Three-generation models in heterotic asymmetric orbifolds

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Based on arXiv:1304.5621 [hep-th] and 1311.4687 [hep-th]

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Plan of Talk

1. Introduction
2. Heterotic asymmetric orbifold models
3. Narain lattices, group breaking patterns
4. Three-generation models
5. Conclusion

Introduction

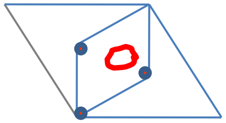
- String → Standard Model ----- String compactification : 10-dim → 4-dim

  Orbifold compactification, Calabi-Yau, Intersecting D-brane, Magnetized D-brane, F-theory, M-theory, …

- (Symmetric) orbifold compactification

  Dixon, Harvey, Vafa, Witten '85,'86
  Ibanez, Kim, Nilles, Quevedo '87

  - SM or several GUT gauge symmetries
  - N=1 supersymmetry
  - Chiral matter spectrum



- MSSM searches in symmetric orbifold vacua :
  Embedding higher dimensional GUT into string
  Three generations,
  Quarks, Leptons and Higgs,
  No exotics,
  Top Yukawa,
  Proton longetivity,
  R-parity,
  Doublet-triplet splitting,
  ...

Kobayashi, Raby, Zhang '04
Buchmuller, Hamaguchi, Lebedev, Ratz '06
Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter '07
Kim, Kyae '07
……

Introduction

- Asymmetric orbifold compactification of heterotic string theory Narain, Sarmadi, Vafa '87

Generalization of orbifold action (Non-geometric compactification)

- SM or several GUT gauge symmetries
- N=1 supersymmetry
- Chiral matter spectrum
- Increase the number of possible models (symmetric → asymmetric)

⇒ All Yukawa hierarchies ?

- A few/no moduli fields (non-geometric)

⇒ Moduli stabilization ?

However, in asymmetric orbifold construction, a systematic search for SUSY SM or other GUT extended models has not been investigated so far.

Goal : Search for SUSY SM in heterotic asymmetric orbifold vacua

SUSY SM in asymmetric orbifold vacua

- First step for model building : Gauge symmetry

Four-dimensions,
N=1 supersymmetry,
Standard model group(SU(3)xSU(2)xU(1)),
Three generations,
Quarks, Leptons and Higgs,
No exotics,
Yukawa hierarchy,
Proton stability,
R-parity,
Doublet-triplet splitting,
Moduli stabilization,
…

What types of gauge symmetries can be derived in these vacua ?

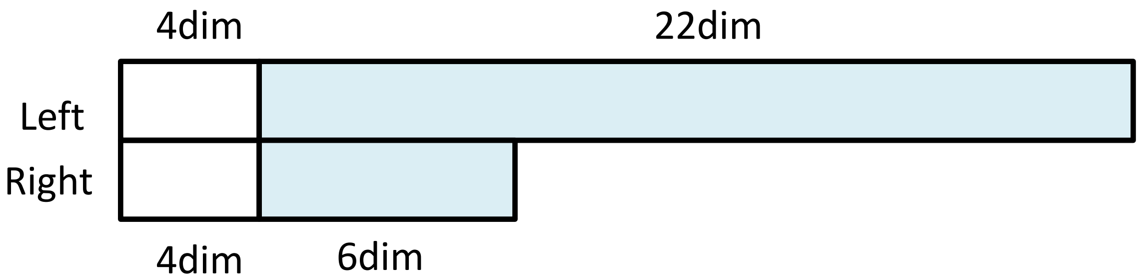
- SM group ?
- GUT group ?
- Flavor symmetry ?
- Hidden sector ?

Heterotic asymmetric orbifold models

Asymmetric Orbifold Compactification

- Asymmetric orbifold compactification
  - We start from (22,6)-dimensional Narain lattices $\Gamma_{22,6}$
  - General flat compactification of heterotic string
    --- Left : 22 dim
    --- Right : 6 dim
  - 4D N=4 SUSY
  - Left-right combined momentum $(p_{\rm L}, p_{\rm R})$ are quantized.

  - Modular invariance → The even and self-dual conditions



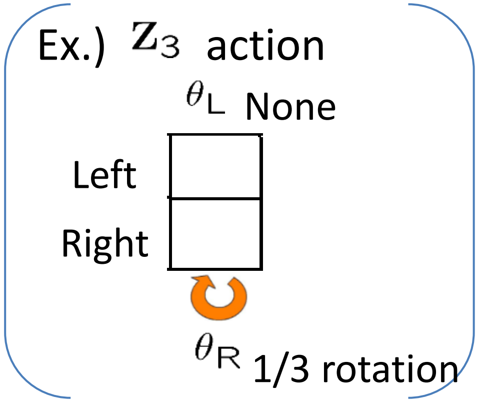
Asymmetric Orbifold Compactification

- Asymmetric orbifold compactification
  - We start from (22,6)-dimensional Narain lattices $\Gamma_{22,6}$
  - Narain lattice is not necessarily "left-right symmetric"
  - Orbifold action $\theta = (\theta_{\mathsf{L}}, \theta_{\mathsf{R}})$ (Twist, Shift)

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

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

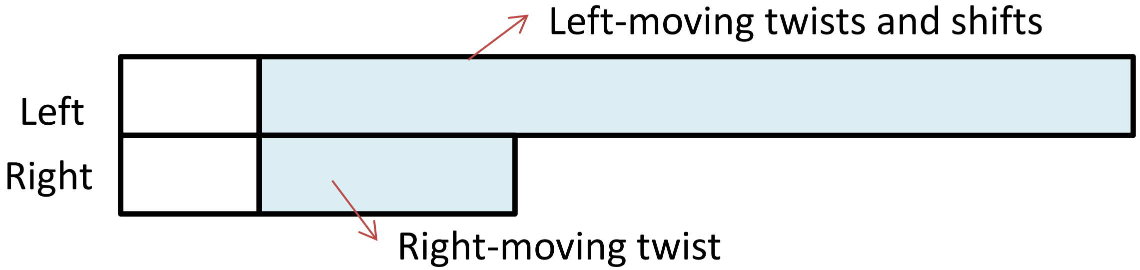
$\Psi_{\mathrm{R}} \to \theta_{\mathrm{R}} \Psi_{\mathrm{R}}$



Orbifold actions for left and right movers can be chosen independently

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

- N=4 SUSY → N=1 SUSY
- Modular invariance



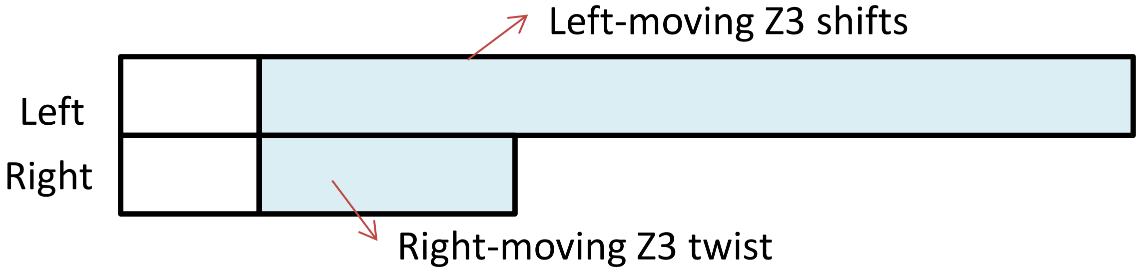
Z3 Asymmetric Orbifold Compactification

In this work, we consider

- Z3 orbifold action
- Abelian orbifolds
- No twist action for the left-mover $\theta_{\mathrm{L}} = 1$

