The $Z_2 \times Z_2$ *Universe*

Alon E Faraggi

- AEF, D.V Nanopoulos, K. Yuan
  A Standard Like Model in the 4D Free Fermionic String Formulation,
  Nucl. Phys. B335 (1990) 347.
- + • • • Antoniadis, Bachas, Kounnas, Petropoulos, Rizos, + • • •
- + • • •
- Luke Detraux, AEF, Benjamin Percival,
  Classification of Pati–Salam Asymmetric $Z_2 \times Z_2$ Heterotic String Orb-
  ifolds, Phys. Rev. D114 (2026) 026002

Corfu Summer Institute 2026, Corfu, 12 September 2026

Fermionic $Z_2 \times Z_2$ orbifolds

'Phenomenology of the Standard Model and Unification'

- Minimal Superstring Standard Model — NPB 335 (1990) 347 (with Nanopoulos & Yuan)
- Top quark mass $\sim$ 175–180GeV — PLB 274 (1992) 47
- Fermion masses and mixing — NPB 416 (1994) 63 (with Halyo)
- Stringy seesaw mechanism — PLB 307 (1993) 311 (with Halyo)
- Gauge coupling unification — NPB 457 (1995) 409 (with Dienes)
- Proton stability — NPB 428 (1994) 111
- Squark degeneracy — NPB 526 (1998) 21 (with Pati)
- Moduli fixing — NPB 728 (2005) 83
- Classification — 2003 – · · ·

  (with Kounnas, Rizos & ... Percival, Matyas, Detraux)
- ... String Cosmology ... (... Kounnas *et. al.* ...)
- ... vacuum stability ... (with Matyas, Percival, Avalos–Diaz, Detraux...)

The Z2xZ2 Universe

Searching for Life:

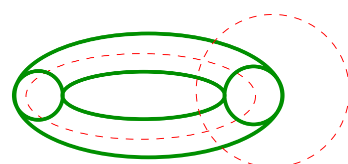
"There may be life in another universe"

Fermionic Construction

Left-Movers: $\psi^{\mu=1,2}$, $\chi_i,$ $y_i,$ ω_i $(i = 1, \cdots, 6)$

Right-Movers

$$\bar\phi_{A=1,\cdots,44} = \begin{cases} \bar y_i \;,\; \bar\omega_i & i = 1,\cdots,6 \\ & \\ \bar\eta_i & U(1)_i \quad i = 1,2,3 \\ \bar\psi_{1,\cdots,5} & SO(10) \\ \bar\phi_{1,\cdots,8} & SO(16) \end{cases}$$



$$V \longrightarrow V \qquad\qquad f \longrightarrow -e^{i\pi\alpha(f)} f$$

$$Z = \sum_{\substack{all\ spin \\ structures}} c\binom{\vec\alpha}{\vec\beta}\, Z\binom{\vec\alpha}{\vec\beta}$$

Models $\longleftrightarrow$ Basis vectors $+$ one–loop phases

Classification of fermionic $Z_2 \times Z_2$ orbifolds

Basis vectors:

$$
\begin{aligned}
1 &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\} \\
S &= \{\psi^\mu, \chi^{1,\dots,6}\}, && S + \Xi \quad \longrightarrow \quad \text{SUSY generator} \\
z_1 &= \{\bar{\phi}^{1,\dots,4}\}, \\
z_2 &= \{\bar{\phi}^{5,\dots,8}\}, \\
e_i &= \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6, && N = 4 \text{ Vacua} \\
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}, && N = 4 \to N = 2 \\
b_2 &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}, && N = 2 \to N = 1 \\
\alpha &= \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\} && \&\quad SO(10) \ \rightarrow\ SO(6) \times SO(4) \times \cdots \\
\beta &= \{\bar{\psi}^{1,\cdots,5} \equiv \tfrac{1}{2}, \cdots\} && \&\quad SO(10) \ \rightarrow\ SU(5) \times U(1) \times \cdots \\
\gamma &= \{\bar{\psi}^{1,\cdots,3} \equiv \tfrac{1}{2}, \cdots\} && \&\quad SO(10) \ \rightarrow\ SU(3) \times U(1) \times SU(2)^2 \cdots
\end{aligned}
$$

Independent phases $c\begin{bmatrix} vi \\ v_j \end{bmatrix} = \exp[i\pi(v_i|v_j)]$: upper block

$$
\begin{array}{c c}
 & \begin{array}{ccccccccccccc} 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & z_1 & z_2 & b_1 & b_2 & \alpha \end{array} \\
\begin{array}{c} 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ z_1 \\ z_2 \\ b_1 \\ b_2 \\ \alpha \end{array} &
\begin{pmatrix}
-1 & -1 & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 \\
 & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & & & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & & & & \pm & \pm & \pm & \pm \\
 & & & & & & & & & & \pm & \pm & \pm \\
 & & & & & & & & & & & \pm & \pm \\
 & & & & & & & & & & & -1 & \pm \\
 & & & & & & & & & & & &
\end{pmatrix}
\end{array}
$$

A priori 66 independent coefficients $\rightarrow$ 2^{66} distinct vacua

$+$ systematic application of GGSO projections for spectrum analysis

Classifications:

- Classification of the chiral $Z_2 \times Z_2$ fermionic models in the heterotic superstring
  AEF, Costas Kounnas, Sander Nooij, John Rizos
  Nucl.Phys.B 695 (2004), 41-72 — $SO(10)$ spinorials

