Heterotic asymmetric orbifolds

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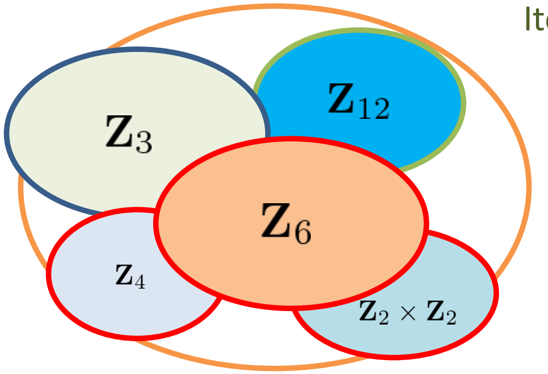
Introduction

- Asymmetric orbifold compactification of heterotic string theory — Narain, Sarmadi, Vafa '87
  - Generalization of orbifold action (Non-geometric compactification)
  - Free boson worldsheet constructions
    -- cf. Free fermion worldsheet constructions (Z2 x Z2 orbifolds)
  - Applied to GUT construction — Erler '96; Kakushadze, Tye '97; Ito et al. 2011
  - Applicable to SUSY SM building



Goal : Search for SUSY SM in heterotic asymmetric orbifold vacua

Asymmetric Orbifold Compactification

Asymmetric orbifold compactification = 4D Heterotic string theory on Narain lattice $\Gamma_{22,6}$
+ Asymmetric orbifold action

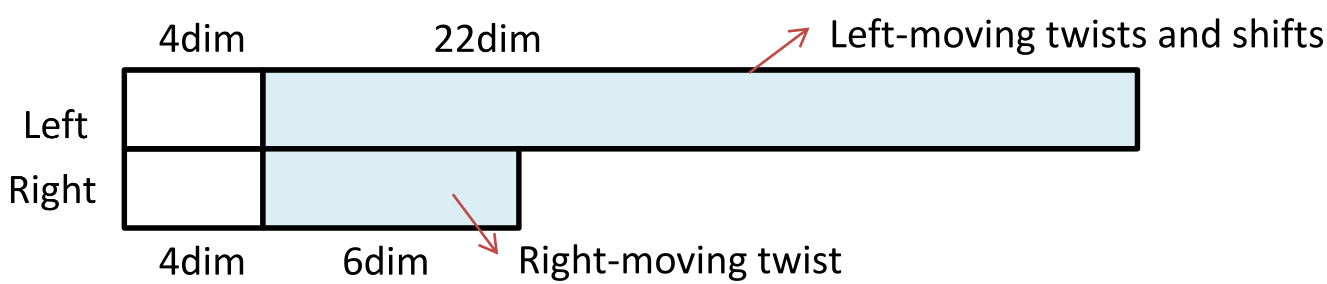
- Starting points : Narain lattices (enhancement point → rank 22)
- Generalization of orbifold action
- Orbifold action $\theta = (\theta_{\mathrm{L}}, \theta_{\mathrm{R}})$ (Twist, Shift)

Left mover : $X_{\mathrm{L}} \to \theta_{\mathrm{L}} X_{\mathrm{L}}$

Right mover : $X_{\mathrm{R}} \to \theta_{\mathrm{R}} X_{\mathrm{R}}$
$\Psi_{\mathrm{R}} \to \theta_{\mathrm{R}} \Psi_{\mathrm{R}}$

Orbifold actions for left and right movers can be chosen independently

$$\theta = (\theta_{\mathrm{L}}, \theta_{\mathrm{R}}) \quad \theta_{\mathrm{L}} \neq \theta_{\mathrm{R}}$$