A Z3 asymmetric orbifold model is specified by

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



Narain lattices and group breaking patterns

Lattice and gauge symmetry

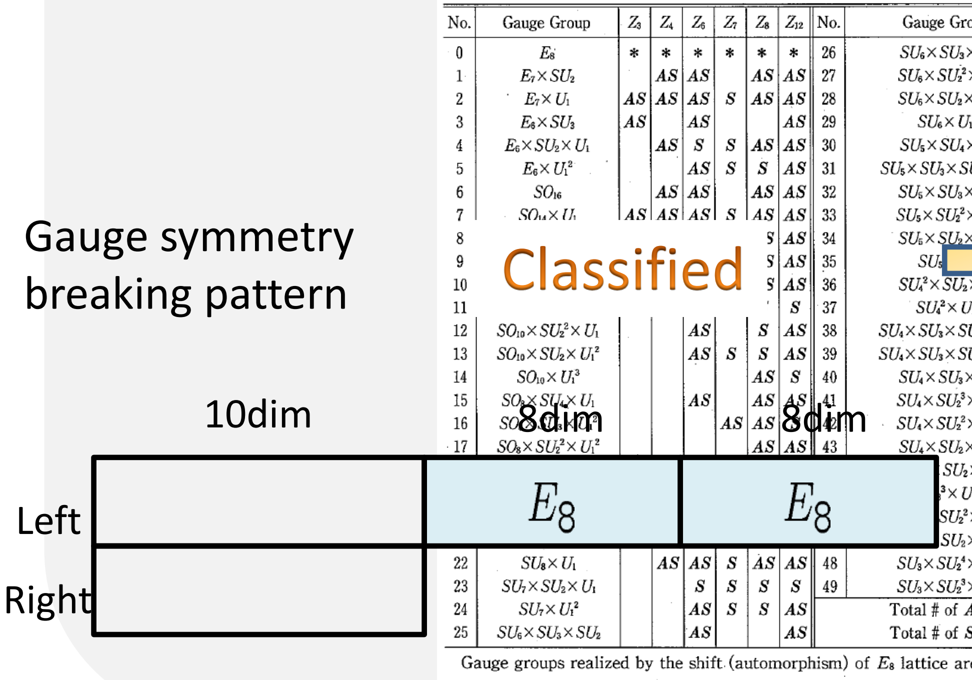
- Our starting point → Narain lattice

Symmetric orbifolds

Lattice E8 x E8, SO(32)

Gauge symmetry breaking pattern

Classified



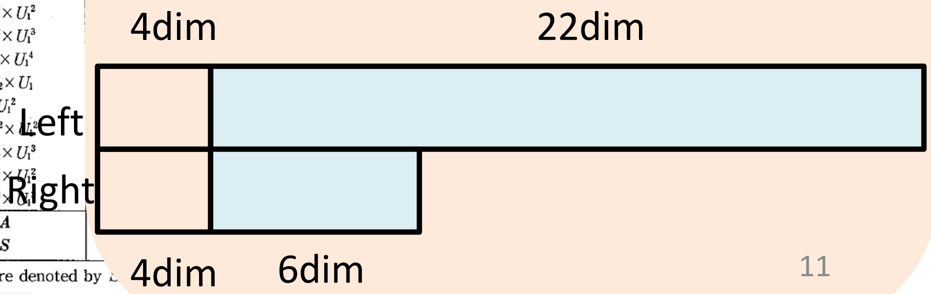
No.	Gauge Group	Z_3	Z_4	Z_6	Z_7	Z_8	Z_{12}	No.	Gauge Group
0	E_8	*	*	*	*	*	*	26	$SU_6\times SU_3\times U_1$
1	$E_7\times SU_2$		AS	AS		AS	AS	27	$SU_6\times SU_2^2\times U_1$
2	$E_7\times U_1$	AS	AS	AS	S	AS	AS	28	$SU_6\times SU_2\times U_1^2$
3	$E_6\times SU_3$	AS		AS			AS	29	$SU_6\times U_1^3$
4	$E_6\times SU_2\times U_1$		AS	S	S	AS	AS	30	$SU_5\times SU_4\times U_1$
5	$E_6\times U_1^2$			AS	S	S	AS	31	$SU_5\times SU_3\times SU_2\times U_1$
6	SO_{16}		AS	AS		AS	AS	32	$SU_5\times SU_3\times U_1^2$
7	$SO_{14}\times U_1$	AS	AS	AS	S	AS	AS	33	$SU_5\times SU_2^2\times U_1^2$
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	S	AS	34	$SU_5\times SU_2\times U_1^3$
9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	S	AS	35	SU_5 [illegible]
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	S	AS	36	$SU_4^2\times SU_2\times U_1$
11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	S	37	$SU_4^2\times U_1^2$
12	$SO_{10}\times SU_2^2\times U_1$			AS		S	AS	38	$SU_4\times SU_3\times SU_2^2\times U_1$
13	$SO_{10}\times SU_2\times U_1^2$			AS	S	S	AS	39	$SU_4\times SU_3\times SU_2\times U_1^2$
14	$SO_{10}\times U_1^3$					AS	S	40	$SU_4\times SU_3\times U_1^3$
15	$SO_8\times SU_4\times U_1$			AS		AS	AS	41	$SU_4\times SU_2^3\times U_1^2$
16	$SO_8\times SU_3\times U_1^2$				AS	AS	[illegible]	42	$SU_4\times SU_2^2\times U_1^3$
17	$SO_8\times SU_2^2\times U_1^2$					AS	AS	43	$SU_4\times SU_2\times U_1^4$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $SU_2\times U_1$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $\times U_1^2$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $SU_2^2\times$ [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $SU_2\times U_1^3$
22	$SU_8\times U_1$		AS	AS	S	AS	AS	48	$SU_3\times SU_2^4\times U_1^2$
23	$SU_7\times SU_2\times U_1$			S	S	S	S	49	$SU_3\times SU_2^3\times$ [illegible]
24	$SU_7\times U_1^2$			AS	S	S	AS	Total # of A	
25	$SU_6\times SU_3\times SU_2$			AS			AS	Total # of S	

Gauge groups realized by the shift (automorphism) of E_8 lattice are denoted by

Asymmetric orbifolds

What types of (22,6)-dimensional Narain lattices can be used for starting points ?

What types of gauge symmetries can be realized ?



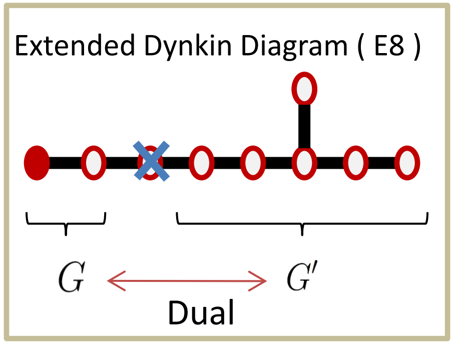
Lattice Engineering Technique

- Lattice engineering technique

Lerche, Schellekens, Warner '88

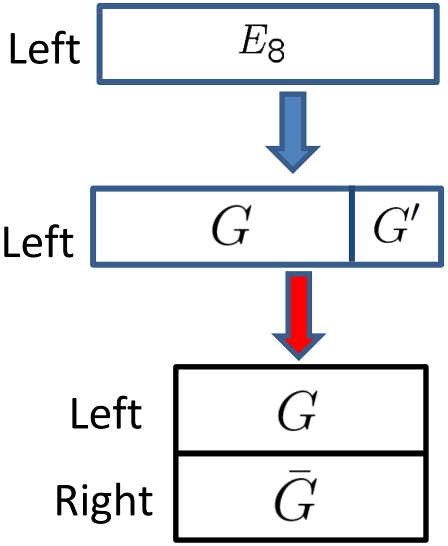
  - We can construct new Narain lattice from known one.
  - We can replace one of the left-moving group factor with a suitable right-moving group factor.

