 1 \, , \; n_1 = H^0(\tilde{X}, \mathcal{O}_{\widetilde{X}}) \, , \; n_{10} = H^1(\tilde{X}, \wedge^2 \widetilde{V}) \, ,$$
$$n_{\overline{10}} = H^1(\tilde{X}, \wedge^2 \widetilde{V}^*) \, , \; n_5 = H^1(\tilde{X}, \widetilde{V}) \, , \; n_5 = H^1(\tilde{X}, \widetilde{V}^*) \, .$$

Math Question: How to construct the suitable Calabi–Yau threefold X?

(2) SO(10) Model

- A Calabi–Yau threefold X with a $SU(4)$ holomorphic vector bundle $\mathcal{V}$.
- $\Pi_1(X) = Z_3 \times Z_3$.
- $N_{\text{gen}} = \frac{1}{2} c_3(\mathcal{V}) = 3$.
- Anomaly cancellation: $c_2(\mathcal{V}) + c_2(\mathcal{V}') + [W] = c_2(TX)$.
- Natural doublet-triplet splitting.

Symmetry breaking:

$$E_8 \xrightarrow{\text{Bundle } \mathcal{V}} Spin(10) \xrightarrow{\text{Wilson line}} SU(3)_C \times SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L} \, .$$

$E_8 \supset SU(4) \times SO(10)$

$$\mathbf{248} = (\mathbf{15}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{45}) \oplus (\mathbf{4}, \mathbf{16}) \oplus (\bar{\mathbf{4}}, \overline{\mathbf{16}}) \oplus (\mathbf{6}, \mathbf{10}) \, .$$

Math Question: How to construct the suitable Calabi–Yau threefold X?

UPENN Math-Physics group have developed the techniques to construct the Calabi-Yau threefolds with the $SU(4)$ and $SU(5)$ vector bundles and with non-trivial fundamental groups.

Realistic model building and systematically search are needed!

III. Type II Orientifolds

Due to the advent of D-branes, we can construct the open string models that are non-perturbative from the dual heterotic string description.

There are two kinds of theories with chiral fermions from the D-brane constructions:

- D-branes located at orbifold singularities where the chiral fermions appear on the worldvolume of D-branes.
- Intersecting D-branes on Type II orientifolds where the open string spectrum contains chiral fermions localized at the D-brane intersections.

A lot of non-supersymmetric three-family Standard-like models and grand unified models, were constructed on the Type IIA orientifolds with D6-brane intersections during last several years.

Generic Problems:

- There are uncancelled Neveu-Schwarz-Neveu-Schwarz (NSNS) tadpoles.
- There may exist the gauge hierarchy problem.

The supersymmetric models with the quasi-realistic features of the supersymmetric Standard-like models have been constructed in Type IIA theory on $T^6/Z_2 \times Z_2$ orientifold with D6-brane intersections. And the supersymmetric models based on Z_4, $Z_4 \times Z_2$, Z_N, and $Z_3 \times Z_3$ orientifolds with intersecting D6-branes were also constructed.

Briefly Review the Rules for Model Building

- $T^6 = T_1^2 \times T_2^2 \times T_3^2$; $\quad z_i, \; i = 1, \; 2, \; 3$
- $T^6/(Z_2 \times Z_2)$ orbifold is obtained by T^6 moduloing the equivalent classes