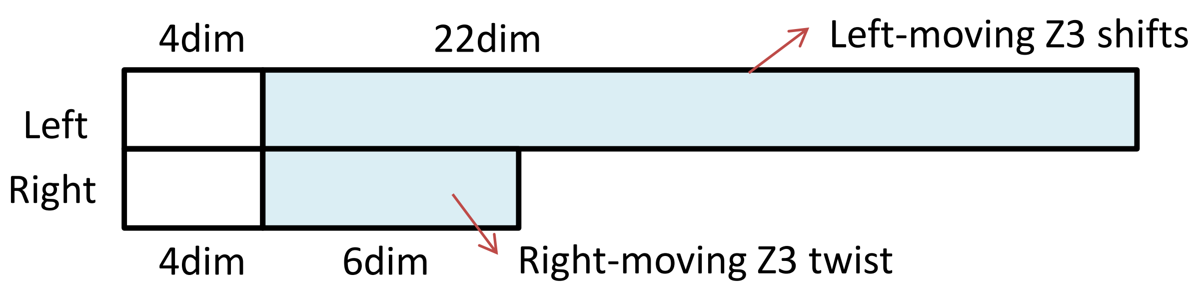


Z3 Asymmetric Orbifold Compactification

- The simplest case : Z3 orbifold action

A Z3 asymmetric orbifold model is specified by

- a (22,6)-dimensional Narain lattice $\Gamma_{22,6}$ which contains a right-moving $\overline{E}_6$ or $\overline{A}_2^3$ lattice (compatible with Z3 automorphism)
- a Z3 shift action $V = (V_{\mathrm{L}}, 0)$
- a Z3 twist action (N=4 SUSY → N=1 SUSY)
- Modular invariance: $\frac{3V_{\mathrm{L}}^2}{2} \in \mathbf{Z}$



(22,6)-dim lattices from 8, 16, 24-dim lattices

- Starting points : Narain lattices

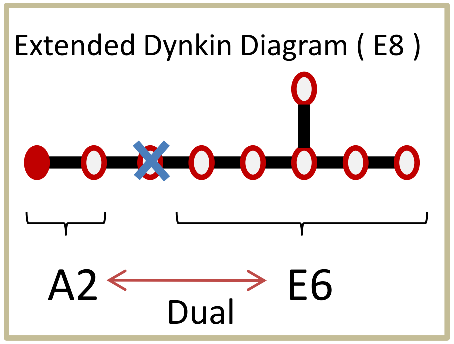
  -- described by left-right combined momentum $(p_{\mathrm{L}}, p_{\mathrm{R}})$
  (or G, B fields and Wilson lines)

- We use lattice engineering technique

Lerche, Schellekens, Warner '88

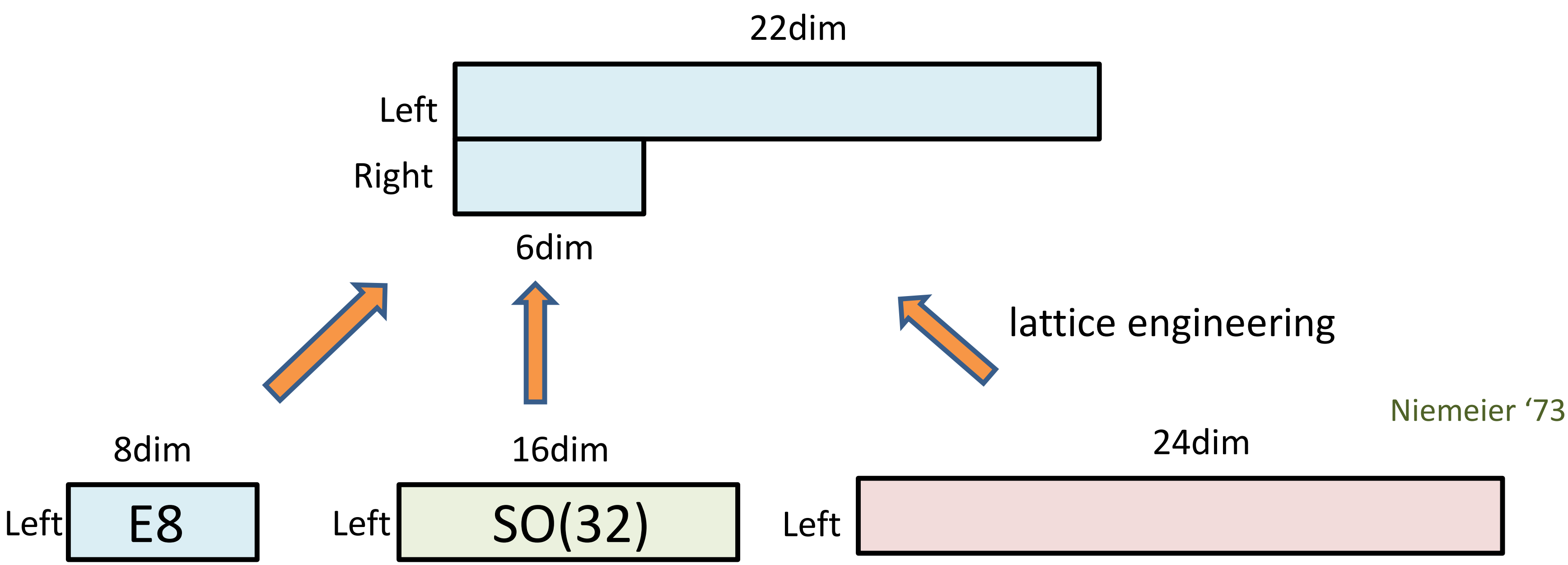
Left-mover	Replace ⟷	Right-mover
E6	⟷	A2