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


Extended Dynkin Diagram (E8)

$G \longleftrightarrow G'$

Dual


Left E_8

Left G | G'

Left G

Right $\bar{G}$

(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	$(1,0)$ $(1,2)$	$\overline{A}_2^2$	$(1,2)$ $(2,0)$
$U(1)^2$	$(1/3,1/2)$ $(1/4,1/4)$	$\overline{D}_4 \times \overline{A}_2$	$(s,1)$ $(c,0)$

Lattice Engineering Technique

- Lattice engineering technique

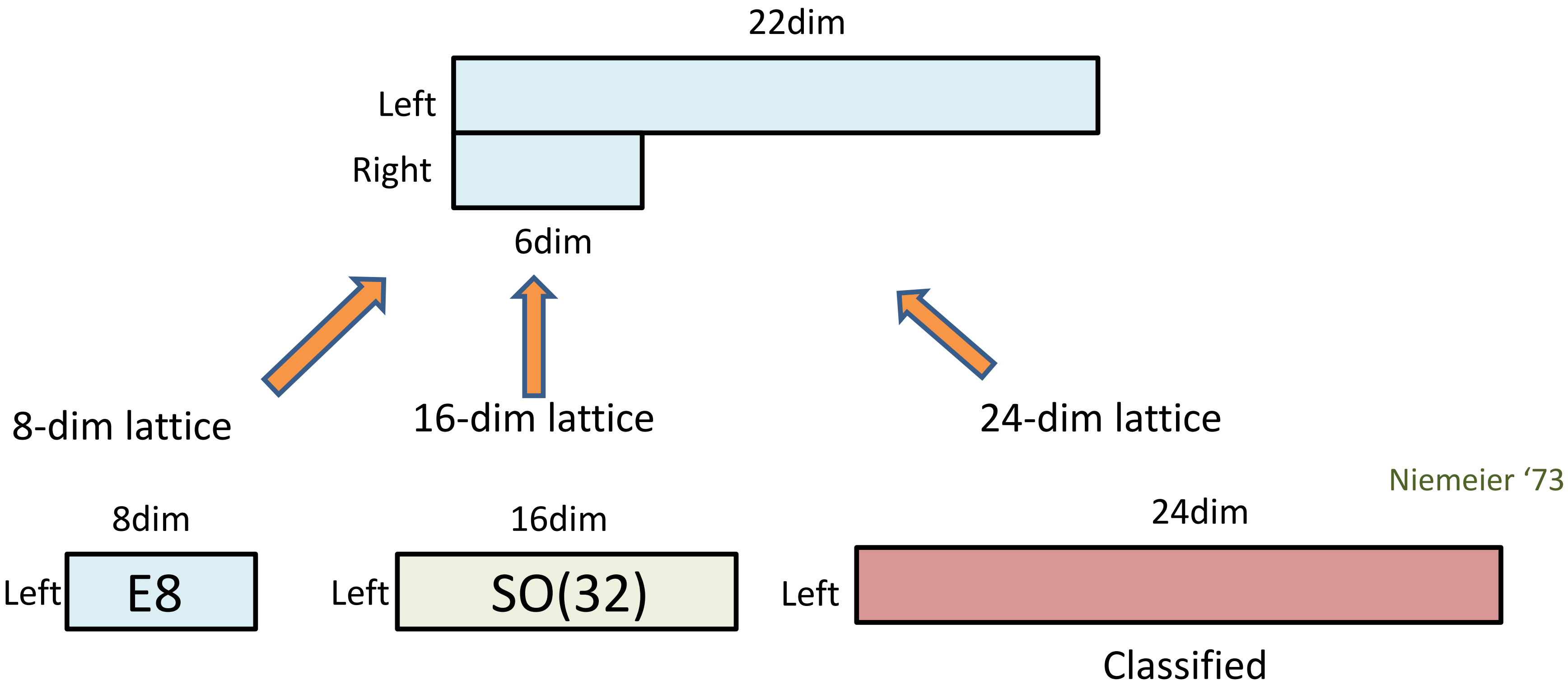
Lerche, Schellekens, Warner '88

  - 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-right replacement can be done in repeating fashion,
    Narain lattice 1 → Narain lattice 2 → Narain lattice 3 → … → Narain lattice $\Gamma_{22,6}$
  - We can construct various Narain lattices $\Gamma_{22,6}$ systematically.

  - Advantage : Various gauge symmetries.
    Easy to find out discrete symmetries of the lattices. → Orbifold

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

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



22dim

Left

Right

6dim

8-dim lattice

16-dim lattice

24-dim lattice

Niemeier '73

8dim

Left

E8

16dim

Left

SO(32)

24dim

Left

Classified

24 types of lattices

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

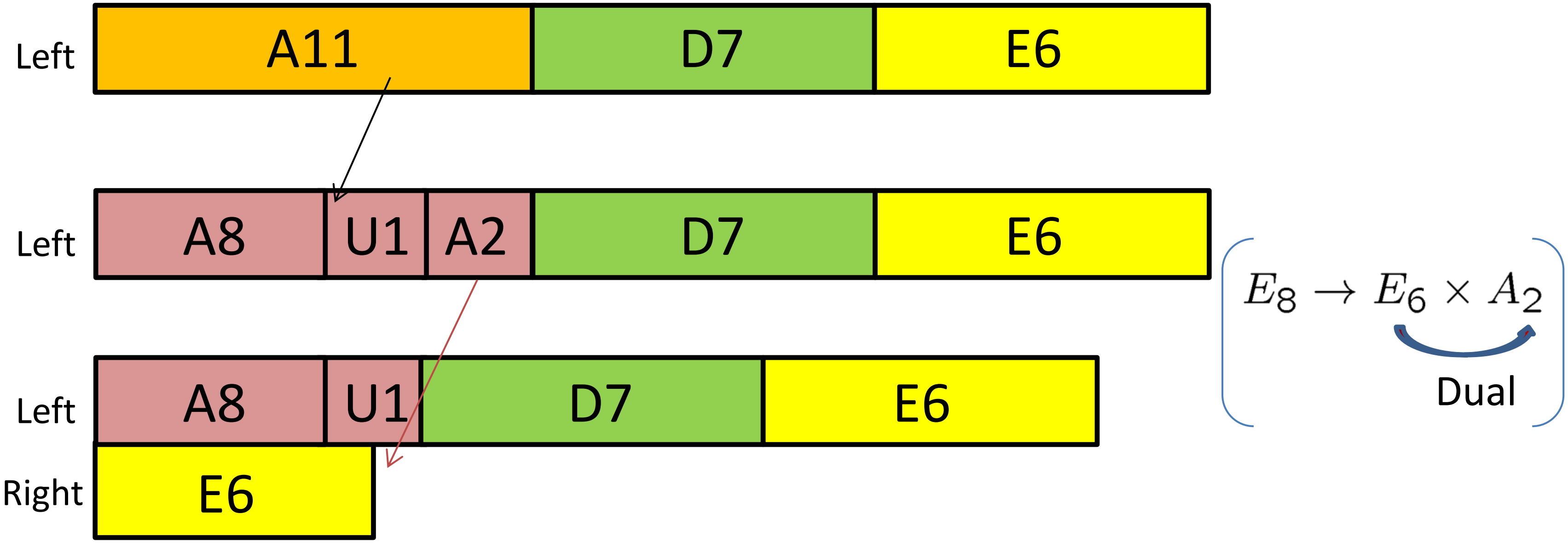
(22,6)-dim lattices from 8, 16, 24-dim lattices

Example :

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

Generator of conjugacy classes : $(1, s, 1)$

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

Generator of conjugacy classes : $(0, 0, 1, 1/9, 1), (s, 1, 1, 1/36, 0)$

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

Gauge symmetry breaking by Z3 action

- Z3 asymmetric orbifold compactification

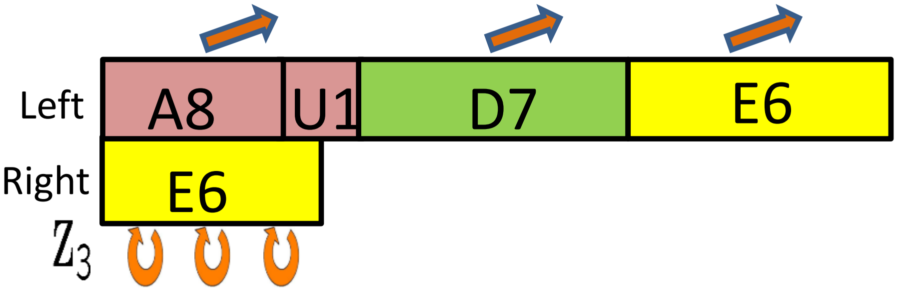
  Z3 action :