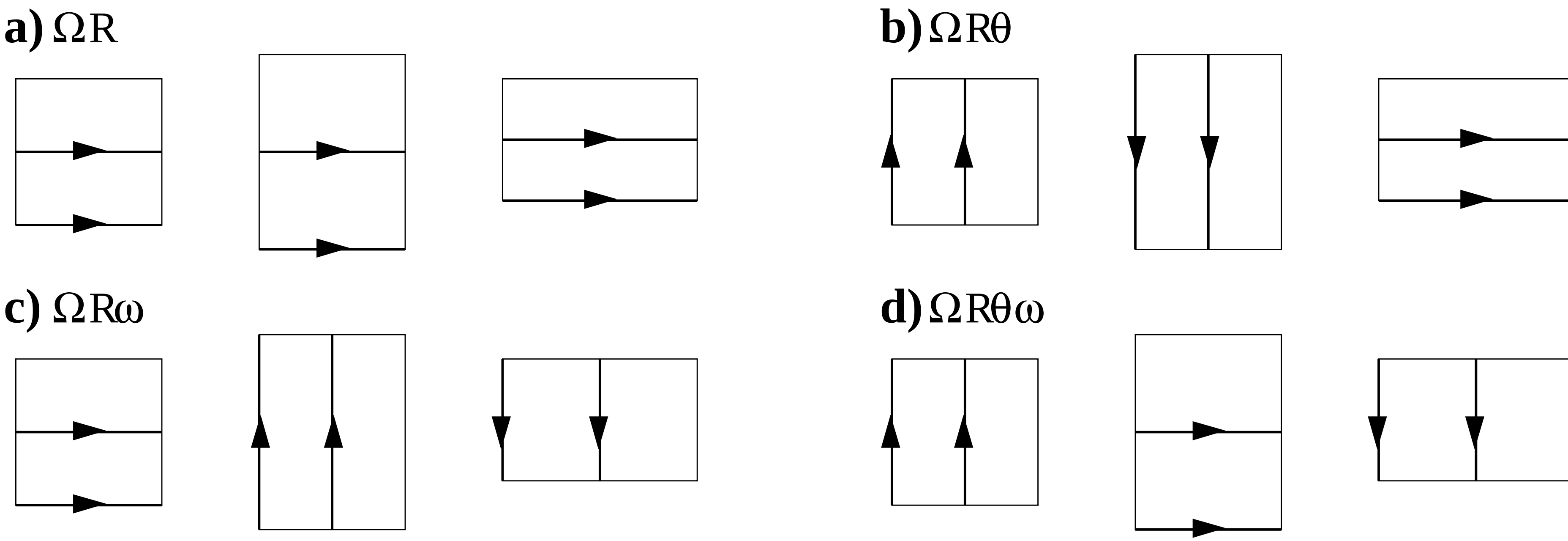
$$\theta : \; (z_1, z_2, z_3) \sim (-z_1, -z_2, z_3) \; ,$$
$$\omega : \; (z_1, z_2, z_3) \sim (z_1, -z_2, -z_3) \; .$$

- The orientifold action ΩR

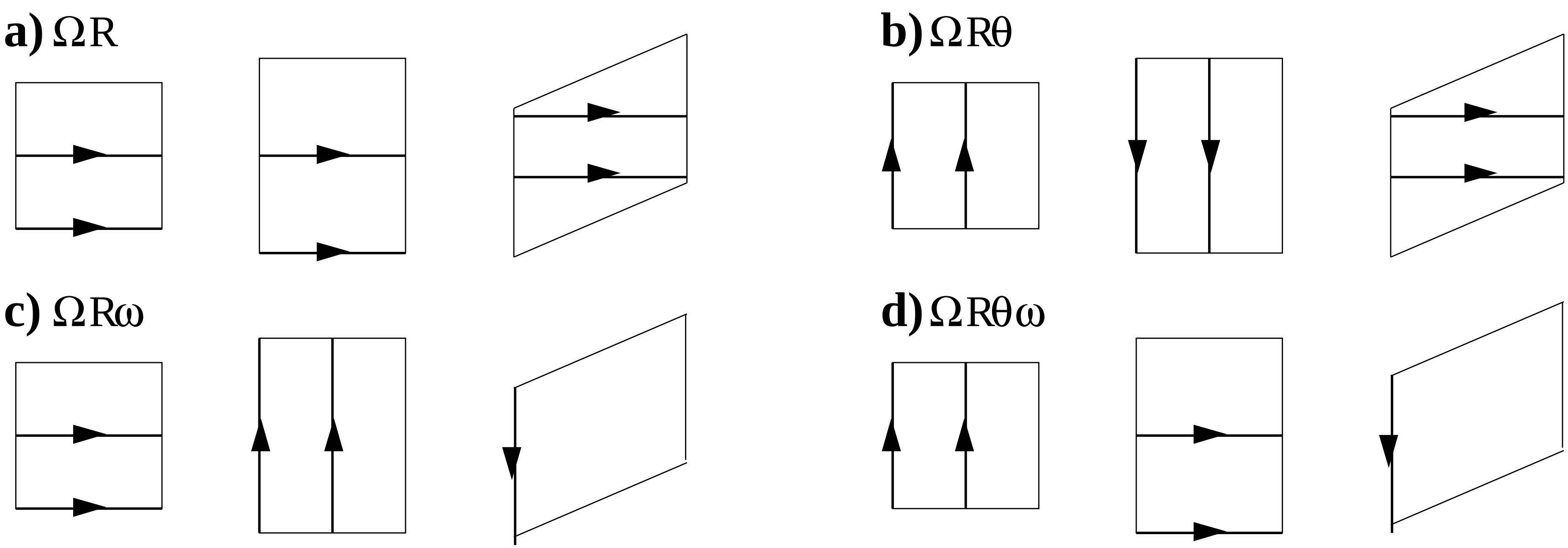
$$R : (z_1, z_2, z_3) \rightarrow (\overline{z}_1, \overline{z}_2, \overline{z}_3) \; .$$

