String Phenomenology from a Worldsheet perspective

- Question: Ten dimensional tachyonic vacua $\rightarrow$ phenomenology ?
- Conjecture: Connectedness of $(2,0)$ and $(2,2)$ vacua

With: Kounnas, Rizos, Tsulaia, Florakis, Sonmez, Harries, Percival ...

AEF, arXiv:1906:09448.

String Phenomenology 2019, CERN, 28 July 2019

PHENOMENA

DATA $\longrightarrow$ STANDARD MODEL

EWX −> PERTUBATIVE

STANDARD MODEL −> UNIFICATION

EVIDENCE: 16 of SO(10), Log running, proton stability, neutrino masses

+ GRAVITY < −− > STRINGS

PRIMARY GUIDES:

3 generations
SO(10) embedding

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
- Generation mass hierarchy — NPB 407 (1993) 57
- CKM 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 – $\cdots$

(with Nooij, Assel, Christodoulides, Kounnas, Rizos & Sonmez)

Other approaches

Geometrical

Greene, Kirklin, Miron, Ross (1987)
Donagi, Ovrut, Pantev, Waldram (1999)
Blumenhagen, Moster, Reinbacher, Weigand (2006)
Heckman, Vafa (2008)
....

Orbifolds

Ibanez, Nilles, Quevedo (1987)
Bailin, Love, Thomas (1987)
Kobayashi, Raby, Zhang (2004)
Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter (2007)
Blaszczyk, Groot–Nibbelink, Ruehle, Trapletti, Vaudrevange (2010)
....

Other CFTs

Gepner (1987)
Schellekens, Yankielowicz (1989)
Gato–Rivera, Schellekens (2009)
....

Orientifolds

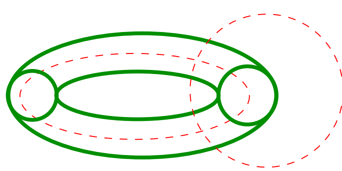
Cvetic, Shiu, Uranga (2001)
Ibanez, Marchesano, Rabadan (2001)
Kiristis, Schellekens, Tsulaia (2008)
....

Free Fermionic Construction

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

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

Old School:

The NAHE set : $\{ \mathbf{1},\ S\ ,\quad b_1\ ,\quad b_2\ ,\quad b_3\ \}$

$N = \quad 4 \quad \rightarrow \quad 2 \qquad 1 \qquad 1$ vacua

$Z_2 \times Z_2$ orbifold compactification

$\Longrightarrow$ Gauge group $SO(10) \times SO(6)^{1,2,3} \times E_8$

beyond the NAHE set Add $\{\alpha, \beta, \gamma\}$ $e.g.$ FNY model

number of generations is reduced to three

$$SO(10) \longrightarrow SU(3) \times SU(2) \times U(1)_{T_{3_R}} \times U(1)_{B-L}$$

$$U(1)_Y = \tfrac{1}{2}(B-L) + T_{3_R} \in SO(10) \; !$$

$$SO(6)^{1,2,3} \longrightarrow U(1)^{1,2,3} \times U(1)^{1,2,3}$$

Classification of fermionic $Z_2 \times Z_2$ orbifolds (Modern School)

Basis vectors:

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

$$S = \{\psi^\mu, \chi^{1,\dots,6}\},$$

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

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

$$e_i = \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6, \qquad N = 4 \text{ Vacua}$$

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

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

$$\alpha = \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\} \qquad \& \quad SO(10) \rightarrow SO(6) \times SO(4) \times \cdots$$

$$\beta = \{\bar{\psi}^{1,\cdots,5} \equiv \tfrac{1}{2}, \cdots\} \qquad \& \quad SO(10) \rightarrow SU(5) \times U(1) \times \cdots$$

Independent phases $c\left[{v_i \atop v_j}\right] = \exp[i\pi(v_i|v_j)]$: upper block

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

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

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

Starting with: $$Z^{+}_{10d} = (V_8 - S_8)\left(\overline{O}_{16} + \overline{S}_{16}\right)\left(\overline{O}_{16} + \overline{S}_{16}\right),$$

using the level–one $SO(2n)$ characters

$$O_{2n} = \frac{1}{2}\left(\frac{\theta_3^n}{\eta^n} + \frac{\theta_4^n}{\eta^n}\right), \qquad V_{2n} = \frac{1}{2}\left(\frac{\theta_3^n}{\eta^n} - \frac{\theta_4^n}{\eta^n}\right),$$

$$S_{2n} = \frac{1}{2}\left(\frac{\theta_2^n}{\eta^n} + i^{-n}\frac{\theta_1^n}{\eta^n}\right), \qquad C_{2n} = \frac{1}{2}\left(\frac{\theta_2^n}{\eta^n} - i^{-n}\frac{\theta_1^n}{\eta^n}\right).$$

where

$$\theta_3 \equiv Z_f\begin{pmatrix}0\\0\end{pmatrix} \qquad \theta_4 \equiv Z_f\begin{pmatrix}0\\1\end{pmatrix} \qquad \theta_2 \equiv Z_f\begin{pmatrix}1\\0\end{pmatrix} \qquad \theta_1 \equiv Z_f\begin{pmatrix}1\\1\end{pmatrix}$$