-- Reconstructing a lattice to a new lattice with different dimensionality
-- Modular transformation laws are the same



(22,6)-dim lattices from 8, 16, 24-dim lattices

- Starting points : Narain lattices
- We construct (22,6)-dim Narain lattices from 8, 16, 24-dim lattices by lattice engineering technique



Classified

24 types of lattices

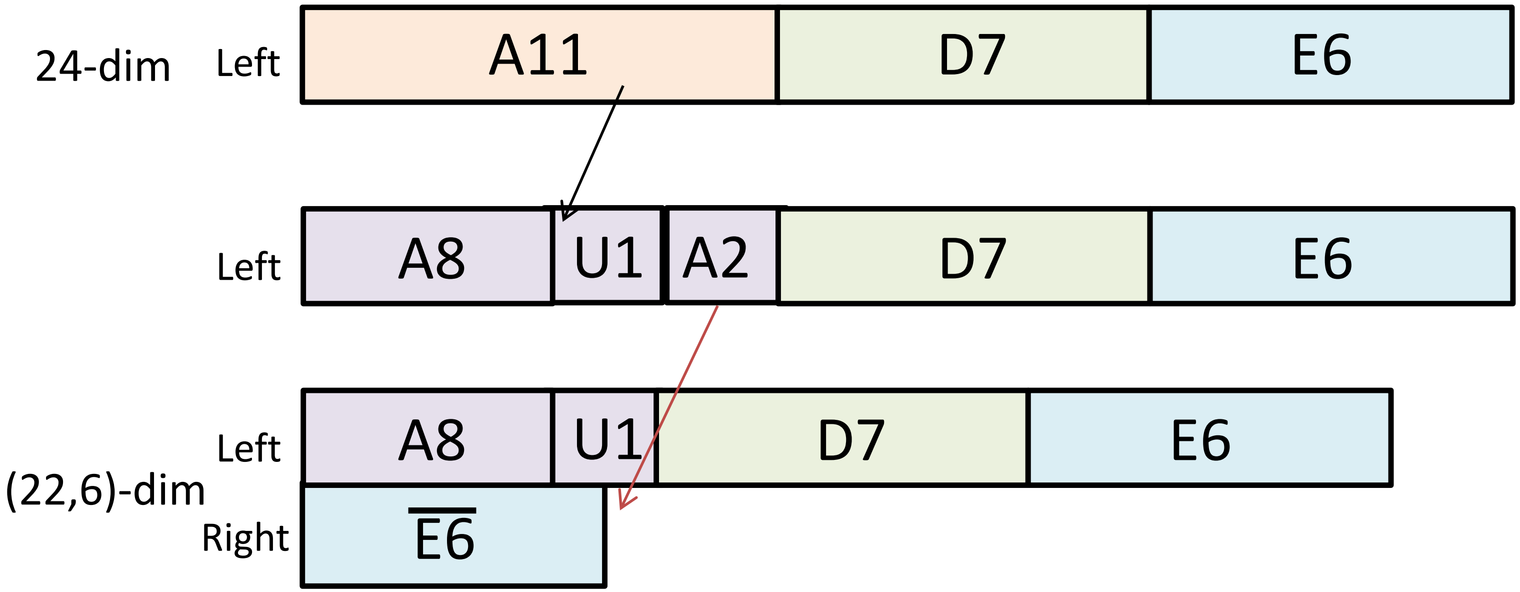
$$D_{24}, D_{16}\times E_8, E_8^3, A_{24}, D_{12}^2,$$
$$A_{17}\times E_7, D_{10}\times E_7^2, A_{15}\times D_9, D_8^3,$$
$$A_{12}^2, A_{11}\times D_7\times E_6,\ E_6^4, A_9^2\times D_6, D_6^4, A_8^3,$$
$$A_7^2\times D_5^2, A_6^4, A_5^4\times D_4, D_4^6,\ A_4^6, A_3^8, A_2^{12}, A_1^{24}.$$

(22,6)-dim lattices from 8, 16, 24-dim lattices

Example :

$A_{11} \times D_7 \times E_6$ 24-dim lattice

Gauge symmetry : SU(12) x SO(14) x E6



$D_7 \times E_6 \times A_8 \times U(1) \times \overline{E}_6$ (22,6)-dim lattice

Gauge symmetry : SO(14) x E6 x SU(9) x U(1)