  Four kinds of orientifold 6-planes (O6-planes) for the actions of ΩR, $\Omega R\theta$, $\Omega R\omega$, and $\Omega R\theta\omega$.

- Two kinds of complex structures for a torus – rectangular and tilted.



a) ΩR
b) ΩRθ
c) ΩRω
d) ΩRθω



a) ΩR
b) ΩRθ
c) ΩRω
d) ΩRθω

For each stack of D6-branes and its ΩR image, the orientifold group actions on the Chan-Paton indices are

$$\gamma_{\theta,a} = \mathrm{diag}\left(i\mathbf{1}_{N_a/2}, -i\mathbf{1}_{N_a/2}\,; -i\mathbf{1}_{N_a/2}, i\mathbf{1}_{N_a/2}\right) ,$$

$$\gamma_{\omega,a} = \mathrm{diag}\left[\begin{pmatrix} 0 & \mathbf{1}_{N_a/2} \\ -\mathbf{1}_{N_a/2} & 0 \end{pmatrix} ; \begin{pmatrix} 0 & \mathbf{1}_{N_a/2} \\ -\mathbf{1}_{N_a/2} & 0 \end{pmatrix}\right] ,$$

$$\gamma_{\Omega R,a} = \begin{pmatrix} 0 & 0 & \mathbf{1}_{N_a/2} & 0 \\ 0 & 0 & 0 & \mathbf{1}_{N_a/2} \\ \mathbf{1}_{N_a/2} & 0 & 0 & 0 \\ 0 & \mathbf{1}_{N_a/2} & 0 & 0 \end{pmatrix} .$$

$\gamma_{\theta,a}$, $\gamma_{\omega,a}$, and $\gamma_{\Omega R,a}$ are traceless.

Symmetry breaking chains:

$$\begin{aligned} U(2N) &\rightarrow \text{(due to } \gamma_{\Omega R}\text{)}\ U(N) \\ &\rightarrow \text{(due to } \gamma_{\theta}\text{)}\ U(N/2) \times U(N/2) \\ &\rightarrow \text{(due to } \gamma_{\omega}\text{)}\ U(N/2)\ , \end{aligned}$$

$$\begin{aligned} U(2N) &\rightarrow \text{(due to } \gamma_{\theta}\text{)}\ U(N) \times U(N) \\ &\rightarrow \text{(due to } \gamma_{\omega}\text{)}\ U(N) \\ &\rightarrow \text{(due to } \gamma_{\Omega R}\text{)}\ USp(N)\ . \end{aligned}$$

We denote the homology class wrapped by the a D6-brane stack as $[\Pi_a]$, denote the homology class wrapped by its ΩR image as $[\Pi_{a'}]$.

The intersection numbers are

$$I_{ab} = [\Pi_a] \cdot [\Pi_b] \ , \ I_{ab'} = [\Pi_a] \cdot [\Pi_{b'}] \ ,$$

$$I_{aa'} = [\Pi_a] \cdot [\Pi_{a'}] \ , \ I_{aO6} = [\Pi_a] \cdot [\Pi_{O6}] \ .$$

Table 1: General spectrum on intersecting D6-branes at generic angles which is valid for both rectangular and tilted tori.