- Chiral family classification of fermionic heterotic orbifold models
  AEF, Costas Kounnas, John Rizos
  Phys.Lett.B 648 (2007), 84-89 — ... $+$ vectorials

- Classification of Heterotic Pati-Salam Models
  Benjamin Assel, Kyriakos Christodoulides, AEF, Costas Kounnas, John Rizos
  Nucl.Phys.B 844 (2011), 365-396 — ... $+$ exotics

- Classification of Flipped $SU(5)$ Heterotic-String Vacua
  AEF, John Rizos, Hassan Sonmez
  Nucl.Phys.B 886 (2014), 202-242 — ... $+ \frac{1}{2}$ BC

- Classification of $SU(4) \times SU(2) \times U(1)$ Heterotic-String Models
  AEF, Hassan Sonmez
  Phys.Rev.D 91 (2015) 066006 — No viable models

- Classification of standard-like heterotic-string vacua
  AEF, John Rizos, Hassan Sonmez
  Nucl.Phys.B 927 (2018), 1-34 — Fertility method

- Classification of left–right symmetric heterotic string vacua
  AEF, Glyn Harries, John Rizos
  Nucl.Phys.B 936 (2018), 472-500 — Fertility method

- Classification of Tachyon-Free Models From Tachyonic Ten-Dimensional Heterotic String Vacua
  AEF, Victor Matyas, Benjamin Percival
  Nucl.Phys.B 961 (2020), 115231 — ... + tachyonic sectors; vacuum analysis

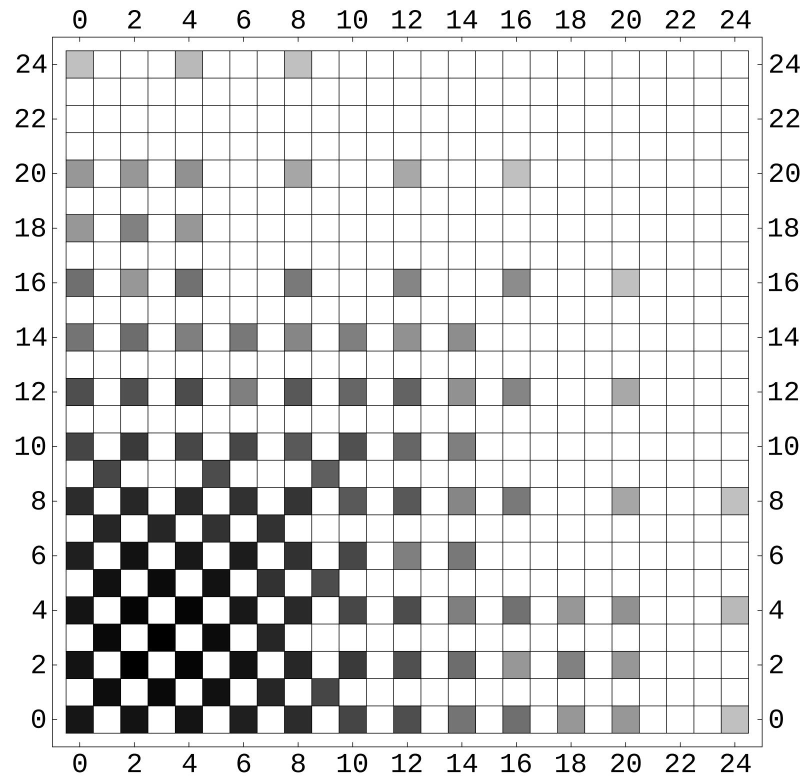
- Classification of nonsupersymmetric Pati-Salam heterotic string models
  AEF, Viktor Matyas, Benjamin Percival
  Phys.Rev.D 104 (2021) 4, 046002 — ... ↓ tachyonic and non–tachyonic 10D vacua

- Towards classification of $\mathcal{N}=1$ and $\mathcal{N}=0$ flipped $SU(5)$ asymmetric heterotic string orbifolds
  AEF, Viktor Matyas, Benjamin Percival
  Phys.Rev.D 106 (2022) 2, 026011 — ... + asymmetric BC; Yukawa coupling selection; moduli fixing

- Classification of Pati–Salam Asymmetric $Z_2 \times Z_2$ Heterotic String Orbifolds
  Luke Detraux, AEF, Benjamin Percival
  e-Print: 2604.07950 [hep-th] (PRD) — ... + doublet–triplet splitting; landscape reduction

Spinor–vector duality:

Invariance under exchange of $\#(16+\overline{16}) \; <-> \; \#(10)$



Symmetric under exchange of rows and columns

$$E_6 \; : \qquad 27 = 16 + 10 + 1 \qquad \overline{27} = \overline{16} + 10 + 1$$

Self-dual: $\#(16+\overline{16}) \; = \; \#(10)$ without E_6 symmetry

Spinor–vector duality and mirror symmetry

Enhance $SO(10) \to E_6$

from $X = 1 + S + \sum_i e_i + z_1 + z_2 = \{\bar\psi^{1,\cdots,5}, \bar\eta^{1,2,3}\}$

Euler characteristic $\chi \; = \; \#(\mathbf{27} - \overline{\mathbf{27}}) \;\; \longrightarrow \;\; -\chi$

Exchanges complex and Kähler structure moduli

Moduli of the internal compactified space

SVD $\quad\longleftrightarrow\quad$ exchange of Wilson line moduli $W \leftrightarrow \tilde W$

Imprint in the EFT limit:

Uncovering a spinor–vector duality on a resolved orbifold

AEF, S. Groot Nibbelink, M. Hurtado-Heredia

Nucl.Phys.B969 (2021), 115473

Moduli spaces of $(2,0)$ string compactifications

A Swampland Conjecture: AEF, EPJC 79 (2019) 703

- Every EFT $(2,0)$ heterotic–string compactification has to be connected to a (2,2) heterotic–string compactification by an orbifold or by continuous interpolation. If not $\rightarrow$ it is in the swampland
- Completeness?!