Lattice and gauge symmetry

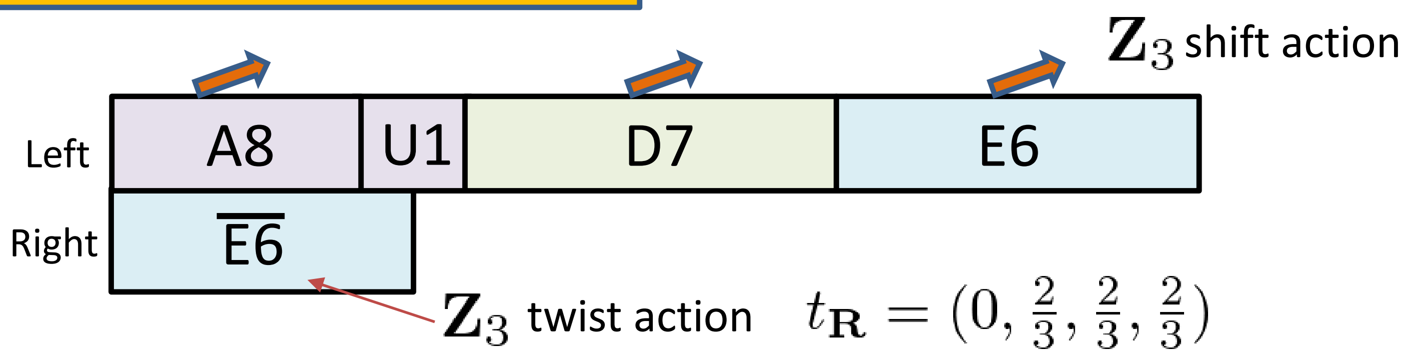
- 90 Narain lattices for Z3 model building
- Group breaking patterns by Z3 shift action

Beye, Kobayashi, Kuwakino
arXiv:1304.5621 [hep-th]

+ other lattices

Group Shift	Group breaking patterns $(0,0,0,0,0)$	Group breaking patterns $(s,1,1,1/36,0)$
D_7	D_7 $A_6\times U(1)$ $D_6\times U(1)$ $A_1\times D_5\times U(1)$ $A_2\times D_4\times U(1)$ $A_3^2\times U(1)$ $A_5\times U(1)^2$ $A_1^2\times A_4\times U(1)$	D_7 $A_6\times U(1)$ $D_6\times U(1)$ $A_1\times D_5\times U(1)$ $A_2\times D_4\times U(1)$ $A_3^2\times U(1)$ $A_5\times U(1)^2$ $A_1^2\times A_4\times U(1)$
E_6	E_6 $A_5\times U(1)$ $A_2\times A_2\times A_2$ $D_4\times U(1)^2$ $D_5\times U(1)$ $A_4\times A_1\times U(1)$	$D_5\times U(1)$ $A_4\times A_1\times U(1)$
A_8	A_8 $A_6\times U(1)^2$ $A_5\times A_2\times U(1)$ $A_4\times A_1^2\times U(1)^2$ $A_3^2\times U(1)^2$ $A_2^3\times U(1)^2$	$A_7\times U(1)$ $A_6\times A_1\times U(1)$ $A_5\times A_1\times U(1)^2$ $A_4\times A_3\times U(1)$ $A_4\times A_2\times U(1)^2$ $A_3\times A_2\times A_1\times U(1)^2$
$U(1)$	$U(1)$	$U(1)$

Group	SM	Flipped $SO(10)$	Flipped $SU(5)$	Pati-Salam	Left-right symmetric
#1		√	√		
#2	√	√	√		√
#3	√	√	√		√
#4					
#5	√		√		
#6	√	√	√	√	√
#7	√	√	√		√
#8	√		√	√	√
#9	√	√	√	√	√
#10	√	√	√	√	√
#11	√	√	√	√	√
#12	√	√	√	√	√
#13	√	√	√	√	√
#14	√		√	√	√
#15	√	√	√	√	√
#16	√	√	√	√	√
#17	√	√	√	√	√
#18	√	√	√		√



Z3 three generation left-right symmetric model

- Z3 asymmetric orbifold compactification

Beye, Kobayashi, Kuwakino
arXiv: 1311.4687 [hep-th]

- Narain lattice: $A_1^2 \times A_4^4 \times U(1)^2 \times \overline{A}_2^2$ lattice $\oplus$ $A_2 \times \overline{A}_2$ lattice
- LET:

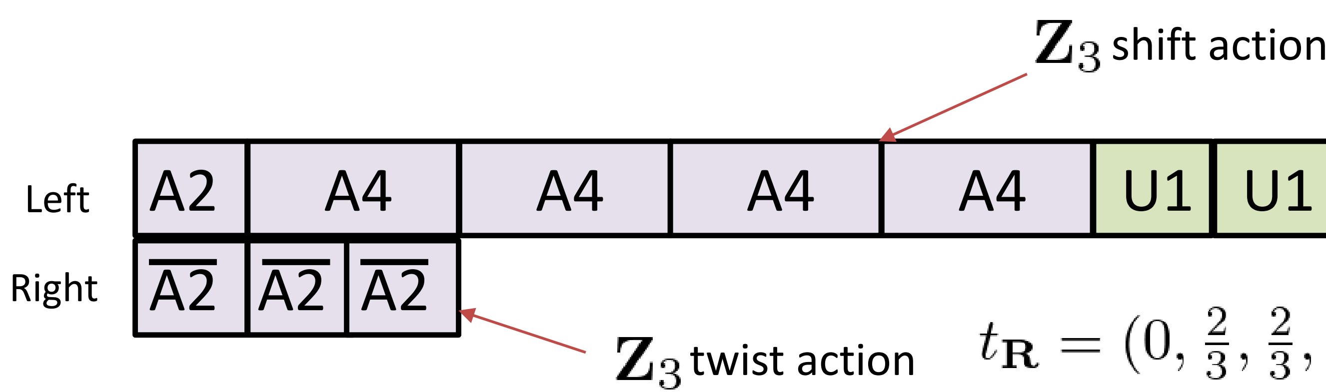
$$A_4^6 \xrightarrow[\text{decompose}]{} (A_2 \times A_1 \times U(1))^2 \times A_4^4 \xrightarrow[\text{replace}]{} A_1^2 \times A_4^4 \times U(1)^2 \times \overline{A}_2^2$$

$$E_8 \xrightarrow[\text{decompose}]{} E_6 \times A_2 \xrightarrow[\text{replace}]{} A_2 \times \overline{A}_2$$

- Z3 shift vector:

$$V = (0, \omega_1^{A_1}, 2\omega_1^{A_4} + \omega_3^{A_4} - 3\alpha_1^{A_4} - 4\alpha_2^{A_4} - 2\alpha_3^{A_4} - \alpha_4^{A_4}, -\omega_1^{A_4} + \alpha_1^{A_4} + \alpha_2^{A_4} + \alpha_3^{A_4} + \alpha_4^{A_4}, -\omega_3^{A_4} - 2\omega_4^{A_4} + 2\alpha_4^{A_4}, \omega_2^{A_4} + 2\omega_4^{A_4} - 2\alpha_3^{A_4} - 2\alpha_4^{A_4}, \frac{\sqrt{30}}{5}, \frac{3\sqrt{30}}{10}, 0, 0, 0, 0)/3$$

- Group breaking: $SU(5)^4 \times SU(3) \times SU(2)^2 \times U(1)^2 \rightarrow SU(4)^2 \times SU(3)^3 \times SU(2)^3 \times U(1)^7$



$$t_{\mathbf{R}} = (0, \tfrac{2}{3}, \tfrac{2}{3}, \tfrac{2}{3})$$

Z3 three generation left-right symmetric model

Massless spectrum ($SU(3)_C \times SU(2)_L \times SU(2)_R \times SU(2)_F \times SU(3)^2 \times SU(4)^2$)

U/T		Irrep.	Q_{B-L}	Deg.
U	Q_R	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{6}$	3
U		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	3
T	$\overline{Q}_R$	$(\mathbf{3},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	Q_R	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{6}$	1
T	Q_{L2}	$(\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	Q_{L1}	$(\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	H	$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T	H	$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{6},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{4}})$	$-\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{2};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{1})$	$-\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{6})$	$-\frac{1}{2}$	1

U/T		Irrep.	Q_{B-L}	Deg.
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4})$	0	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{4}{3}$	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{3}$	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{2}{3}$	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{4}})$	$-\frac{1}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{4}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{2}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1})$	$\frac{1}{3}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	1	1
T		$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	-1	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	-1	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	1	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1})$	-1	1

+ other fields

- Three-generation $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model
- The number of fields = 80

Z3 three generation left-right symmetric model

Massless spectrum ($SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(2)_{\rm R} \times SU(2)_{\rm F} \times SU(3)^2 \times SU(4)^2$)

U/T		Irrep.	Q_{B-L}	Deg.
U	$Q_{\rm R}$	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{6}$	3
U		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	3
T	$\overline{Q}_{\rm R}$	$(\mathbf{3},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	$Q_{\rm R}$	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{6}$	1
T	$Q_{\rm L2}$	$(\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	$Q_{\rm L1}$	$(\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	H	$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T	H	$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{6},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{4}})$	$-\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{2};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{1})$	$-\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1})$	$\frac{1}{2}$	1
T		$(\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{6})$	$-\frac{1}{2}$	1