Sector	**Representation**
aa	$U(N_a/2)$ vector multiplet 3 adjoint chiral multiplets
$ab+ba$	I_{ab} $(\square_a, \overline{\square}_b)$ fermions
$ab'+b'a$	$I_{ab'}$ $(\square_a, \square_b)$ fermions
$aa'+a'a$	$\frac{1}{2}(I_{aa'} - \frac{1}{2}I_{a,O6})$ $\square\!\square$ fermions $\frac{1}{2}(I_{aa'} + \frac{1}{2}I_{a,O6})$ $\begin{smallmatrix}\square\\\square\end{smallmatrix}$ fermions

RR Tadpole Cancellation

Orientifolds by ΩR action do not generate the twisted crosscaps. And the twisted disk tadpoles vanish because of the traceless Chan-Paton matrices. Cancellation of untwisted RR tadpoles simply requires that the total RR charges of D6-branes and O6-planes be zero

$$\sum_{i=1}^{4} N^{(i)}[\Pi_{O6}^{(i)}] + \sum_a N_a[\Pi_a] + \sum_a N_a\,[\Pi_{a'}] - 4[\Pi_{O6}] = 0\ .$$

The tadpole cancellation conditions directly lead to the $SU(N_a)^3$ cubic non-abelian anomaly cancellation. And the cancellation of U(1) mixed gauge and gravitational anomaly or $[SU(N_a)]^2 U(1)$ gauge anomaly can be achieved by Green-Schwarz mechanism mediated by untwisted RR fields.

4-Dimensional $N = 1$ Supersymmetric D6-Brane Configuration

The rotation angle of any D6-brane with respect to the O6-plane is an element of $SU(3)$

$$\theta_1 + \theta_2 + \theta_3 = 0 \bmod 2\pi \ .$$

All the possible $N = 1$ Supersymmetric D6-brane configurations are

(1) All the wrapping numbers are non-zero.

(2) One wrapping number is zero.

(3) Three wrapping numbers are zero.

Searching Conditions and Symmetry Breakings

- Three stacks of D6-branes, a, b, and c with number of D6-branes 8, 4, and 4. The gauge symmetries are $U(4)_C$, $U(2)_L$ and $U(2)_R$.
- The anomalies from three $U(1)$s are cancelled by the Green-Schwarz mechanism, and the gauge fields of these $U(1)$s obtain masses via the linear $B \wedge F$ couplings.
- The unbroken gauge symmetry is $SU(4)_C \times SU(2)_L \times SU(2)_R$.

We require that the intersection numbers satisfy

$$I_{ab} + I_{ab'} ~=~ 3~,$$

$$I_{ac} ~=~ -3~,~ I_{ac'} ~=~ 0~.$$

$I_{ac'} = 0$ implies that a stack of D6-branes is parallel to the orientifold (ΩR) image c' of the c stack of D6-branes along at least one torus, for example, the third torus. If the a and c' stack of D6-branes are on the top of each other on the third torus, we obtain the $I_{ac'}^{(1,2)}$ pairs of the massless vector-like chiral multiplets with quantum numbers $(\mathbf{\bar{4}}, \mathbf{1}, \mathbf{2})$ and $(\mathbf{4}, \mathbf{1}, \mathbf{2})$.

To stabilize the modulus and possibly break the SUSY by gaugino condensation, we require that there be at least two USp groups with negative β functions in the model building.

Symmetry Breaking

- $SU(4)_C$ and $SU(2)_R$ can be broken down to $SU(3)_C \times U(1)_{B-L}$ and $U(1)_{I_{3R}}$ by brane splittings. The gauge symmetry is $SU(3)_C \times SU(2)_L \times U(1)_{B-L} \times U(1)_{I_{3R}}$
- $I_{ac'}^{(1,2)}$ pairs of massless vector-like chiral multiplets with quantum numbers $(\mathbf{1}, \mathbf{1}, -\mathbf{1}, \mathbf{1/2})$ and $(\mathbf{1}, \mathbf{1}, \mathbf{1}, -\mathbf{1/2})$ from $N = 2$ subsector.
- $SU(3)_C \times SU(2)_L \times U(1)_{B-L} \times U(1)_{I_{3R}}$ can be broken down to the SM gauge symmetry.

Systematically Pati-Salam Model Searching

We only consider the models which are not equivalent under the T-duality and its variations.

Strategy: we analytically exclude most of the parameter space for the D6-brane wrapping numbers which can not give the models that we want to construct, and then scan the rest parameter space numerically. If no torus is tilted, we can not have odd families of the SM fermions. So, there are three possibilities: one tilted torus, two tilted tori, and three tilted tori.