- SVD in type II string. SVD induced by a spectral flow operator on the bosonic side of the heterotic–string in $(2,2) \rightarrow (2,0)$ compactifications. Mirror symmetry: type IIA $\leftrightarrow$ type IIB $? \rightarrow$ break $(2,2) \rightarrow (2,0)$ in type II & induce spectral flow operation?
- So far : analysis of spectra, $i.e.$ one loop amplitude with no external lines. Extend to correlators, $e.g.$ Yukawa couplings in the worldsheet and EFT.

Mirror symmetry & SVD $\leftrightarrow$ tip o the iceberg

Asymmetric classification

Classification of Pati–Salam Asymmetric $Z_2 \times Z_2$ Heterotic String Orbifolds,
Luke Detraux, AEF, Benjamin Percival, e-Print: 2604.07950 [hep-th] (PRD)

Moduli $\rightarrow$ WS Thirring interactions $(R - \frac{1}{R}) J_L^i(z) \bar{J}_R^j(\bar{z}) = (R - \frac{1}{R}) y^i \omega^i \bar{y}^j \bar{\omega}^j$

To identify the untwisted moduli in the free fermionic models

$\rightarrow$ find the operators of the form $\quad J_L^I(z) \bar{J}_R^J(\bar{z}) \equiv y^I \omega^I \bar{y}^J \bar{\omega}^J$

that are allowed by the orbifold (fermionic) symmetry group

$$Z_2 \times Z_2 \qquad \{ 1 , S , z_1 , z_2 \} + \{ b_1 , b_2 \}$$

The Thirring interactions that remain invariant are

$$J_L^{1,2} \bar{J}_R^{1,2} \quad ; \quad J_L^{3,4} \bar{J}_R^{3,4} \quad ; \quad J_L^{5,6} \bar{J}_R^{5,6}$$

$$y^{1,2} \omega^{1,2} \bar{y}^{1,2} \bar{\omega}^{1,2} \quad ; \quad y^{3,4} \omega^{3,4} \bar{y}^{3,4} \bar{\omega}^{3,4} \quad ; \quad y^{5,6} \omega^{5,6} \bar{y}^{5,6} \bar{\omega}^{5,6}$$

These moduli are always present in symmetric $Z_2 \times Z_2$ orbifolds in realistic models

$$\{ 1 , S , z_1 , z_2 \} \oplus \{ b_1 , b_2 \} \oplus \{ \alpha , \beta , \gamma \}$$

$$N = 4 \qquad\qquad N = 1$$

$$E_8 \times E_8 \qquad\qquad Z_2 \times Z_2$$

new feature Asymmetric orbifold $y^i\omega^i\bar{y}^i\bar{\omega}^i \quad \rightarrow \quad - y^i\omega^i\bar{y}^i\bar{\omega}^i$

the key focus: boundary conditions of the internal fermions

$$\{ y , \omega \mid \bar{y} , \bar{\omega} \}$$

WS fermions that have same B.C. in all basis vectors are paired

pairing of LR fermions $\rightarrow$ Ising model $\rightarrow$ symmetric real fermions

pairing of LL & RR fermions $\rightarrow$ complex fermions $\rightarrow$ asymmetric

STRING DERIVED STANDARD-LIKE MODEL (PLB278)

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	$y^{3,\ldots,6}$	$\bar{y}^{3,\ldots,6}$	$y^{1,2},\omega^{5,6}$	$\bar{y}^{1,2},\bar{\omega}^{5,6}$	$\omega^{1,\ldots,4}$	$\bar{\omega}^{1,\ldots,4}$	$\bar{\psi}^{1,\ldots,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,\ldots,8}$
$\mathbf{1}$	1	1	1	1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1	1	1	1,...,1
S	1	1	1	1	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0	0	0	0,...,0
b_1	1	1	0	0	1,...,1	1,...,1	0,...,0	0,...,0	0,...,0	0,...,0	1,...,1	1	0	0	0,...,0
b_2	1	0	1	0	0,...,0	0,...,0	1,...,1	1,...,1	0,...,0	0,...,0	1,...,1	0	1	0	0,...,0
b_3	1	0	0	1	0,...,0	0,...,0	0,...,0	0,...,0	1,...,1	1,...,1	1,...,1	0	0	1	0,...,0

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	y^3y^6	$y^4\bar{y}^4$	$y^5\bar{y}^5$	$\bar{y}^3\bar{y}^6$	$y^1\omega^5$	$y^2\bar{y}^2$	$\omega^6\bar{\omega}^6$	$\bar{y}^1\bar{\omega}^5$	$\omega^2\omega^4$	$\omega^1\bar{\omega}^1$	$\omega^3\bar{\omega}^3$	$\bar{\omega}^2\bar{\omega}^4$	$\bar{\psi}^{1,\ldots,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}$
α	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1 1 1 0 0	0	0	0	1 1 1
β	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0	1	1 1 1 0 0	0	0	0	1 1 1
γ	0	0	0	0	0	1	0	1	0	1	0	1	1	0	0	0	$\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$ 0 1

Asymmetric $BC \Rightarrow$ all untwisted moduli are projected out!