+ other fields

Three-generation fields of LR symmetric model
+
Vector-like fields

Higgs fields for $SU(2)_{\rm R} \times U(1)_{\rm B-L} \rightarrow U(1)_Y$

- Three-generation $SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(2)_{\rm R} \times U(1)_{\rm B-L}$ model
- The number of fields = 80
- Additional fields are vector-like

Z3 three generation left-right symmetric model

Massless spectrum ($SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times SU(2)_{\mathrm{F}} \times SU(3)^2 \times SU(4)^2$)

U/T		Irrep.	Q_{B-L}	Deg.
U	Q_{R}	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{6}$	3
U		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	3
T	$\overline{Q}_{\mathrm{R}}$	$(\mathbf{3},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	Q_{R}	$(\overline{\mathbf{3}},\mathbf{1},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{6}$	1
T	Q_{L2}	$(\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	Q_{L1}	$(\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	1
T	H	$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T	H	$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	1

The first two-generation is unified into SU(2)F doublet.
(No left-moving twist action
→ Zero point energy does not increase)

U/T		Irrep.	Q_{B-L}	Deg.
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	0	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4})$	0	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{4}{3}$	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{3}$	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{2}{3}$	1
T		$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{4}})$	$-\frac{1}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{4}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{2}{3}$	1
T		$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1})$	$\frac{1}{3}$	1
T		$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	1	1
T		$(\mathbf{1},\mathbf{2},\mathbf{2},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	-1	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	-1	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	1	1
T		$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1})$	-1	1

+ other fields

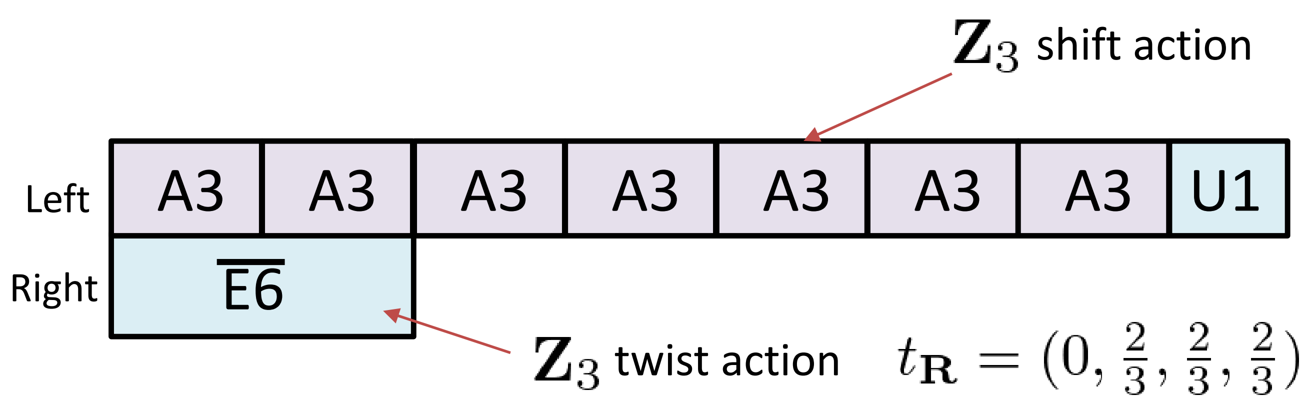
SU(2)F flavon

Vector-like fields

- Three-generation $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)_{\mathrm{B-L}}$ model
- The number of fields = 80
- Additional fields are vector-like
- Gauge flavor symmetry $SU(2)_F$

Z3 three generation SU(3)xSU(2)xU(1) model

- Z3 asymmetric orbifold compactification
  - Narain lattice: $A_3^7 \times \overline{E}_6 \times U(1)$ lattice
  - LET: $A_3^8 \xrightarrow[\text{decompose}]{} A_3^7 \times A_2 \times U(1) \xrightarrow[\text{replace}]{} A_3^7 \times \overline{E}_6 \times U(1)$
  - Z3 shift vector: $V = (\alpha_1^{A_3} + 2\alpha_2^{A_3}, \alpha_1^{A_3} + 2\alpha_2^{A_3}, -\alpha_1^{A_3} - 2\alpha_2^{A_3}, \alpha_3^{A_3}, 0, \alpha_3^{A_3}, \alpha_3^{A_3}, 0, 0)/3$
  - Group breaking: $SU(4)^7 \times U(1) \to SU(4) \times SU(3)^3 \times SU(2)^3 \times U(1)^{10}$