Numerical results indicate that no model is available for the cases with two and three tilted tori. For the case with one-tilted torus, we find 11 inequivalent models

- Nine models have no gauge coupling unification for $SU(2)_L$ and $SU(2)_R$ at string scale.
- Two models have the $SU(2)_L$ and $SU(2)_R$ gauge coupling unification at string scale, and their Higgs fields arise from an $N = 2$ subsector.
- In eight of our models, the number of the pairs of Higgs doublets is less than 9. In particular, there are only two pairs of Higgs doublets in one model.
- Generic Problem: How to explain the fermion masses and mixings, especially the neutrino masses and mixings.

Table 2: D6-brane configurations and intersection numbers for the three-family left-right symmetric model I-Z-5

model I-Z-5	$U(4)\times U(2)_L\times U(2)_R\times USp(2)\times USp(2)\times USp(2)$										
stack	N	$(n^1,l^1)\times(n^2,l^2)\times(n^3,l^3)$	$n_{\square\square}$	$n_{\begin{smallmatrix}\square\\\square\end{smallmatrix}}$	b	b'	c	c'	1	2	3
a	8	$(0,-1)\times(1,1)\times(1,1)$	0	0	3	0	-3	0	1	-1	0
b	4	$(3,1)\times(1,0)\times(1,-1)$	-2	2	-	-	0	-3	0	1	0
c	4	$(3,-2)\times(0,1)\times(1,-1)$	1	-1	-	-	-	-	-2	0	3
1	2	$(1,0)\times(1,0)\times(2,0)$	$X_A=X_B=\frac{3}{2}X_C=3X_D$								
2	2	$(1,0)\times(0,-1)\times(0,2)$	$\beta^g_1=-2,\beta^g_2=-3,\beta^g_3=-3$								
3	2	$(0,-1)\times(1,0)\times(2,0)$									

Table 3: The chiral spectrum in the open string sector of model I-Z-5

I-Z-5	$SU(4) \times SU(2)_L \times SU(2)_R \times USp(2)^3$	Q_4	Q_{2L}	Q_{2R}	Q_{em}	Field
ab	$3 \times (4, \overline{2}, 1, 1, 1, 1, 1)$	1	-1	0	$-\frac{1}{3},\ \frac{2}{3},\ -1,\ 0$	Q_L, L
ac	$-3 \times (\overline{4}, 1, 2, 1, 1, 1, 1)$	-1	0	1	$\frac{1}{3},\ -\frac{2}{3},\ 1,\ 0$	Q_R, R
bc'	$-3 \times (1, 2, 2, 1, 1, 1, 1)$	0	-1	-1	$1,\ 0,\ 0,\ -1$	H
$a1$	$1 \times (4, 1, 1, 2, 1, 1, 1)$	1	0	0	$\frac{1}{6},\ -\frac{1}{2}$	
$a2$	$-1 \times (\overline{4}, 1, 1, 1, 2, 1, 1)$	-1	0	0	$-\frac{1}{6},\ \frac{1}{2}$	
$b2$	$1 \times (1, 2, 1, 1, 2, 1, 1)$	0	1	0	$\pm\frac{1}{2}$	
$c1$	$-2 \times (1, 1, \overline{2}, 2, 1, 1, 1)$	0	0	-1	$\pm\frac{1}{2}$	
$c3$	$3 \times (1, 1, 2, 1, 1, 2, 1)$	0	0	1	$\pm\frac{1}{2}$	
$b_{\Box\!\Box}$	$-2 \times (1, 3, 1, 1, 1, 1, 1)$	0	-2	0	$0, \pm 1$	
$b_{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	$2 \times (1, 1, 1, 1, 1, 1, 1)$	0	2	0	0	
$c_{\Box\!\Box}$	$1 \times (1, 1, 3, 1, 1, 1, 1)$	0	0	2	$0, \pm 1$	
$c_{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}$	$-1 \times (1, 1, 1, 1, 1, 1, 1)$	0	0	-2	0	

Briefly Comment on the Other Models

Model 1. Standard-like Model with gauge symmetry $[U(4)_C \times USp(8)_L \times USp(8)_R]_{\rm observable} \times [U(4) \times USp(8) \times USp(8)]_{\rm hidden}$.