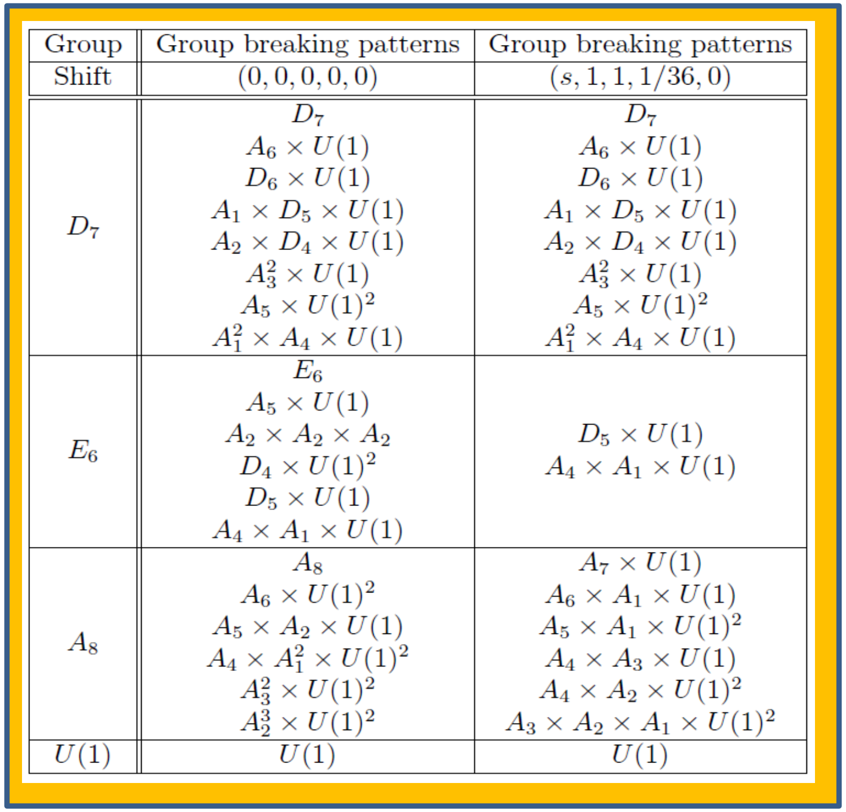
  Right mover → twist action → N=1 SUSY

  Left mover → shift action → Gauge symmetry breaking

  Modular invariance

- SO(14) x E6 x SU(9) x U(1) Gauge group breaks to Several gauge symmetries.
- Some group combinations lead to modular invariant models.
- SM group, Flipped SO(10)xU(1), Flipped SU(5)xU(1), Trinification SU(3)^3 group can be realized.
- Important data for model building.





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

Result: Lattice and gauge symmetry

- Our starting point → Narain lattice

Symmetric orbifolds

Asymmetric orbifolds

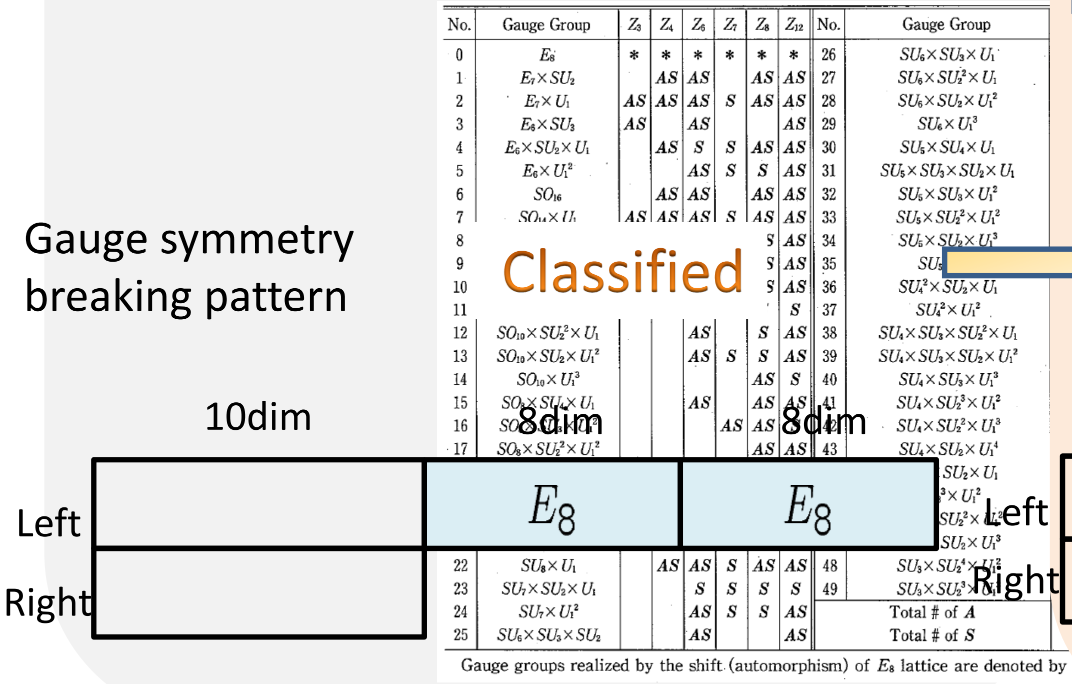
Lattice

E8 x E8, SO(32) → 90 lattices

(with right-moving non-Abelian factor, from 24 dimensional lattices)