$t_{\mathbf{R}} = (0, \frac{2}{3}, \frac{2}{3}, \frac{2}{3})$

Z3 three generation SU(3)xSU(2)xU(1) model

Massless spectrum ($SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(2)^2 \times SU(3)^2 \times SU(4)$)

U/T		Irrep.	Q_Y	Deg.
U	l^u	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	3
U	$\bar{l}^u$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	3
U	$\bar{d}$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{3}$	3
T	c_1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{3}$	3
T	c_2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{2}{3}$	3
T	$\bar{c}_1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{3}$	3
T	$\bar{c}_2$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{2}{3}$	3
T		$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	3
T		$(\mathbf{1},\mathbf{2};\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	3
T		$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\overline{\mathbf{3}},\mathbf{1},\mathbf{1})$	$-\frac{1}{2}$	3
T	q	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{6}$	3
T	$\bar{u}$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$-\frac{2}{3}$	3
T	h_u	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	$\frac{1}{2}$	3

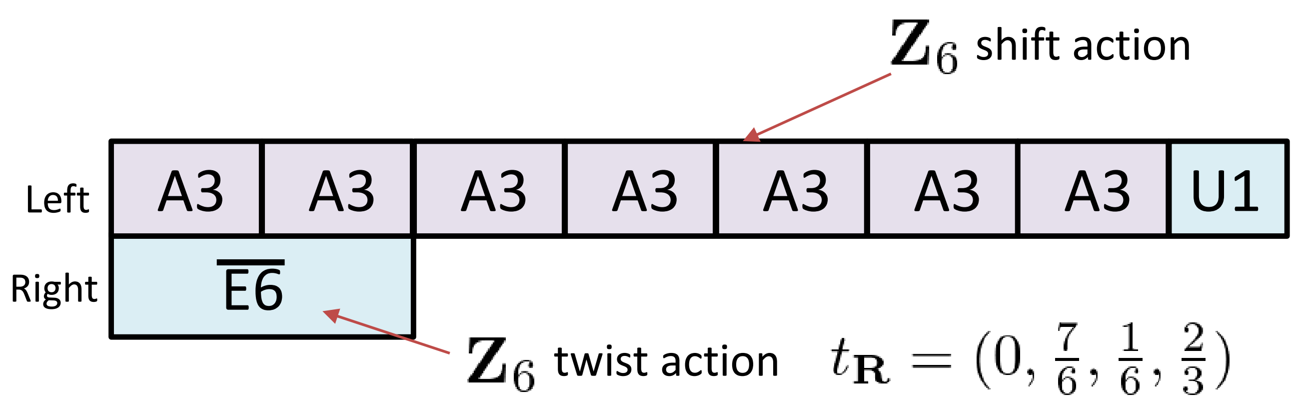
+ other fields

Three-generation fields of
SUSY SM model
+
Vector-like fields

- Three-generation $SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$ model
- The number of fields = 147
- "3"-generation comes from a degeneracy "3“
- Additional fields are vector-like
- Top Yukawa from twisted sector

Z6 three generation SU(3)xSU(2)xU(1) model

- Z6 asymmetric orbifold compactification
  - Narain lattice: $A_3^7 \times \overline{E}_6 \times U(1)$ lattice
  - LET: $A_3^8 \xrightarrow[\text{decompose}]{} A_3^7 \times A_2 \times U(1) \xrightarrow[\text{replace}]{} A_3^7 \times \overline{E}_6 \times U(1)$
  - Z6 shift vector: $$V = (0, 0, -4\omega_3^{A_3}, 4\omega_3^{A_3}, 2\omega_2^{A_3}, \omega_1^{A_3} + 5\omega_3^{A_3} - \alpha_1^{A_3} - \alpha_2^{A_3}, \omega_1^{A_3} + 2\omega_2^{A_3} + \omega_3^{A_3}, 0, 0)/6$$
  - Group breaking: $SU(4)^7 \times U(1) \rightarrow SU(4)^2 \times SU(3)^2 \times SU(2)^4 \times U(1)^8$



Z6 three generation SU(3)xSU(2)xU(1) model

Massless spectrum ($SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(4)^2 \times SU(3) \times SU(2)^3$)

Irrep.	#
$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	1
$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})$	1
$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1})$	2
$(\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{2},\mathbf{1})$	1
$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	5
$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})$	3
$(\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1})$	1
$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	4
$(\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	1
$(\mathbf{3},\mathbf{2},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	3