all $y_i\omega_i\bar{y}_i\bar{\omega}_i$ are disallowed

can be translated to asymmetric bosonic identifications

$$X_L + X_R \rightarrow X_L - X_R$$

moduli fixed at enhanced symmetry point

Classification of asymmetric $Z_2 \times Z_2$ orbifolds

Basis vectors:

$$1 = \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\}$$

$$S = \{\psi^\mu, \chi^{1,\dots,6}\}, \qquad S + \Xi \longrightarrow \text{SUSY generator}$$

$$z_1 = \{\bar{\phi}^{1,\dots,4}\},$$

$$z_2 = \{\bar{\phi}^{5,\dots,8}\},$$

$$e_i = \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i =?, \qquad N = 4 \text{ Vacua}$$

$$b_1 = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}, \qquad N = 4 \to N = 2$$

$$b_2 = \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}, \qquad N = 2 \to N = 1$$

$$\alpha = \{\vec{\mathbf{A}}, \bar{\psi}^{1,2,3}, \bar{\phi}^{1,2}\}$$

$$\vec{\mathbf{A}} = \{A(y^{1,\dots,6}, w^{1,\dots,6}) \mid A(\bar{y}^{1,\dots,6}, \bar{w}^{1,\dots,6}); A(\bar{\eta}^1), A(\bar{\eta}^2), A(\bar{\eta}^3)\},$$

Class Label	Real moduli (M_1, M_2, M_3)	Coset (complex) moduli space	Kähler potential	Representative $\boldsymbol{\alpha}$ vector
1a)	$(4,4,0)$	$\left(\frac{SU(1,1)}{U(1)} \otimes \frac{SU(1,1)}{U(1)}\right)^2$	$-\sum_{i=1}^{2}\left[\log(1-\lvert T_i\rvert^2) + \log(1-\lvert U_i\rvert^2)\right]$	$\boldsymbol{\alpha} = \left\{ \begin{array}{l} \bar{y}^{56}; \\ \bar{\psi}^{1,2,3}, \bar{\eta}^{2,3}, \bar{\phi}^{1,2} \end{array} \right\}$
1b)	$(4,2,2)$	$\left(\frac{SU(1,1)}{U(1)}\right)^2 \times \left(\frac{SU(1,1)}{U(1)}\right)^2$	$-\log(1-\lvert T_1\rvert^2)$ $-\log(1-\lvert U_1\rvert^2)$ $-\log(1-\lvert H_2\rvert^2)$ $-\log(1-\lvert H_3\rvert^2)$	$\boldsymbol{\alpha} = \left\{ \begin{array}{l} \bar{y}^{46}; \\ \bar{\psi}^{1,2,3}, \bar{\eta}^{2,3}, \bar{\phi}^{1,2} \end{array} \right\}$
2a)	$(4,0,0)$	$\frac{SU(1,1)}{U(1)} \otimes \frac{SU(1,1)}{U(1)}$	$-\log(1-\lvert T_1\rvert^2) - \log(1-\lvert U_1\rvert^2)$	$\boldsymbol{\alpha} = \left\{ \begin{array}{l} \bar{w}^{34}, \bar{y}^{56}; \\ \bar{\psi}^{1,2,3}, \bar{\eta}^{2}, \bar{\phi}^{1,2} \end{array} \right\}$
2b)	$(2,2,0)$	$\left(\frac{SU(1,1)}{U(1)}\right)^2$	$-\log(1-\lvert H_1\rvert^2) - \log(1-\lvert H_2\rvert^2)$	$\boldsymbol{\alpha} = \left\{ \begin{array}{l} \bar{w}^{24}, \bar{y}^{56}; \\ \bar{\psi}^{1,2,3}, \bar{\eta}^{2}, \bar{\phi}^{1,2} \end{array} \right\}$
3)	$(0,0,0)$	1 (All geometric moduli frozen)	0 (no contribution)	$\boldsymbol{\alpha} = \left\{ \begin{array}{l} \bar{y}^{1}\bar{w}^{6}, \bar{w}^{24}, \bar{y}^{35}; \\ \bar{\psi}^{1,2,3}, \bar{\phi}^{1,2} \end{array} \right\}$