Gauge symmetry breaking pattern

Classified → Classified



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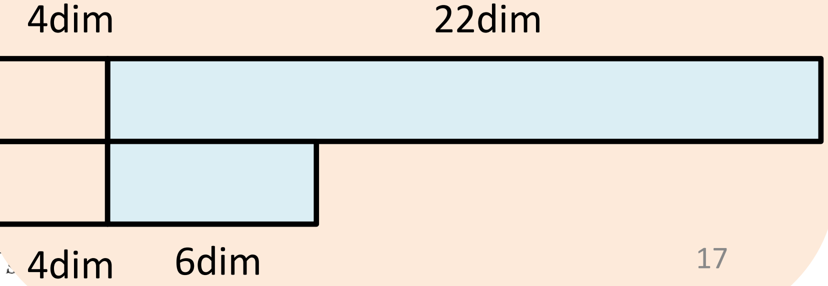
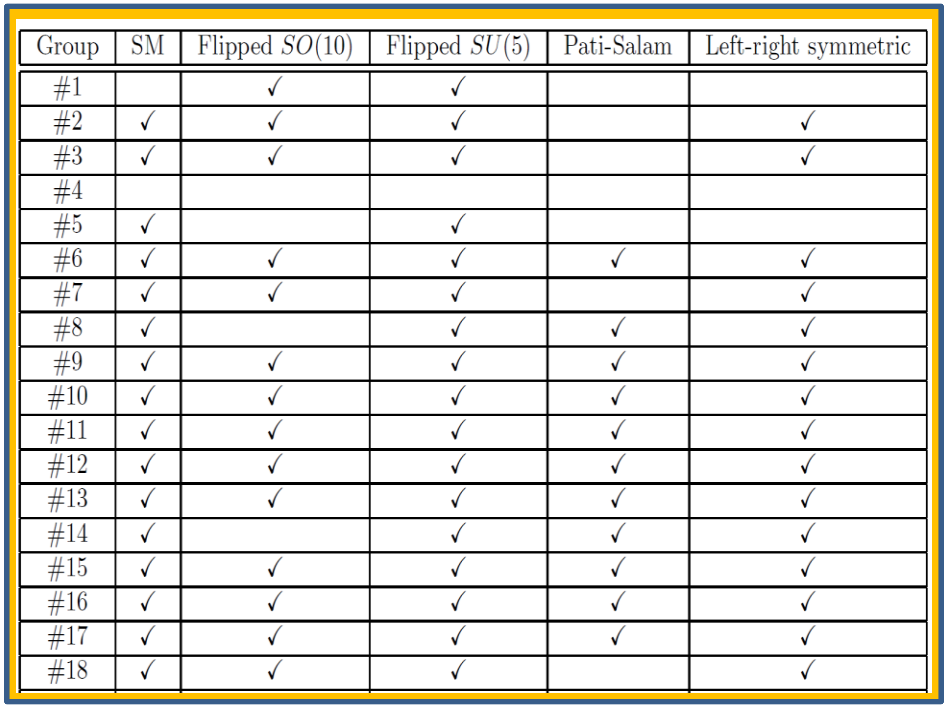
2	$E_7\times U_1$	AS	AS	AS	S	AS	AS	28	$SU_6\times SU_2\times U_1^2$
3	$E_6\times SU_3$	AS		AS			AS	29	$SU_6\times U_1^3$
4	$E_6\times SU_2\times U_1$		AS	S	S	AS	AS	30	$SU_5\times SU_4\times U_1$
5	$E_6\times U_1^2$			AS	S	S	AS	31	$SU_5\times SU_3\times SU_2\times U_1$
6	SO_{16}		AS	AS		AS	AS	32	$SU_5\times SU_3\times U_1^2$
7	$SO_{14}\times U_1$	AS	AS	AS	S	AS	AS	33	$SU_5\times SU_2^2\times U_1^2$
8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AS	34	$SU_5\times SU_2\times U_1^3$
9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AS	35	SU_5 [illegible]
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	AS	36	$SU_4^2\times SU_2\times U_1$
11	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		S	37	$SU_4^2\times U_1^2$
12	$SO_{10}\times SU_2^2\times U_1$			AS		S	AS	38	$SU_4\times SU_3\times SU_2^2\times U_1$
13	$SO_{10}\times SU_2\times U_1^2$			AS	S	S	AS	39	$SU_4\times SU_3\times SU_2\times U_1^2$
14	$SO_{10}\times U_1^3$					AS	S	40	$SU_4\times SU_3\times U_1^3$
15	$SO_8\times SU_4\times U_1$			AS		AS	AS	41	$SU_4\times SU_2^3\times U_1^2$
16	[illegible]				AS	AS	[illegible]	42	$SU_4\times SU_2^2\times U_1^3$
17	$SO_8\times SU_2^2\times U_1^2$					AS	AS	43	$SU_4\times SU_2\times U_1^4$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $SU_2\times U_1$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $\times U_1^2$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible] $SU_2\times U_1^3$
22	$SU_8\times U_1$		AS	AS	S	AS	AS	48	$SU_3\times SU_2^4\times U_1^2$
23	$SU_7\times SU_2\times U_1$			S	S	S	S	49	$SU_3\times SU_2^3\times$ [illegible]
24	$SU_7\times U_1^2$			AS	S	S	AS	Total # of A	
25	$SU_6\times SU_3\times SU_2$			AS			AS	Total # of S	

Gauge groups realized by the shift (automorphism) of E_8 lattice are denoted by



Gauge group patterns of models

SM or GUT group patterns of Z3 asymmetric orbifold models from 90 Narain lattices



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	✓	✓	✓		✓

+ also for the other lattices.

Three-generation asymmetric orbifold models

Three generation left-right symmetric model

Z3 asymmetric orbifold compactification

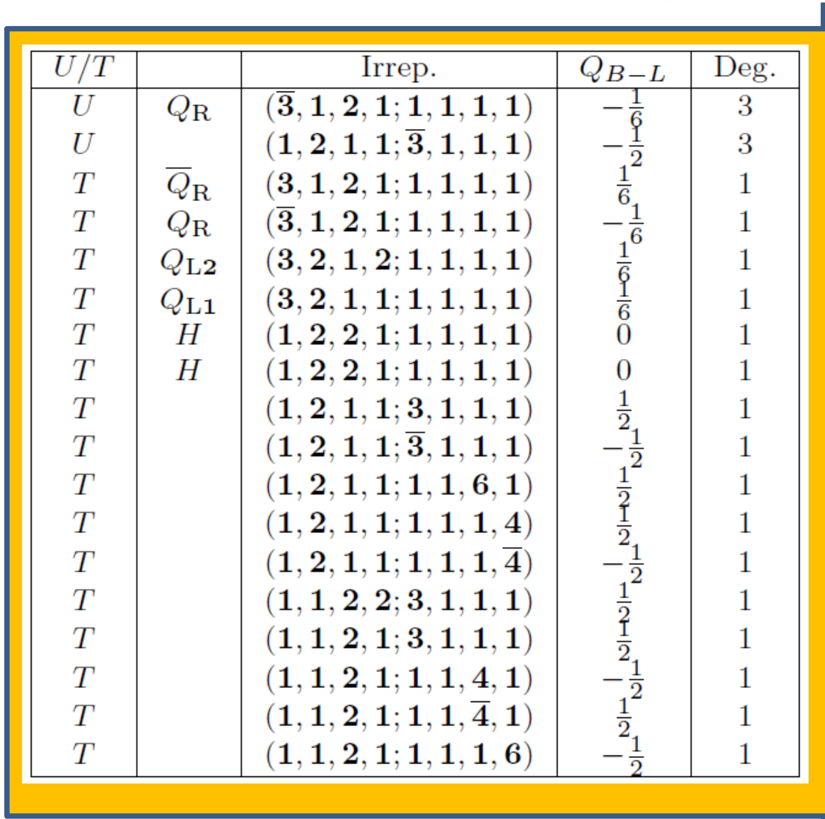
- Narain lattice: $A_1^2 \times A_4^4 \times U(1)^2 \times \overline{A}_2^2$ lattice $\oplus$ $A_2 \times \overline{A}_2$ lattice
- LET: $A_4^6 \xrightarrow[\text{decompose}]{} (A_2 \times A_1 \times U(1))^2 \times A_4^4 \xrightarrow[\text{replace}]{} A_1^2 \times A_4^4 \times U(1)^2 \times \overline{A}_2^2$

  $E_8 \xrightarrow[\text{decompose}]{} E_6 \times A_2 \xrightarrow[\text{replace}]{} A_2 \times \overline{A}_2$
- Z3 shift vector: $V = (0, \omega_1^{A_1}, 2\omega_1^{A_4} + \omega_3^{A_4} - 3\alpha_1^{A_4} - 4\alpha_2^{A_4} - 2\alpha_3^{A_4} - \alpha_4^{A_4}, -\omega_1^{A_4} + \alpha_1^{A_4} + \alpha_2^{A_4} + \alpha_3^{A_4} + \alpha_4^{A_4},$