Apply $g = (-1)^{F+F_{z_1}+F_{z_2}}$

$$\begin{aligned} Z^{-}_{10d} = & \Big[\, V_8\left(\overline{O}_{16}\overline{O}_{16} + \overline{S}_{16}\overline{S}_{16}\right) - S_8\left(\overline{O}_{16}\overline{S}_{16} + \overline{S}_{16}\overline{O}_{16}\right) \\ + & \underline{O_8\left(\overline{C}_{16}\overline{V}_{16} + \overline{V}_{16}\overline{C}_{16}\right)} - C_8\left(\overline{C}_{16}\overline{C}_{16} + \overline{V}_{16}\overline{V}_{16}\right)\Big]. \end{aligned}$$

In fermionic language: $\{\ \mathbf{1}\ ,\ z_1\ ,\ z_2\ \}$

where $z_1 = \{\bar{\psi}^{1,\cdots,5}, \bar{\eta}^{1,2,3}\}$; $z_2 = \{\bar{\phi}^{1,\cdots,8}\}$ $\Rightarrow$ $S = \mathbf{1} + z_1 + z_2$

$c\binom{z_1}{z_2} = +1 \implies E_8 \times E_8$; $c\binom{z_1}{z_2} = -1 \implies SO(16) \times SO(16)$

non-SUSY string phenomenology

Alternatively: Apply $g = (-1)^{F+F_{z_1}}$

$$Z^{-}_{10d} = (V_8\overline{O}_{16} - S_8\overline{S}_{16} + \underline{O_8\overline{V}_{16}} - C_8\overline{C}_{16})\,(\overline{O}_{16} + \overline{S}_{16}),$$

$O_8\overline{V}_{16}\overline{O}_{16} \implies$ tachyon

In fermionic language: $\{\ \mathbf{1}\ ,\ z_2\ \}$ $\implies$ No S

A tachyon free model

$$
\begin{aligned}
1 &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} | \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\}, \\
b_1 &= \{\psi^\mu, \chi^{1,2}, y^{3,\dots,6} | \overline{y}^{3,\dots,6}, \overline{\psi}^{1,\dots,5}, \overline{\eta}^1\} \\
b_2 &= \{\psi^\mu, \chi^{3,4}, y^{1,2}, \omega^{5,6} | \overline{y}^{1,2}, \overline{\omega}^{5,6}, \overline{\psi}^{1,\dots,5}, \overline{\eta}^2\} \\
b_3 &= \{\psi^\mu, \chi^{5,6}, \omega^{1,\dots,4} | \overline{\omega}^{1,\dots,4}, \overline{\psi}^{1,\dots,5}, \overline{\eta}^3\} \\
\alpha &= \{y^{1,\dots,6}, \omega^{1,\dots,6} | \overline{\omega}^1, \overline{y}^2, \overline{\omega}^3, \overline{y}^{4,5}, \overline{\omega}^6, \overline{\psi}^{1,2,3}, \overline{\phi}^{1,\dots,4}\} \\
\beta &= \{y^2, \omega^2, y^4, \omega^4 | \overline{y}^{1,\dots,4}, \overline{\omega}^5, \overline{y}^6, \overline{\psi}^{1,2,3}, \overline{\phi}^{1,\dots,4}\} \\
\gamma &= \{y^1, \omega^1, y^5, \omega^5 | \overline{\omega}^{1,2}, \overline{y}^3, \overline{\omega}^4, \overline{y}^{5,6}, \overline{\psi}^{1,\dots,5} = \frac{1}{2}, \overline{\eta}^{1,2,3} = \frac{1}{2}, \overline{\phi}^{2,\dots,5} = \frac{1}{2}\}
\end{aligned}
\tag{1}
$$

with a suitable set of GGSO projection coefficients

Tachyon free six generation SLM model with suitable Higgs spectrum

Reduction to three generation $\longrightarrow$ S–like vector on the left

Connection with MSDS vacua in two dimensions ? (Kounnas & Florakis)

$Z_2 \times Z_2$ orbifolds

torus: One complex parameter $Z = Z + n e_1 + m e_2$

$T^2 \times T^2 \times T^2 \longrightarrow$ Three complex coordinates z_1, z_2 and z_3