Class Label	N_M	(M_1, M_2, M_3)	$(N_{\rm as}^1, N_{\rm as}^2, N_{\rm as}^3)$	$N_D \in$	Representative $\boldsymbol{A}$	Count
0)	12	$(4,4,4)$	$(2,0,0)$	$\{0,2\}$	$\{\bar{y}^{12}, \bar{w}^{12};\ \bar{\eta}^1\}$	192
0)	12	$(4,4,4)$	$(1,1,1)$	$\{1,3\}$	$\{\bar{y}^1\bar{w}^5, \bar{y}^{35}, \bar{w}^{13}\}$	256
0)	12	$(4,4,4)$	$(2,2,0)$	$\{0,2\}$	$\{y^1, w^1 \mid \bar{y}^2, \bar{y}^{34}, \bar{w}^{2,3,4};\ \bar{\eta}^2\}$	144
0)	12	$(4,4,4)$	$(2,2,2)$	$\{0,2\}$	$\{y^{1,3}, w^{1,3} \mid \bar{y}^{2,4,5,6}, \bar{w}^{2,4,5,6};\ \bar{\eta}^3\}$	32
1a)	8	$(4,4,0)$	$(0,0,0)$	$\{0,1\}$	$\{\bar{y}^{56};\ \bar{\eta}^{2,3}\}$	288
1a)	8	$(4,4,0)$	$(2,0,0)$	$\{0,1,2,3\}$	$\{\bar{y}^{12}, \bar{w}^{12}, \bar{y}^{56}\}$	576
1a)	8	$(4,4,0)$	$(1,1,0)$	$\{0,1,2,3\}$	$\{\bar{y}^{46}, \bar{w}^{24}, \bar{y}^2\bar{w}^5\}$	960
1a)	8	$(4,4,0)$	$(2,2,0)$	$\{0,1,2,3\}$	$\{y^2, y^{34}, w^{2,3,4} \mid \bar{y}^1, \bar{w}^{1,5,6}\}$	240
1b)	8	$(4,2,2)$	$(0,0,0)$	$\{0,1\}$	$\{\bar{y}^{46};\ \bar{\eta}^{2,3}\}$	576
1b)	8	$(4,2,2)$	$(0,1,0)$	$\{0,1,2\}$	$\{\bar{y}^{4,6}, \bar{w}^{3,4};\ \bar{\eta}^2\}$	576
1b)	8	$(4,2,2)$	$(1,0,0)$	$\{0,1,2\}$	$\{\bar{y}^1\bar{w}^5, \bar{w}^{1,3};\ \bar{\eta}^1\}$	576
1b)	8	$(4,2,2)$	$(0,1,1)$	$\{0,1,2,3\}$	$\{\bar{y}^{4,6}, \bar{w}^{5,6}, \bar{w}^{3,4}\}$	480
1b)	8	$(4,2,2)$	$(1,1,0)$	$\{0,1,2,3\}$	$\{\bar{y}^2\bar{w}^6, \bar{y}^{34}, \bar{w}^{23}\}$	1920
1b)	8	$(4,2,2)$	$(2,0,0)$	$\{0,1,2,3\}$	$\{y^{12}, w^{12} \mid \bar{y}^{46}\}$	576
1b)	8	$(4,2,2)$	$(1,1,1)$	$\{0,1,2,3\}$	$\{y^6, w^6 \mid \bar{y}^{2,3,4,5}, \bar{w}^{24}, \bar{w}^{5,6}\}$	768
1b)	8	$(4,2,2)$	$(2,1,0)$	$\{0,1,2,3\}$	$\{y^{1,2,4}, w^{1,2,4} \mid \bar{y}^{3,4,6}, \bar{w}^3\}$	960
1b)	8	$(4,2,2)$	$(2,1,1)$	$\{0,1,2,3\}$	$\{y^2, w^2 \mid \bar{y}^1, \bar{y}^{46}, \bar{w}^{1,3,4}, \bar{w}^{5,6}\}$	384
2a)	4	$(4,0,0)$	$(0,0,0)$	$\{0,1,2\}$	$\{\bar{y}^{3,4}, \bar{w}^{5,6};\ \bar{\eta}^3\}$	480
2a)	4	$(4,0,0)$	$(1,0,0)$	$\{0,1,2,3\}$	$\{\bar{y}^{1,4,6}, \bar{w}^{1,3,5}\}$	960
2a)	4	$(4,0,0)$	$(2,0,0)$	$\{0,1,2,3\}$	$\{y^{1,2,6}, w^{1,2,6} \mid \bar{y}^{3,4,6}, \bar{w}^5\}$	480
2b)	4	$(2,2,0)$	$(0,0,0)$	$\{0,1,2\}$	$\{\bar{w}^{24}, \bar{w}^{56}; \bar{\eta}^1\}$	1920
2b)	4	$(2,2,0)$	$(1,0,0)$	$\{0,1,2,3\}$	$\{\bar{y}^2\bar{w}^5, \bar{y}^{46}, \bar{w}^{12}\}$	3840
2b)	4	$(2,2,0)$	$(1,1,0)$	$\{0,1,2,3\}$	$\{y^{2,3,4}, w^{2,3,4} \mid \bar{y}^1, \bar{w}^4, \bar{w}^{5,6}\}$	1728
3)	0	$(0,0,0)$	$(0,0,0)$	$\{0,1,2,3\}$	$\{\bar{y}^1\bar{w}^6, \bar{w}^{24}, \bar{y}^{35}\}$	576

Table 2: *Phenomenological statistics from sample of* 10^9 *Class 0) models.*

	Total models in sample: 10^9				
	SUSY or Non-SUSY:	$\mathcal{N}=1$	Probability	$\mathcal{N}=0$	Probability
	Total	3905613	3.91×10^{-3}	996096718	0.996
(1)	+ Tachyon-Free			2073173	2.07×10^{-3}
(2)	+ No Observable Enhancements	3498607	3.50×10^{-3}	1968976	1.97×10^{-3}
(3)	+ No Enhancements	2204351	2.20×10^{-3}	1223035	1.22×10^{-3}
(4)	+ Complete Generations	285093	2.85×10^{-4}	164856	1.65×10^{-4}
(5)	+ Three Generations	26817	2.69×10^{-5}	15941	1.59×10^{-5}
(6)	+ Heavy Higgs	166	1.66×10^{-7}	15841	1.59×10^{-5}
(7)	+ TQMC	166	1.66×10^{-7}	15941	1.59×10^{-5}
(8)	+ No Chiral Exotics	87	8.7×10^{-8}	6235	6.24×10^{-6}
(9)	+ No Fermionic Exotics	41	4.1×10^{-8}	644	6.44×10^{-7}

Table 3: *Phenomenological statistics from sample of* 10^9 *Class 3) models, where we note that all models satisfy condition 9 an account of being exophobic.*