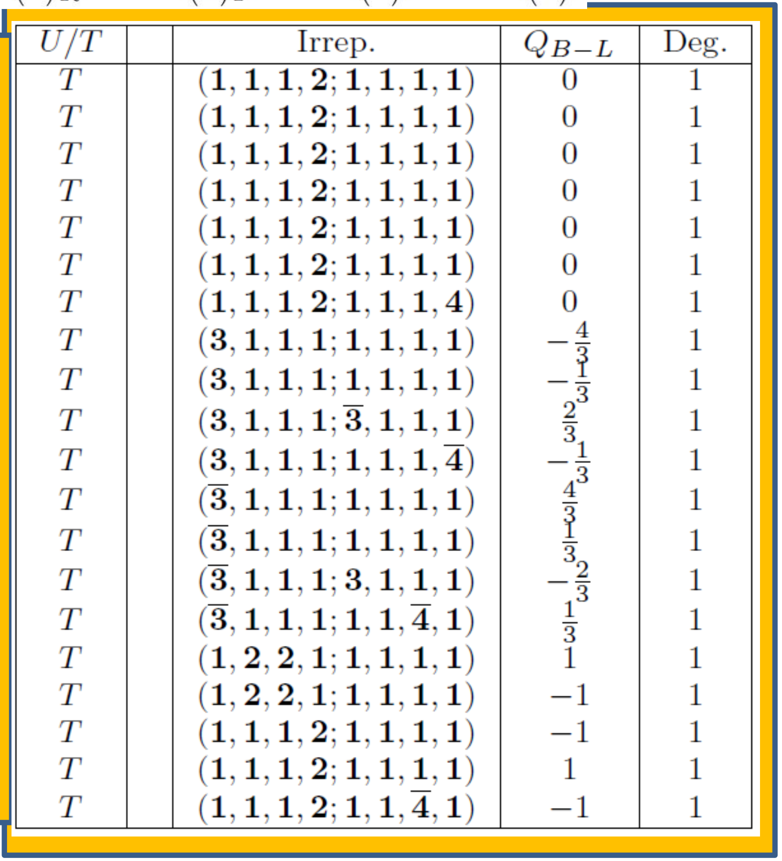
  $- \omega_3^{A_4} - 2\omega_4^{A_4} + 2\alpha_4^{A_4}, \omega_2^{A_4} + 2\omega_4^{A_4} - 2\alpha_3^{A_4} - 2\alpha_4^{A_4}, \frac{\sqrt{30}}{5}, \frac{3\sqrt{30}}{10}, 0, 0, 0, 0)/3$
- Group breaking: $SU(5)^4 \times SU(3) \times SU(2)^2 \times U(1)^2 \rightarrow SU(4)^2 \times SU(3)^3 \times SU(2)^3 \times U(1)^7$
- One anomalous $U(1)_A$ gauge symmetry

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



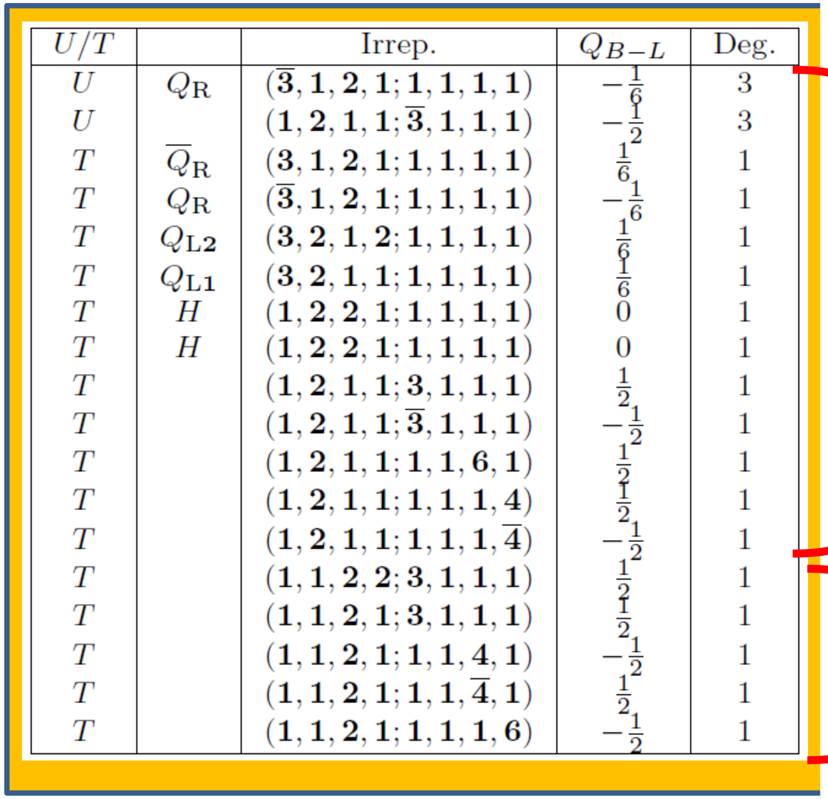
U/T		Irrep.	Q_{B-L}	Deg.
T		$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}; \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})$	0	1
T		$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}; \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})$	0	1
T		$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}; \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})$	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 $SU(3)_{\rm C} \times SU(2)_{\rm L} \times SU(2)_{\rm R} \times U(1)_{\rm B-L}$ model

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
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

+

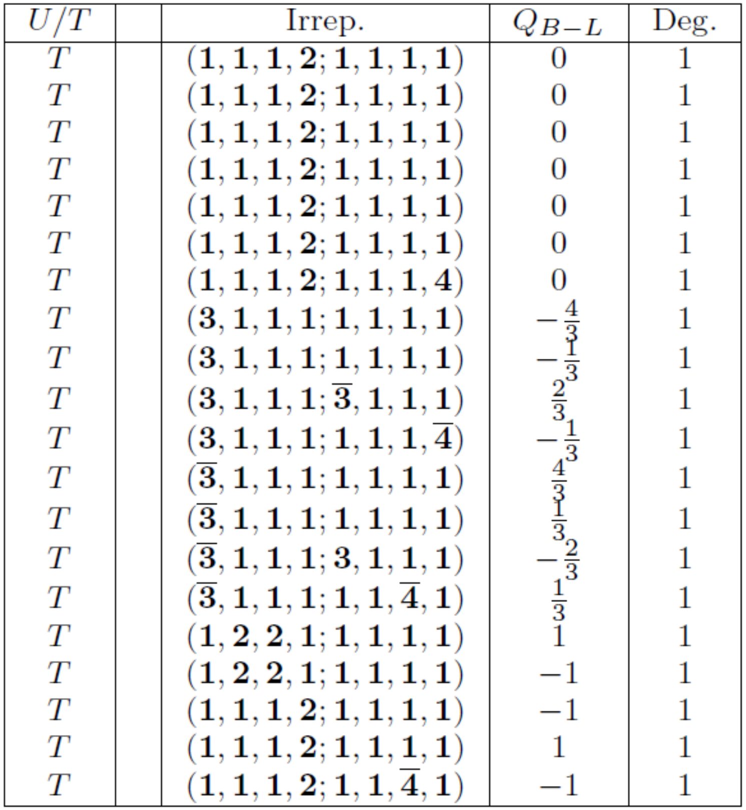
Vector-like fields

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

- Three-generation $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)_{\mathrm{B-L}}$ model
- Additional fields are vector-like

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.
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