- $U(4)_C \times USp(8)_L \times USp(8)_R$ and $U(4) \times USp(8) \times USp(8)$ are symmetric.
- The $SU(4)_C \times USp(8)_L \times USp(8)_R$ gauge symmetry can be broken down to $SU(3)_C \times U(1)_{B-L} \times U(2)_L \times U(2)_R$ via brane splitting.
- There is no exotic particle.
- The gauge couplings of $U(2)_L$ and $U(2)_R$ can be unified at string scale.
- The beta functions for two $USp(8)$ groups in the hidden sector are negative.
- Problem: Four families and 16 pairs of Higgs doublets.

Model 2. Standard-like Model with gauge symmetry $[U(4)_C \times USp(6)_L \times USp(6)_R]_{\rm observable} \times [U(5) \times USp(8) \times USp(8)]_{\rm hidden}$.

- The $SU(4)_C \times USp(6)_L \times USp(6)_R$ gauge symmetry can be broken down to $SU(3)_C \times U(1)_{B-L} \times SU(2)_L \times SU(2)_R$ via the brane splittings and the Higgs mechanism which breaks the SUSY.
- There is no exotic particle.
- Three families of the SM fermions.
- The gauge couplings of $SU(2)_L$ and $SU(2)_R$ can be unified at string scale.
- The beta functions for two $USp(8)$ groups in the hidden sector are negative.
- 9 pairs of Higgs doublets.

Model 3. Standard-like Model with gauge symmetry $[U(4)_C \times USp(2)_L \times USp(2)_R]_{\text{observable}} \times [U(1) \times USp(6) \times USp(42)]_{\text{hidden}}$.

- The gauge symmetry is $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
- Three families of the SM fermions.
- One pair of Higgs doublets.
- A lot of exotic particles.
- Only one family of the SM fermions can have masses.

D-brane models in Type II B theory with flux compactification.

- Due to the Dirac quantization, the NSNS and RR fluxes contribute large positive D3-brane charges, $N_{\text{flux}} = 64 \times n_f$.
- It is very diffcult to cancel D3-brane RR tadpoles.
- Magnetized D9-branes, which carry large negative D3-brane charges, are introduced in the hidden sector.
- The supersymetry is broken explicitly due to $n_f = 1$.
- The soft supersymmetry breaking masses are about $M_{soft} \sim \frac{M_s^2}{M_{Pl}}$. To stabilize the electroweak scale, we either have an intermediate string scale or an inhomogeneous warp factor in the internal space.

Questions:

- Can we construct the SUSY flux models with $n_f = 3$?
- The NSNS and RR fluxes stabilize the dilaton and toroidal complex structure moduli. Can we stabilize the Kähler moduli?
- All the previous flux models are T-dual to the intersecting D6-brane models where the D3-brane RR tadpoles are cancelled similarly. Can we construct the new flux models?

New Idea:

Magnetized D9-branes, which carry large negative D3-brane charges, are introduced in the observable sector.

The constructions of SM-like flux vacua are much less constrained and a large class of new models can be constructed.

Supersymmetric three-family and four-family SM-like models

- String scale can be close to the Planck scale.
- The toroidal Kähler moduli can be stabilized by supersymmetry conditions.
- No Yukawa couplings.

Non-supersymmetric three-family and four-family models

- Yukawa couplings are allowed, but, at most two families of the SM fermions can obtain the suitable masses and mixings.
- The toroidal Kähler moduli can be stabilized by supersymmetry conditions or via SUSY+KKLT [a].
- The rest SM fermion masses can not be generated radiatively because the supersymmetry breaking trilinear soft terms are universal and the supersymmetry breaking soft masses for the left/right-chiral squarks and sleptons are universal.
- Intermediate string scale or inhomogeneous warp factor in the internal space.

[a] Kachru, Kallosh, Linde and Trivedi.

IV. Comments

(A) In the free-fermionic string model building, only the SM-like model ($SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)^n$), the Pati-Salam model and the flipped SU(5) model can be realized semi-realistically because the dimensions of the Higgs fields' representations in these models are smaller than those of the adjoint representations, and then, these models can be constructed at the Kac-Moody level 1.

(B) For the model building in the orbifold compactification of the weakly coupled heterotic string theory, the doublet-triplet can be splitted natually while there generically exist some additional $U(1)$ gauge symmetry.