	Total models in sample: 10^9				
	SUSY or Non-SUSY:	$\mathcal{N}=1$	Probability	$\mathcal{N}=0$	Probability
	Total	31244781	3.12×10^{-2}	968755219	0.969
(1)	+ Tachyon-Free			851557918	0.852
(2)	+ No Observable Enhancements	24404805	2.44×10^{-2}	756848649	0.757
(3)	+ No Hidden Enhancements	13733548	1.37×10^{-2}	590267212	0.590
(4)	+ Complete Generations	13733548	1.37×10^{-2}	590267212	0.590
(5)	+ Three Generations	275372	2.75×10^{-4}	11683005	1.17×10^{-2}
(6)	+ Heavy Higgs	0	0	1923772	1.92×10^{-3}
(7)	+ TQMC			1923772	1.92×10^{-3}
(8)	+ Survival of $\boldsymbol{V}_i$			643232	6.43×10^{-4}
(9)	+ No Fermionic Exotics			643232	6.43×10^{-4}

Table 4: Distribution of vacuum energy values of 10^4 phenomenological $\mathcal{N} = 0$ Class 3) models, the assosiated partition function, and a representitive GGSO matrix, for completely fixed models free from all triplets.

Representitive GGSO Matrix	Partition Function	Vacuum Energy / $\mathcal{M}^4$	Frequency
$\begin{array}{c\|ccccccccc} & \mathbf{1} & \boldsymbol{S} & \boldsymbol{b_1} & \boldsymbol{b_2} & \boldsymbol{b_3} & \boldsymbol{\alpha} & \boldsymbol{\beta} & \boldsymbol{\gamma} & \boldsymbol{\delta} \\ \hline \mathbf{1} & -1 & -1 & -1 & -1 & -1 & 1 & -1 & -1 & 1 \\ \boldsymbol{S} & -1 & -1 & -1 & 1 & 1 & 1 & -1 & 1 & -1 \\ \boldsymbol{b_1} & -1 & 1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 \\ \boldsymbol{b_2} & -1 & -1 & -1 & -1 & -1 & 1 & -1 & 1 & -1 \\ \boldsymbol{b_3} & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 \\ \boldsymbol{\alpha} & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & 1 \\ \boldsymbol{\beta} & -1 & -1 & -1 & 1 & 1 & 1 & 1 & 1 & -1 \\ \boldsymbol{\gamma} & -1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \boldsymbol{\delta} & 1 & -1 & 1 & 1 & 1 & 1 & -1 & 1 & 1 \end{array}$	$Z = 296 + 2\bar{q}^{-1} + 24q\bar{q}^{-1} - 32q^{\frac{1}{2}}\bar{q}^{-\frac{1}{2}} + 3552q - 45568q^{\frac{1}{2}}\bar{q}^{\frac{1}{2}} + 10240q^{-\frac{1}{4}}\bar{q}^{\frac{3}{4}} - 20480q^{\frac{3}{4}}\bar{q}^{\frac{3}{4}} + 183168\bar{q} + 2198016q\bar{q}$	-0.0280	4,262
$\begin{array}{c\|ccccccccc} & \mathbf{1} & \boldsymbol{S} & \boldsymbol{b_1} & \boldsymbol{b_2} & \boldsymbol{b_3} & \boldsymbol{\alpha} & \boldsymbol{\beta} & \boldsymbol{\gamma} & \boldsymbol{\delta} \\ \hline \mathbf{1} & -1 & 1 & -1 & -1 & -1 & 1 & -1 & 1 & -1 \\ \boldsymbol{S} & 1 & 1 & -1 & -1 & 1 & -1 & -1 & 1 & 1 \\ \boldsymbol{b_1} & -1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 \\ \boldsymbol{b_2} & -1 & 1 & -1 & -1 & -1 & -1 & 1 & -1 & 1 \\ \boldsymbol{b_3} & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 \\ \boldsymbol{\alpha} & 1 & -1 & -1 & -1 & 1 & -1 & 1 & -1 & 1 \\ \boldsymbol{\beta} & -1 & -1 & 1 & -1 & -1 & 1 & 1 & 1 & -1 \\ \boldsymbol{\gamma} & 1 & 1 & -1 & -1 & 1 & -1 & 1 & -1 & -1 \\ \boldsymbol{\delta} & -1 & 1 & 1 & -1 & -1 & 1 & -1 & -1 & -1 \end{array}$	$Z = 296 + 2\bar{q}^{-1} + 56q\bar{q}^{-1} - 64q^{\frac{1}{2}}\bar{q}^{-\frac{1}{2}} + 3168q + 2048q^{\frac{1}{4}}\bar{q}^{\frac{1}{4}} + 128q^{-\frac{1}{2}}\bar{q}^{\frac{1}{2}} - 36864q^{\frac{1}{2}}\bar{q}^{\frac{1}{2}} + 7168q^{-\frac{1}{4}}\bar{q}^{\frac{3}{4}} - 407552q^{\frac{3}{4}}\bar{q}^{\frac{3}{4}} + 152448\bar{q} + 1667584q\bar{q}$	-0.0372	4,288
$\begin{array}{c\|ccccccccc} & \mathbf{1} & \boldsymbol{S} & \boldsymbol{b_1} & \boldsymbol{b_2} & \boldsymbol{b_3} & \boldsymbol{\alpha} & \boldsymbol{\beta} & \boldsymbol{\gamma} & \boldsymbol{\delta} \\ \hline \mathbf{1} & -1 & -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 \\ \boldsymbol{S} & -1 & -1 & -1 & 1 & 1 & 1 & 1 & 1 & 1 \\ \boldsymbol{b_1} & -1 & 1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 \\ \boldsymbol{b_2} & 1 & -1 & -1 & 1 & -1 & 1 & 1 & -1 & -1 \\ \boldsymbol{b_3} & 1 & -1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ \boldsymbol{\alpha} & 1 & 1 & -1 & 1 & -1 & -1 & 1 & 1 & -1 \\ \boldsymbol{\beta} & 1 & 1 & -1 & -1 & -1 & 1 & -1 & -1 & 1 \\ \boldsymbol{\gamma} & -1 & 1 & -1 & -1 & -1 & 1 & -1 & 1 & 1 \\ \boldsymbol{\delta} & -1 & 1 & -1 & 1 & -1 & -1 & 1 & 1 & -1 \end{array}$	$Z = -24 + 2\bar{q}^{-1} + 56q\bar{q}^{-1} - 672q + 2048q^{\frac{1}{4}}\bar{q}^{\frac{1}{4}} + 128q^{-\frac{1}{2}}\bar{q}^{\frac{1}{2}} - 24576q^{\frac{1}{2}}\bar{q}^{\frac{1}{2}} + 9216q^{-\frac{1}{4}}\bar{q}^{\frac{3}{4}} - 411648q^{\frac{3}{4}}\bar{q}^{\frac{3}{4}} + 133248\bar{q} + 1437184q\bar{q}$	0.0191	1,450