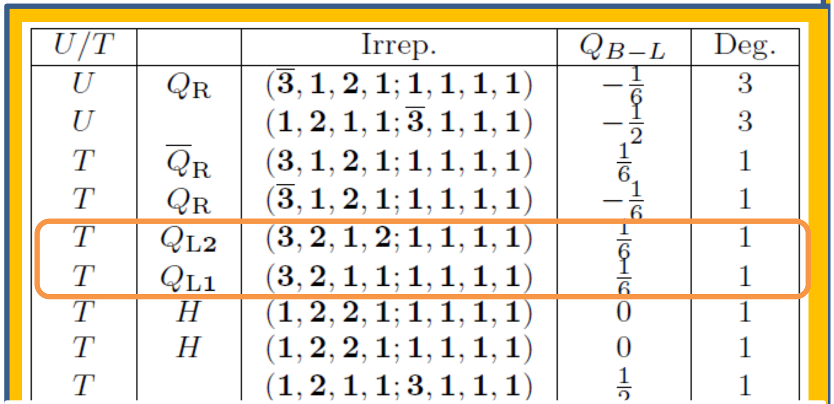
+ other fields

Vector-like fields

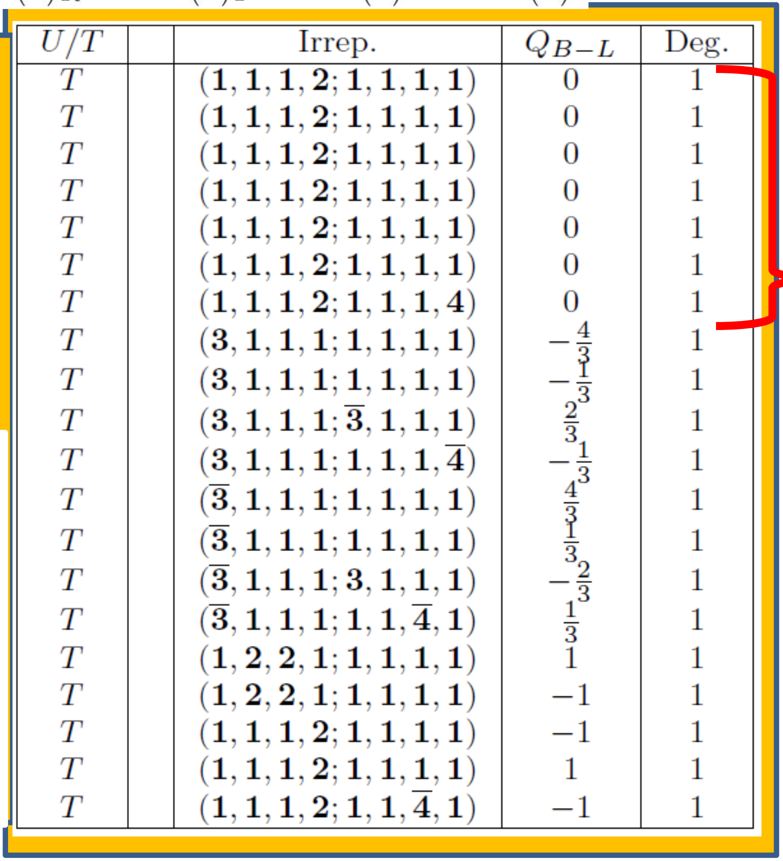
- Three-generation $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)_{\mathrm{B-L}}$ model
- Additional fields are vector-like

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



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

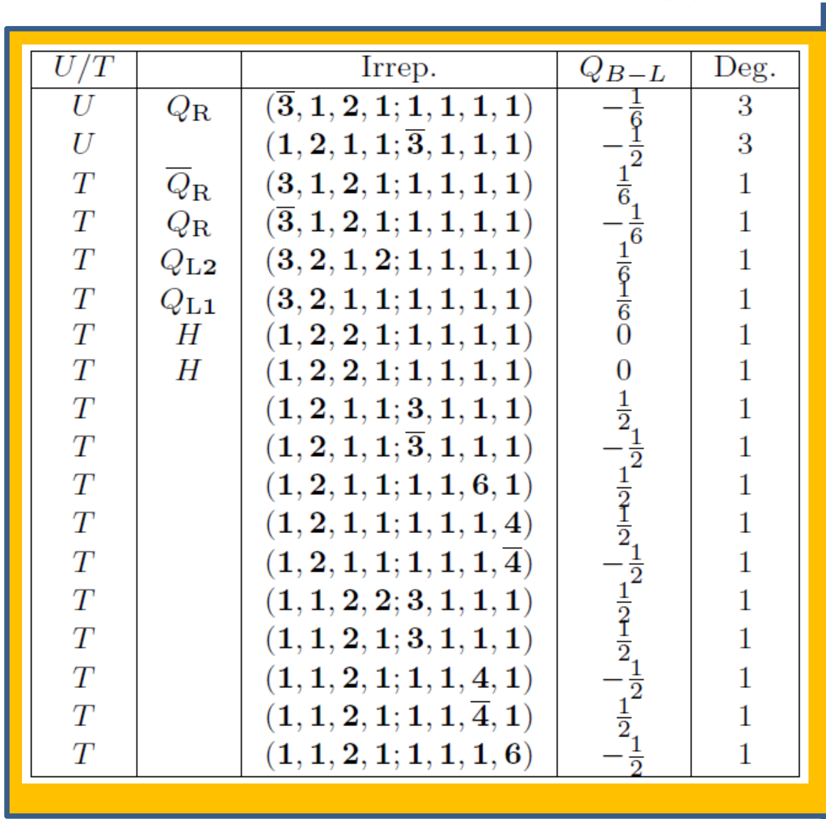
SU(2)F flavon

The first two-generation is unified into SU(2)F doublet.
This is a characteristic property of asymmetric orbifolds since we do not consider any left-moving twist action, zero point energy is $\Delta c_{\rm L}=0$

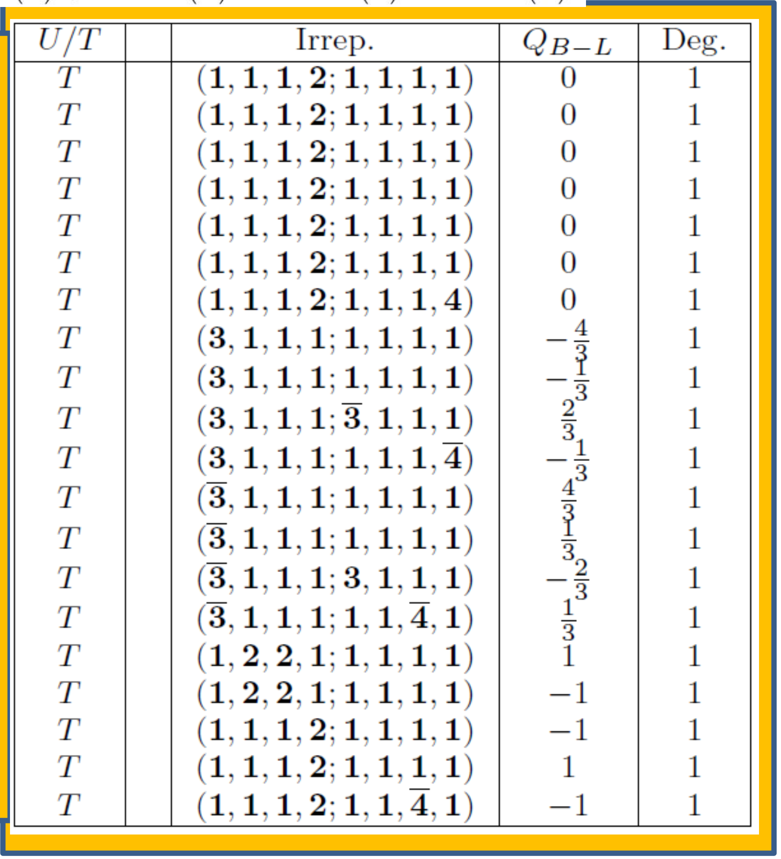
- Three-generation $SU(3)_{\rm C}\times SU(2)_{\rm L}\times SU(2)_{\rm R}\times U(1)_{\rm B-L}$ model
- Additional fields are vector-like
- Gauge flavor symmetry $SU(2)_F$

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
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 $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times SU(2)_{\mathrm{R}} \times U(1)_{\mathrm{B-L}}$ model
- Additional fields are vector-like
- Gauge flavor symmetry $SU(2)_F$
- No Top Yukawa from twisted sector ($HQ_{\mathrm{L1}}Q_{\mathrm{R}}$)

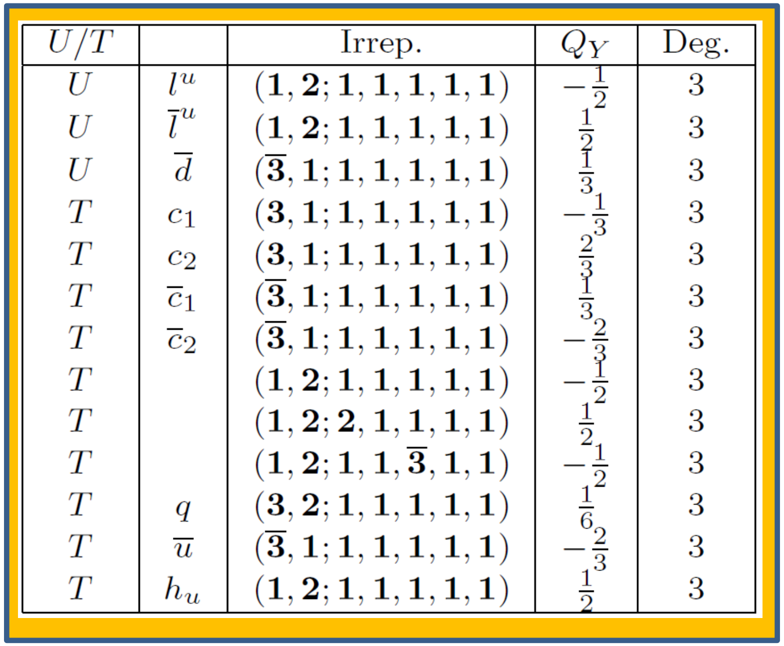
Three generation SU(3)xSU(2)xU(1) model

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: $SU(4)^7 \times U(1) \to SU(4) \times SU(3)^3 \times SU(2)^3 \times U(1)^{10}$
- One anomalous $U(1)_A$ gauge symmetry