(C) String scale gauge coupling unification and its implications.

(i) $XE + \overline{XE}$ with masses about 668 GeV, and $XG + 2(XQ + \overline{XQ})$ with masses around 1.1×10^{13} GeV.

(ii) $XL + \overline{XL} + XU + \overline{XU}$ with masses about 668 GeV, and $XG + 2(XQ + \overline{XQ})$ with masses around 1.1×10^{13} GeV.

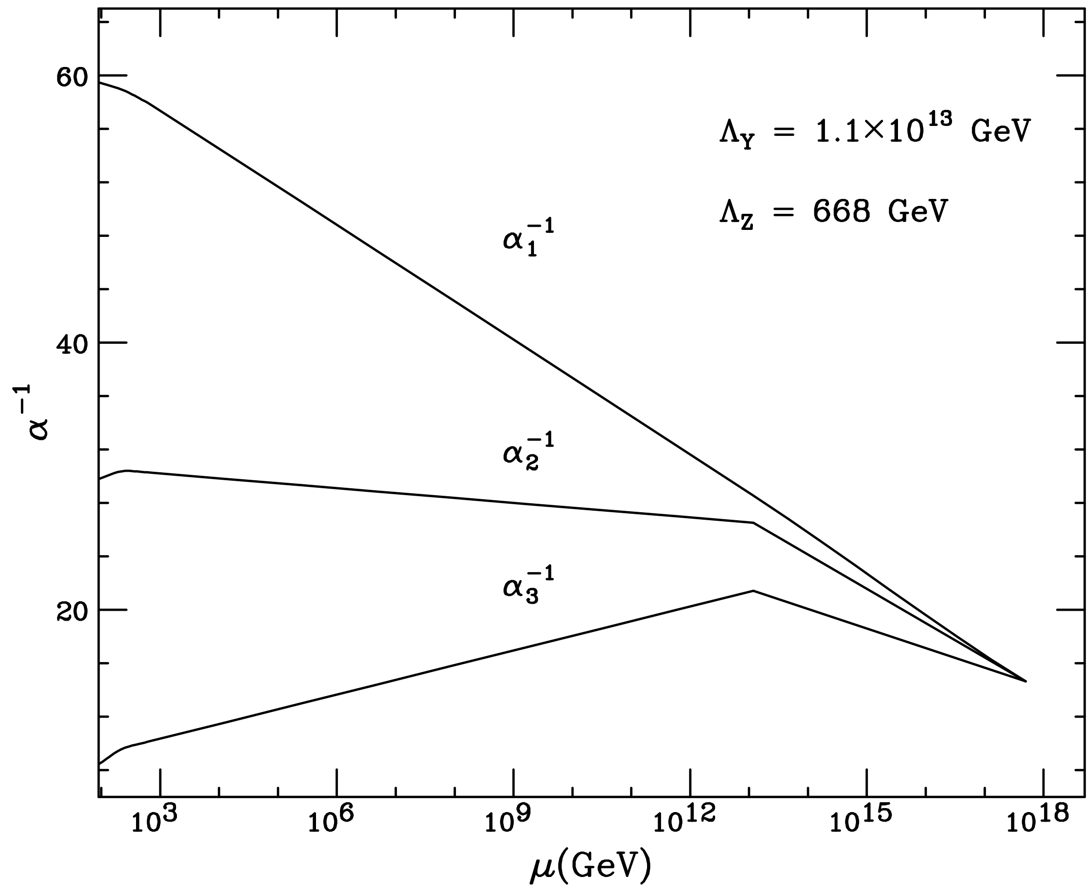


Figure 1: One-loop gauge coupling unifi cation for scenario (i).