Classification of Type II asymmetric vacua

Classification of the $N=2,\ Z_2\times Z_2$ symmetric type II orbifolds

Andrea Gregori, Costas Kounnas, John Rizos, Nucl.Phys.B 549 (1999), 16-62

(AEF, Stefan Groot Nibbelink, Benjamin Percival, to appear)

Asymmetric classification ($e.g.$)

$$\begin{aligned}
1 &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \quad | \quad \bar\psi^\mu, \bar\chi^{1,\dots,6}, \bar y^{1,\dots,6}, \bar\omega^{1,\dots,6}\} \\
S &= \{\psi^\mu, \chi^{1,\dots,6}\}, \qquad \overline{S} = \{\bar\psi^\mu, \bar\chi^{1,\dots,6}\}, \\
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56}\}, \qquad \bar b_1 = \{\bar\chi^{34}, \bar\chi^{56}, \bar y^{34}, \bar y^{56}\}, \\
b_2 &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56}\}, \qquad \bar b_2 = \{\bar\chi^{12}, \bar\chi^{56}, \bar y^{12}, \bar y^{56}\},
\end{aligned}$$

New feature: SUSY enhancement from twisted sectors

In All Cases: Twisted spin $\frac{3}{2}$ fields fit into supergravity multiplets

Q: ETF limit? Interactions? Mirror symmetry? SVD?

Classification of asymmetric Standard–like model and the hidden sector

The hidden sector is relevant to BSM phenomenology

$e.g.$ Hidden sector glueball dark matter, AEF, Maxim Pospelov,

Astropart.Phys. 16 (2002) 451

Standard Model Classification

$$\{\mathbf{1}, S, z_1, z_2, e_i, b_1, b_2\} \quad \longleftrightarrow \quad SO(10) \quad + \quad \boldsymbol{\alpha}, \boldsymbol{\beta}$$

$$\boldsymbol{\alpha} = \boldsymbol{A} + \{\bar{\psi}^{123}\} + \boldsymbol{B},$$

$$\boldsymbol{\gamma} = \boldsymbol{C} + \{(\bar{\psi}^{12345}, \bar{\eta}^{123}) = \frac{1}{2}\} + \boldsymbol{D},$$

$SO(10) \longrightarrow \mathrm{SM} \quad \Rightarrow$ smaller hidden sector group factors

$$e.g.\ SU(2) \times U(1)^7$$

Fermion mass hierarchy

Fermion mass terms

$$c g f_i f_j h \left(\frac{\langle\phi\rangle}{M}\right)^{N-3}$$

c - calculable coefficients g - gauge coupling

$$f_i,\ f_j \ \in \ b_j \quad j \ = \ 1, 2, 3$$

$h \rightarrow$ light Higgs multiplets $\longleftrightarrow$ FUNDAMENTAL STATES

$$M \ \sim \ 10^{18}\, GeV$$

$\langle\phi\rangle$ generalized VEVs, several sources

Cabibbo mixing PLB 307 (1993) 305

Find anomaly free solution

$$M_d \sim \begin{pmatrix} \epsilon & \frac{V_2\bar{V}_3\Phi_{\alpha\beta}}{M^3} & 0 \\ \frac{V_2\bar{V}_3\Phi_{\alpha\beta}\xi_1}{M^4} & \frac{\bar{\Phi}_2^{-}\xi_1}{M^2} & 0 \\ 0 & 0 & \frac{\Phi_1^{+}\xi_2}{M^2} \end{pmatrix} v_2,$$

$$\epsilon < 10^{-8} \qquad \frac{V_2\bar{V}_3\Phi_{\alpha\beta}}{M^3} = \frac{\sqrt{5}\, g^6}{64\, \pi^3} \approx 2-3\times 10^{-4}.$$

$$\Rightarrow \quad |V| \sim \begin{pmatrix} 0.98 & 0.2 & 0 \\ 0.2 & 0.98 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three generation mixing $\longrightarrow$ NPB 416 (1994) 63 $\quad |J| \sim 10^{-6}$

USSC/FCC–LHC : NbTi - 10 years (10T) *versus* Nb_3Sn – ? (15T)