Z_2 orbifold : $Z = -Z + \sum_i m_i e_i \longrightarrow$ 4 fixed points

$$Z = \{ 0 , 1/2\, e_1 , 1/2\, e_2 , 1/2\, (e_1 + e_2) \}$$

$$\frac{T^2 \times T^2 \times T^2}{Z_2 \times Z_2}$$

$\alpha : (z1 , z2 , z3) \to (-z1 , -z2 , +z3) \to 16$

$\beta : (z1 , z2 , z3) \to (+z1 , -z2 , -z3) \to 16$

$\alpha\beta : (z1 , z2 , z3) \to (-z1 , +z2 , -z3) \to 16$

48

↓

$\gamma : (z1, z2, z3) \to (z1+1/2, z2+1/2, z3+1/2) \longrightarrow 24$

Connectedness of $(2,0)$ & $(2,2)$ vacua

NAHE $\oplus$ $(z_1 = \{\bar\psi^{1,\cdots,5}, \bar\eta^1, \bar\eta^2, \bar\eta^3\} = 1)$ $\;\longrightarrow\;$ $\{1, S, z_1, z_2, b_1, b_2\}$

Gauge group: $SO(4)^3 \times E_6 \times U(1)^2 \times E_8$ and 24 generations.

toroidal compactification

$$g_{ij} = \begin{pmatrix} 2 & -1 & 0 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & 2 & -1 & -1 \\ 0 & 0 & 0 & -1 & 2 & 0 \\ 0 & 0 & 0 & -1 & 0 & 2 \end{pmatrix} \qquad b_{ij} = \begin{cases} g_{ij} & i < j \\ 0 & i = j \\ -g_{ij} & i > j \end{cases}$$

R_i $\longrightarrow$ the free fermionic point $\longrightarrow$ G.G. $SO(12) \times E_8 \times E_8$

mod out by a $Z_2 \times Z_2$ with standard embedding

$\Rightarrow$ Exact correspondence

In the realistic free fermionic models

$c\binom{z_1}{z_2} = +1 \quad \rightarrow \quad -1 \qquad \longrightarrow$ Wilson line in toroidal language

Then $\{\vec{1}, \vec{S}, \vec{z}_1, \vec{z}_2\} \rightarrow$ N=4 SUSY and

$$SO(12) \times SO(16) \times SO(16)$$

apply $b_1 \times b_2 \rightarrow Z_2 \times Z_2 \rightarrow$ N=1 SUSY and

$$SO(4)^3 \times SO(10) \times U(1)^3 \times SO(16)$$

b_1, b_2, b_3 $\Rightarrow (3 \times 8) \cdot 16$ of $SO(10)_O$

$b_1 + 2\gamma$, $b_2 + 2\gamma$, $b_3 + 2\gamma$ $\Rightarrow (3 \times 8) \cdot 16$ of $SO(16)_H$

Connectedness of $(2,0)$ & $(2,2)$ vacua

Question:

$$\frac{T^6}{Z_2 \times Z_2} \;\rightarrow\; 48 \;\text{ fixed points} \qquad\qquad \frac{SO(12)}{Z_2 \times Z_2} \;\rightarrow\; 24 \;\text{ fixed points}$$

$$Z_2 \;\text{ shift } \;: 48 \longleftrightarrow 24$$

Is this the same model? In general, no.

Starting from:

$$Z_+ = (V_8 - S_8) \left(\sum_{m,n} \Lambda_{m,n} \right)^{\otimes 6} (\bar{O}_{16} + \bar{S}_{16}) (\bar{O}_{16} + \bar{S}_{16}) \ ,$$

where as usual, for each circle,

$$p^i_{\rm L,R} = \frac{m_i}{R_i} \pm \frac{n_i R_i}{\alpha'} \, ,$$

and

$$\Lambda_{m,n} = \frac{q^{\frac{\alpha'}{4} p^2_{\rm L}} \, \bar{q}^{\frac{\alpha'}{4} p^2_{\rm R}}}{|\eta|^2} \, .$$

Add shifts : (A_1, A_1, A_1) , (A_3, A_3, A_3)

($48 \rightarrow 24$ yes)
($SO(12)$? no)

Uniquely:

$$A_2 : X_{\rm L,R} \to X_{\rm L,R} + \frac{1}{2}\left(\pi R \pm \frac{\pi\alpha'}{R}\right)$$