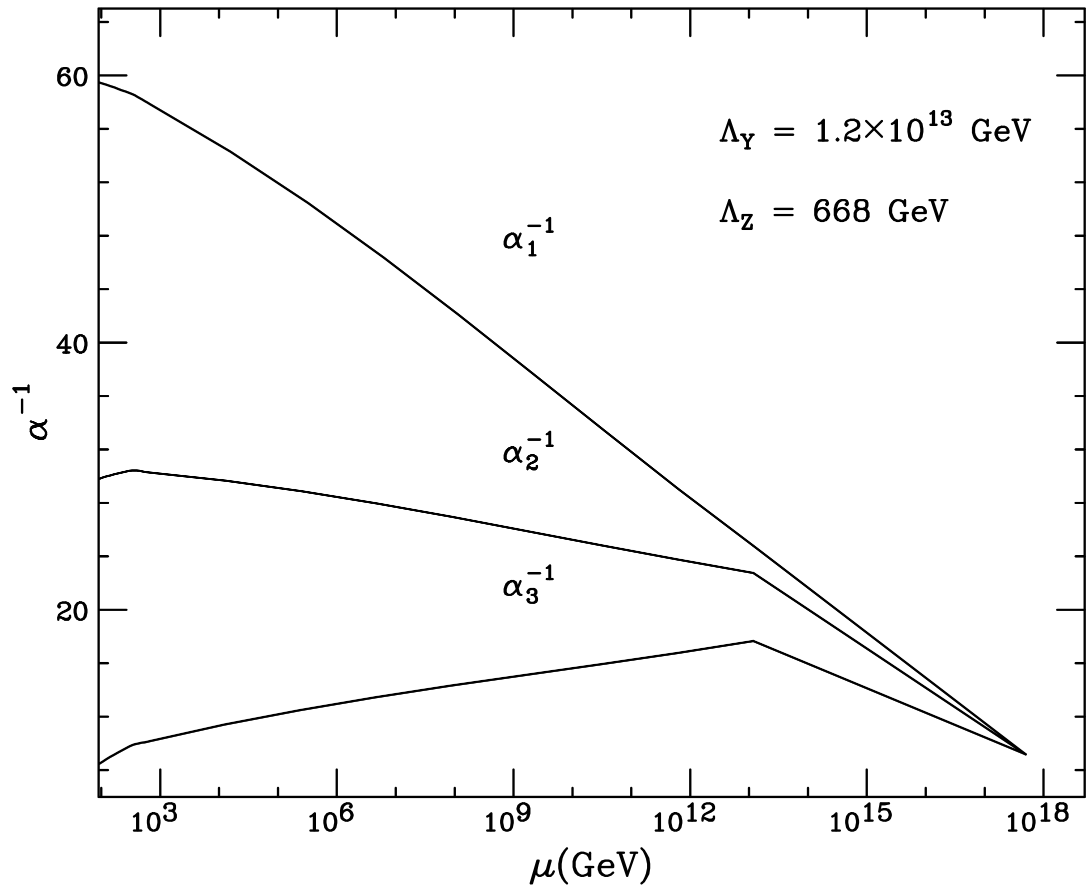


Figure 2: One-loop gauge coupling unifi cation for scenario (ii).

V. SUMMARY

M-theory on S^1/Z_2:

- The 11-dimensional Planck scale and the compactification scale of the Calabi-Yau manifold can be around the GUT scale.
- Unlike the weakly coupled heterotic string theory, the next to the leading order corrections to the Kähler potential, superpotential, and gauge kinetic functions can be very large.
- GUTs can be realized naturally through the elegant E_8 breaking chain while the construction of the suitable Calabi–Yau threefold is very complicated.

Type II Orientifolds.

(A) PS Model:

- Gauge symmetry breaking.
- The moduli can be stabilized, and the SUSY maybe broken.
- Less pairs of the Higgs doublets. In particular, there are only two pairs of Higgs bidoublets in one model.
- The $SU(2)_L$ and $SU(2)_R$ gauge coupling unification in two models.
- Yukawa couplings are allowed in some models.

(B) Other Models:

I briefly discuss the other models:

- $[U(4)_C \times USp(8)_L \times USp(8)_R]_{\text{observable}} \times [U(4) \times USp(8) \times USp(8)]_{\text{hidden}}$ model.

- $[U(4)_C \times USp(6)_L \times USp(6)_R]_{\text{observable}} \times [U(5) \times USp(8) \times USp(8)]_{\text{hidden}}$ model.

- $[U(4)_C \times USp(2)_L \times USp(2)_R]_{\text{observable}} \times [U(1) \times USp(6) \times USp(42)]_{\text{hidden}}$ model.

- Supersymmetric and non-supersymmetric flux models

(C) Generic Problem: How to explain the fermion masses and mixings, especially the neutrino masses and mixings.