- Original SSC: 6T Magnets, 5cm bore; 87.1km ring; 40TeV CoM

  Decision: October 1988; Start: 1996–1999; Cost: \$ 6–11B

- Upgraded SSC: 10T magnets; 5cm bore; 91km; 50–60TeV CoM

  10 years from decision to completion $\sim$ late 2030s

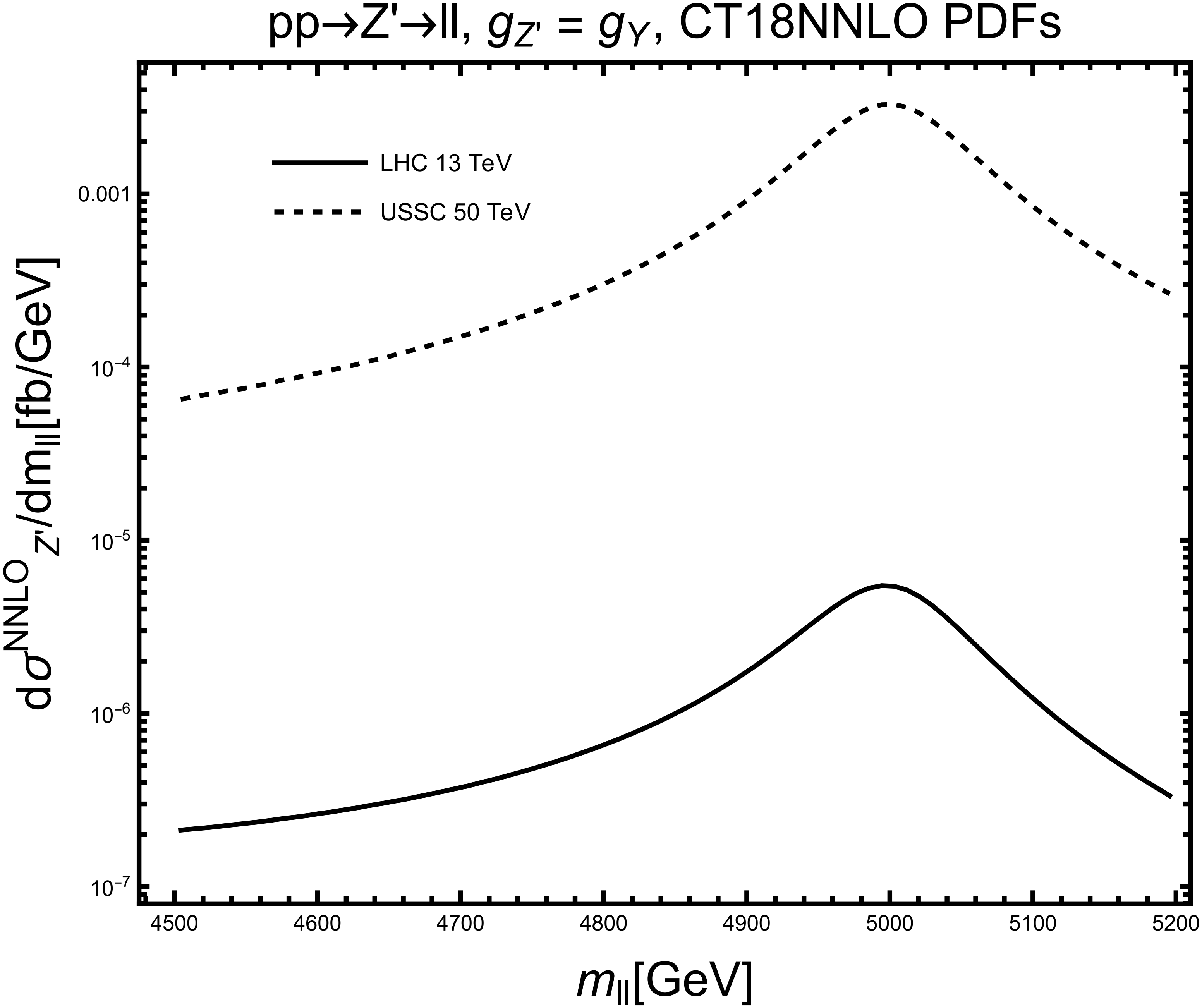
  Cost: \$ 25B; Discovery machine

- Where: Middle East SESAME facility.

  Funded by Saudi–Arabia and other interested parties.

- Under the leadership of the Arab Physical Society

  (President Shaaban Khalil)



pp→Z'→ll, $g_{Z'}$ = g_Y, CT18NNLO PDFs
LHC 13 TeV
USSC 50 TeV
0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
4500
4600
4700
4800
4900
5000
5100
5200
$d\sigma^{NNLO}_{Z'}/dm_{ll}$[fb/GeV]
m_{ll}[GeV]

Conclusions

- $Z_2 \times Z_2$ orbifolds $\longleftrightarrow$ Benchmark models for string phenomenology
- The fermionic formalism provides tools to sift through large number of models and analyse their properties, *fishing and genetic algorithms*
- The classification program mostly focused on particle physics properties and vacuum structure in non–supersymmetric configurations
- The fermionic $Z_2 \times Z_2$ orbifolds provides a playground for cosmological scenarios *e.g.* Kounnas *el al.*
- as well as other mathematical properties *e.g.* MSDS (Florakis & Kounnas); Moonshine (Gaberdiel, Taormina, Volpato, Wendland).
- Fundamental or Composite? The Higgs Enigma @ USSC/FCC–LHC

THANK YOU