Classification of N=1 heterotic string vacua and towards N=0 classification

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Motivation

- String theory ought to reproduce Standard Model at low energies.
- Huge number of vacua in four dimensions.
- Classify vacua and identify general features of (quasi-)realistic vacua.
- Phenomenological requirements:
    1. $\mathcal{N} = 1$ SUSY or $\mathcal{N} = 0$
    2. $SO(10)$ GUT with 3 generations in **16** rep
    3. Higgs particles
    4. Top quark mass coupling
    5. Generation mass hierarchy, Seesaw mechanism, proton stability
    6. ...

Free Fermion Construction I

- Useful, concrete formalism for spectrum analysis from heterotic string, defined at enhanced symmetry point in moduli space.
- $D = 4 \implies$ introduction of free fermions on worldsheet:

$$\{ \underbrace{\psi^\mu}_{\text{S'partners of } X^\mu}, \underbrace{\chi^i}_{\text{S'partners to six compactified dimensions}}, \underbrace{y^i, w^i \, \| \, \bar{y}^i, \bar{w}^i}_{\text{“compactified” directions}}, \underbrace{\bar{\psi}^{1,2,3,4,5}, \bar{\eta}^{1,2,3}}_{\text{observable G. G.}}, \underbrace{\bar{\phi}^{1,2,3,4,5,6,7,8}}_{\text{rank 8 Hidden G. G.}} \} \tag{1}$$

$i = 1, ..., 6$

Free Fermion Construction II

- Model defined through:

1. Boundary Condition Basis vectors:

$$v_i = \{\alpha(f_1), \alpha(f_2), ..., \alpha(f_N)\}, \tag{2}$$

2. GGSO phases:

$$C\begin{pmatrix} v_i \\ v_j \end{pmatrix} = \pm 1 \text{ or } \pm i, \quad i > j \tag{3}$$

$2^{\frac{N(N-1)}{2} - \#\text{constraints}}$: 'ABK rules'.

- GSO projection:

$$e^{i\pi v_i \cdot F_\alpha} |S_\alpha\rangle = \delta_\alpha C\begin{pmatrix} \alpha \\ v_i \end{pmatrix}^* |S_\alpha\rangle \tag{4}$$

References:

I. Antoniadis and C. Bachas, Nuclear Physics B, 298(3):586 - 612, 1988. I. Antoniadis and C. Bachas, and C. Kounnas, Nuclear Physics B, 289(0):87 - 108, 1987.

Basis Vectors

- $SO(10)$ Basis vectors:

  $\mathbf{1} = \{\text{ALL}\}\}$ None transform

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

  $\mathbf{e_i} = \{y^i, w^i | \bar{y}^i, \bar{w}^i\}, \quad i = 1, \dots 6\}$ Internal symmetric shifts

  $$\left.\begin{array}{l}\mathbf{b_1} = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^{1}, \bar{\psi}^{1,..,5}\} \\ \mathbf{b_2} = \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^{2}, \bar{\psi}^{1,..,5}\}\end{array}\right\} \quad \mathbb{Z}_2 \text{ twists}$$

  $$\left.\begin{array}{l}\mathbf{z_1} = \{\bar{\phi}^{1234}\} \\ \mathbf{z_2} = \{\bar{\phi}^{5678}\}\end{array}\right\} \quad SO(8) \times SO(8) \text{ hidden}$$

- $SO(10) \times U(1)^3 \times SO(8) \times SO(8)$ gauge group

$SO(10)$ Subgroups

- Extra basis vector(s) needed to break $SO(10)$.
- Classification methodology applied to:
  1. $\alpha(\bar{\psi}^{1,\ldots,5}) = \{11100\} \implies SO(6) \times SO(4)$ (PS)
  2. $\alpha(\bar{\psi}^{1,\ldots,5}) = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \implies SU(5) \times U(1)$ (FSU5)
  3. $\begin{cases} \alpha(\bar{\psi}^{1,\ldots,5}) = \{11100\} \\ \beta(\bar{\psi}^{1,\ldots,5}) = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \end{cases} \implies SU(3) \times SU(2) \times U(1)^2$ (SLM)
  4. $\alpha(\bar{\psi}^{1,\ldots,5}) = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}00\} \implies SU(3) \times SU(2)^2 \times U(1)$ (LRS)
- Classify through set of numbers e.g. observables: n_{gens}, n_H and number of exotic (fractionally charged) states.

References:

arXiv:1007.2268 (PS), 1403.4107 (FSU5), 1709.08229 (SLM) and 1806.04434, 1912.04768 (LRS)

Highlights of Classification

- General result: Spinor-Vector duality: $\#(\mathbf{16}+\overline{\mathbf{16}}) \leftrightarrow \#\mathbf{10}$ (hep-th/0611251)
- PS classification found $1:10^6$ probability for 3 generation, SM Higgs present and no exotic states (exophobic) vacua
- FSU5 case: no exophobic vacua with an odd number of generations
- SLM and LRS case:
  1. Exotic sectors proliferate as two vectors break SO(10)
  2. Phenomenologically viable vacua rare

$\implies$ change methodology: **Fertility conditions** (1709.08229, 1912.04768)

Fertility Conditions and towards Non-SUSY classification

- Can look at $SO(10)$ level for phenomenological characteristics such as N_{16}, N_{10} and TQMC constraints (J. Rizos, *Eur. Phys. Jour.* **C74** (2014) 2905)
- Classify around 'fertile cores' giving high probabilities of viable vacua.
- Due to absence of SUSY signal at LHC want to explore $SO(10)$ Non-SUSY models and classify.
- Exploring cosmological constant and stability issues for Non-SUSY vacua may shed light on deep, unresolved questions

Non-Supersymmetric Classification

- $\mathcal{N} = 0$ models with $\tilde{S} = \{\psi^\mu, \chi^{1,\dots,6} \mid \bar{\phi}^{3,4,5,6}\}$ (1912.00061 explores non-tachyonic, 3 generation model and discusses stability)
- Fertility conditions: absence of tachyons, presence of chiral generations and, potentially, $n_B - n_F$ ($n_B = n_F$ 'super no-scale models' see, e.g., C. Kounnas and H. Partouche 1607.01767)
- Can probe 1-loop effective potential and explore Non-SUSY vacua with suppressed, positive cosmological constant

References:

I. Florakis and J. Rizos, Nucl. Phys. B913 (2016) 495

Thanks for listening! ☺