Three generation SU(3)xSU(2)xU(1) model

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



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

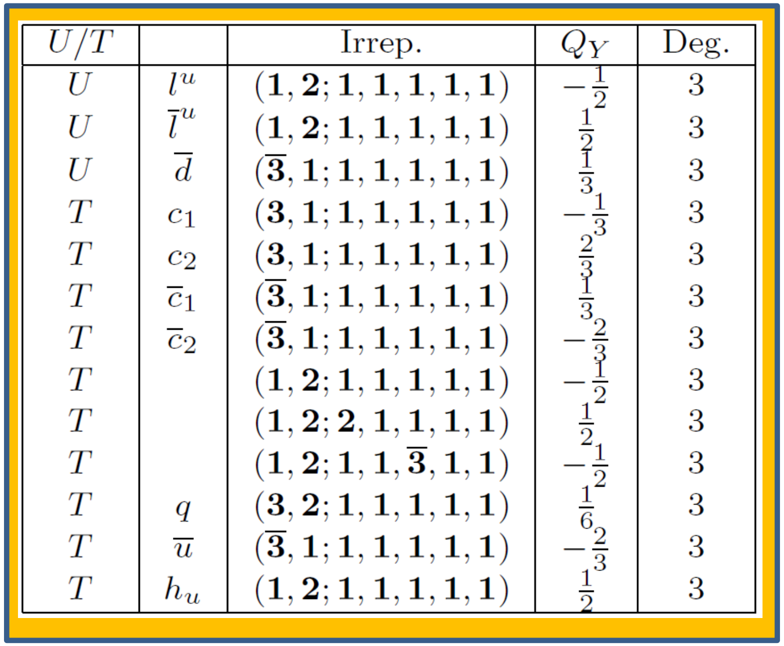
+ other fields

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

- Three-generation $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$ model
- "3"-generation is come from a degeneracy "3“
- Additional fields are vector-like

Three generation SU(3)xSU(2)xU(1) model

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



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 $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$ model
- "3"-generation is come from a degeneracy "3“
- Additional fields are vector-like
- Top Yukawa from twisted sector
- Charm quark becomes heavy (Tree level superpotential)

$$y_{123}q_1h_{u2}\overline{u}_3 + y_{231}q_3h_{u1}\overline{u}_2 + y_{312}q_2h_{u3}\overline{u}_1 + y_{132}q_1h_{u3}\overline{u}_2 + y_{213}q_2h_{u1}\overline{u}_3 + y_{321}q_3h_{u2}\overline{u}_1$$

SUSY SM in asymmetric orbifold vacua

- At this stage, we did model buildings from several lattices of 90 lattices, and get models with

Four-dimensions,
N=1 supersymmetry,
Standard model group(SU(3)*SU(2)*U(1)), LR symmetric group
Three generations,
Quarks, Leptons and Higgs,
No exotics (vector-like)
Top quark mass

Realized

Other quark masses (Charm quark mass)
Proton stability,
R-parity,
Doublet-triplet splitting,
Moduli stabilization,
...

Need to consider further model building from other Narain lattices and effective theory analysis

Conclusion

Conclusion and outlook

- Conclusion :
  - -- 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 models
  - -- Gauge flavor symmetry is possible

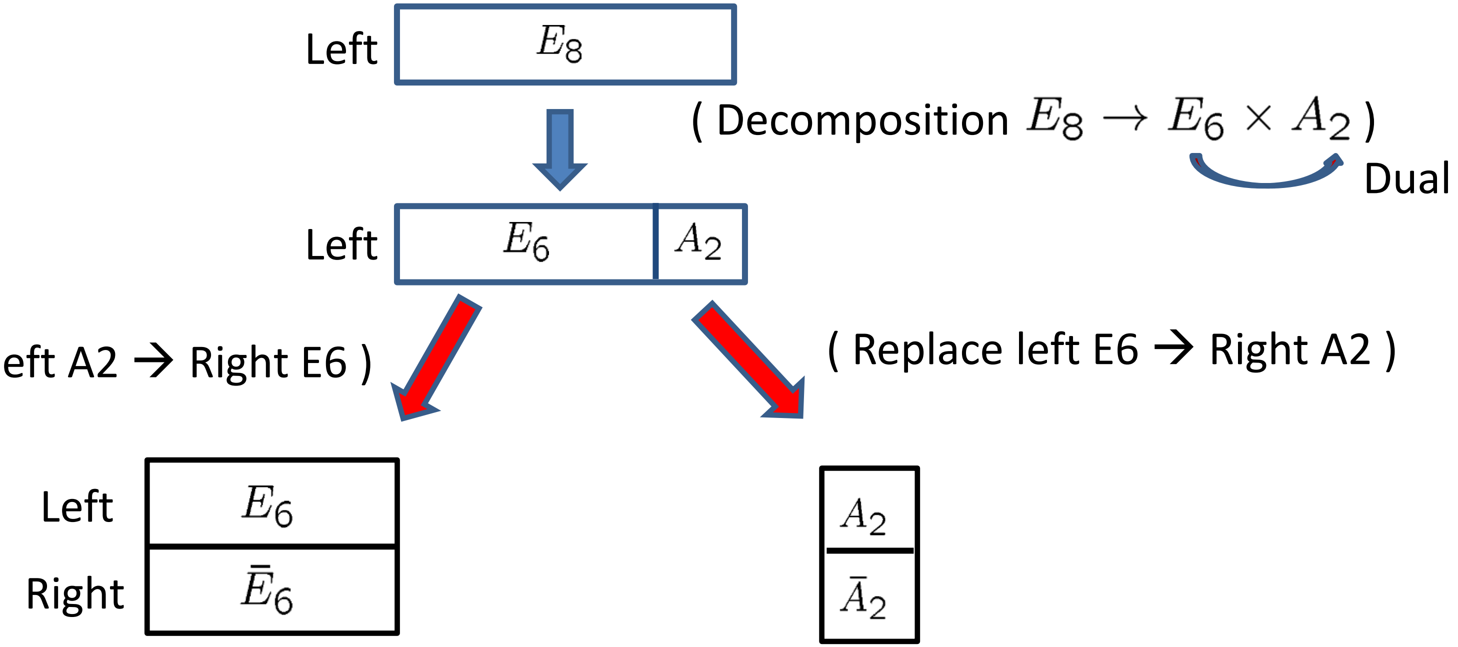
- Outlook: Search for a realistic model
  - -- Search for Z3 models from other lattices
  - -- Other orbifolds Z6, Z12, Z3xZ3…
  - -- Yukawa hierarchy, (Gauge or discrete) Flavor symmetry,
  - -- Moduli stabilization, etc.

Back up

Lattice Engineering Technique

- Lattice engineering technique
  - Simple example

$$G = E_6 \xleftrightarrow[\text{Dual}]{} G' = A_2 \qquad A_2 = SU(3)$$



Left E_8

(Decomposition $E_8 \to E_6 \times A_2$) Dual

Left E_6 A_2

(Replace left A2 → Right E6)

(Replace left E6 → Right A2)

Left E_6

Right $\bar{E}_6$

A_2

$\bar{A}_2$

$E_6 \times \bar{E}_6$ lattice (6-dim)

→ E_6 gauge symmetry

$A_2 \times \bar{A}_2$ lattice (2-dim)

→ A_2 (SU(3)) gauge symmetry