Irrep.	#
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	7
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})$	3
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1})$	6
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{2})$	3
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1})$	6
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{2})$	2
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{3}},\mathbf{1},\mathbf{1},\mathbf{1})$	3
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{3}},\mathbf{2},\mathbf{1},\mathbf{1})$	3
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1})$	2
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	4
$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})$	2
$(\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1})$	2
$(\mathbf{1},\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1})$	2
$(\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	2
$(\mathbf{1},\mathbf{1},\mathbf{4},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1})$	1
$(\mathbf{1},\mathbf{1},\mathbf{6},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	1
$(\mathbf{1},\mathbf{1},\overline{\mathbf{4}},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})$	4

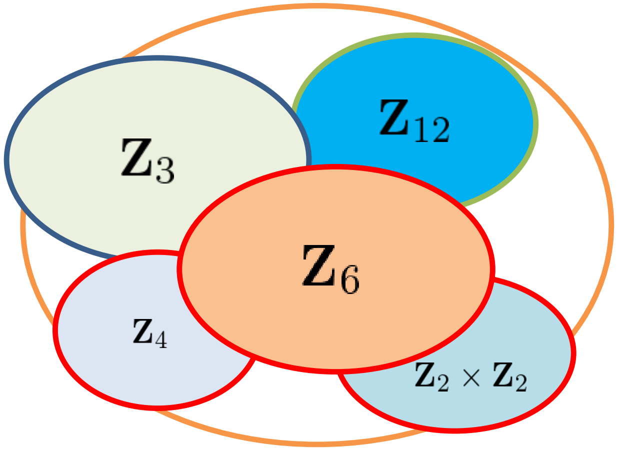
- Three-generation $SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)$ model
- The number of fields = 75

Summary

- Z3 asymmetric orbifold compactification of heterotic string
- Our starting point : Narain lattice
- 90 lattices with right-moving non-Abelian factor can be constructed from 24 dimensional lattices
- We calculate group breaking patterns of Z3 models
- Three generation SUSY SM / left-right symmetric model

- Z6 three-generation model

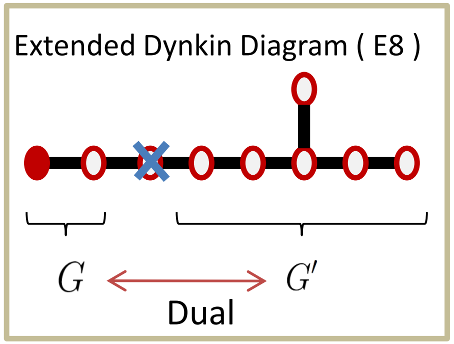
- Outlook: Search for a realistic model
  -- Search for Z3 models from other lattices
  -- Other orbifolds Z6, Z12, Z3xZ3…
  -- Yukawa hierarchy
  -- (Gauge or discrete) Flavor symmetry,
  -- Moduli stabilization, etc.

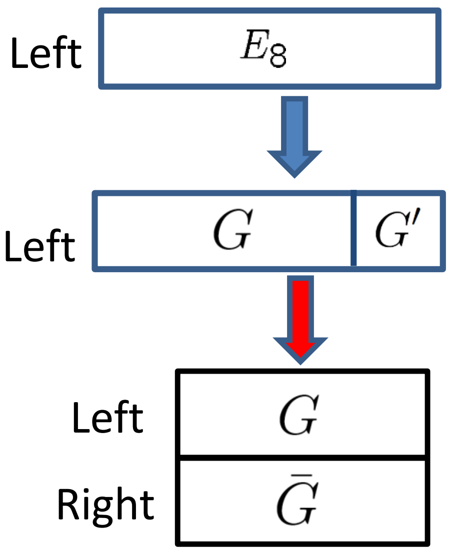


Lattice Engineering Technique

- Lattice engineering technique — Lerche, Schellekens, Warner '88
  - We can construct new Narain lattice from known one.
  - We can replace one of the left-moving group factor with a suitable right-moving group factor.

Left-mover	Replace $\longleftrightarrow$	Right-mover
G	$\longleftrightarrow$	$\mathrm{Dual}(G) = G'$





(Decomposition $E_8 \to G \times G'$)

(Replace left G' → Right $\bar{G}(= G'_{\mathrm{dual}})$)

The resulting lattice is also modular invariant (modular transformation properties of G' part and $\bar{G}$ part are similar)

G_{L}	c_{L}	$\overline{G}_{\mathrm{R}}$	c_{R}
E_6	(1)	$\overline{A}_2$	(1)
D_4	(v) (s)	$\overline{D}_4$	(v) (s)
A_2	(1)	$\overline{E}_6$	(1)
A_2^2	$(1,0)$ $(1,2)$	$\overline{A}_2^2$	$(1,2)$ $(2,0)$
$U(1)^2$	$(1/3,1/2)$ $(1/4,1/4)$	$\overline{D}_4 \times \overline{A}_2$	$(s,1)$ $(c,0)$