$$g \; : \; (A_2, A_2, 0)\,,$$

$$h \; : \; (0, A_2, A_2)\,,$$

where each A_2 acts on a complex coordinate

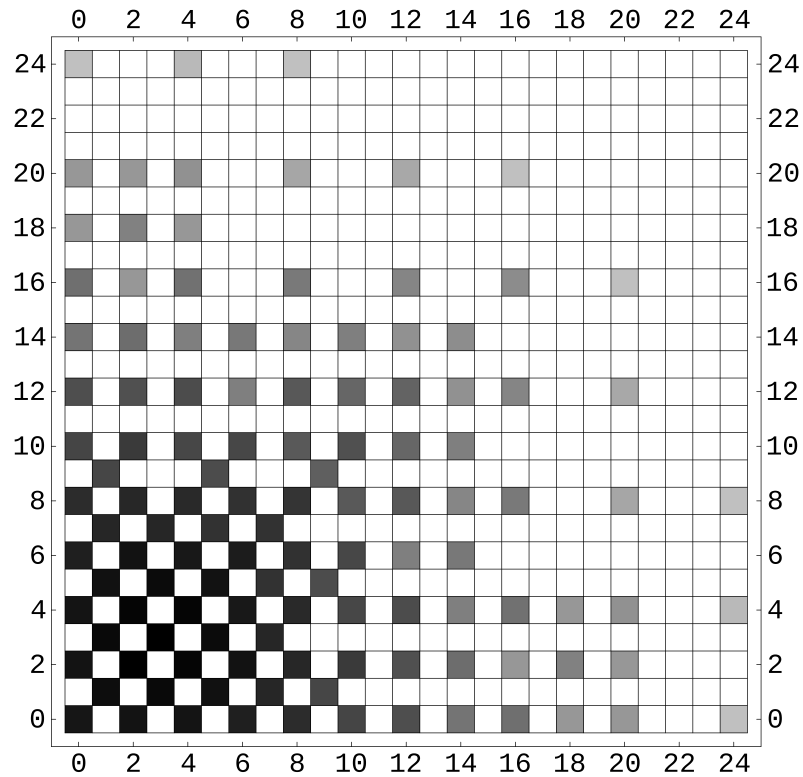
($48 \to 24$ yes)

($SO(12)$? yes)

$$R = \sqrt{\alpha'}$$

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:

Duality under exchange of spinors and vectors.

First Plane			Second plane			Third Plane			
s	$\bar{s}$	v	s	$\bar{s}$	v	s	$\bar{s}$	v	# of models
2	0	0	0	0	0	0	0	0	1325963712
0	2	0	0	0	0	0	0	0	1340075584
1	1	0	0	0	0	0	0	0	3718991872
0	0	2	0	0	0	0	0	0	6385031168

$\#$ of models with $\#(16+\overline{16})$ = $\#$ of models with $\#(10)$

Operates plane ny plane $\longrightarrow$ operates at the $N=2$ level

$N=2$ Continuous interpolation between W_1 & W_2

$N=1$ Discrete exchange of W_1 & W_2

Novel Basis

$$\begin{aligned} S &= \{\psi^\mu, \chi^{1,\dots,6}\}, \\ z_1 &= \{\bar\phi^{1,\dots,4}\}, \\ z_2 &= \{\bar\phi^{5,\dots,8}\}, \\ z_3 &= \{\bar\psi^{1,\dots,4}\}, \\ z_4 &= \{\bar\eta^{0,\dots,3}\}, \\ e_i &= \{y^i, \omega^i | \bar y^i, \bar\omega^i\}, \; i = 1, \dots, 6, \end{aligned}$$

$\bar\eta^0 \equiv \bar\psi^5$

$N = 4$ Vacua

$$\begin{aligned} 1 &= S + \sum e_i + z_1 + z_2 + z_3 + z_4 \\ b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar y^{34}, \bar y^{56}, \bar\eta^2, \bar\eta^3\}, \end{aligned}$$

$N = 4 \rightarrow N = 2$

Vector bosons: NS, $z_{1,2,3,4}$, $z_i + z_j$

NS $\leftrightarrow$ $SO(8)^4 \rightarrow SO(8) \times SO(4)^2 \times SO(8)^2$

$SO(12)$–GUT $\rightarrow$ from enhancement

Duality picture is facilitated

Spinor $\longleftrightarrow$ Vector map $\longrightarrow$ $B \longleftrightarrow B + z_4$

$SO(12)$ enhancement $\longrightarrow$ $B \longleftrightarrow B + z_3$

$z_4 \rightarrow$ right–moving spectral flow operator

The picture extends to compactifications with Interacting Internal CFT

(P. Athanasopoulos, AEF, D. Gepner, PLB 735 (2014) 357)

Conclusions

- DATA $\longrightarrow$ UNIFICATION
- STRINGS THEORY $\longrightarrow$ GAUGE & GRAVITY UNIFICATION
- STRINGS PHENOMENOLOGY $\longrightarrow$ AT ITS INFANCY

  STILL LEARNING HOW TO WALK
- 10D vacua without S–SUSY generator
- Connectedness of $(2, 0)$ & $(2, 2)$ vacua
- String Phenomenology $\longrightarrow$ Physics of the third millenium

  $e.g.$ Aristarchus to Copernicus