String Derived Exophobic $SU(6) \times SU(2)$ GUTs

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String Phenomenology 2013

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Outline

- Heterotic String Phenomenology
- Free Fermionic Construction
- Pati-Salam: $SU(4) \times SU(2) \times SU(2)$
- $SU(6) \times SU(2)$
- Future Work

Heterotic String Phenomenology

Free Fermionic Formulation

- 4D Theory
- N = 1 Supersymmetry
- 3 Generation Standard Model Fermions
- S0(10) GUTs
- Absence of exotic states

Free Fermionic Construction

Properties

- Conformally invariance
- Decoupling left and right moving modes
- D = 4 theory

Result

- $C_L = -26 + 11 + D + \frac{D}{2} + \frac{N_{f_L}}{2} = 0$

  $\Longrightarrow$ 18 left-moving real fermions
- $C_R = 0$

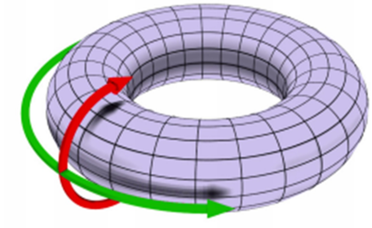
  $\Longrightarrow$ 44 right-moving real fermions

Free Fermionic Construction

- Partition function is used to include all physical states

$$Z = \sum_{\alpha,\beta} C \binom{\alpha}{\beta} Z[\alpha, \beta]$$

- Taking the one-loop partition function transforms the worldsheet into a torus.



Free Fermionic Construction

$$\alpha = \left\{ \psi^{1,2}, \chi^i, y^i, \omega^i | \bar{y}^i, \bar{\omega}^i, \bar{\psi}^{1,..,5}, \bar{\eta}^{1,2,3}, \bar{\phi}^{1,..,8} \right\}$$

- Left-movers
  - X_L^μ, $\mu = 1, 2$ 2 transverse coordinates
  - ψ_L^μ, $\mu = 1, 2$ The fermionic partners
  - Ω^i, $i = 1, .., 18$ 18 internal real fermions
- Right-movers
  - X_R^μ, $\mu = 1, 2$ 2 transverse coordinates
  - $\bar{\Omega}^i$, $i = 1, .., 44$ 44 internal real fermions

Free Fermionic Construction

- ABK Rules
  - $\sum_i m_i b_i = 0$
  - $N_{ij} \cdot b_i \cdot b_j = \text{mod } 4$
  - $N_i \cdot b_i \cdot b_i = \text{mod } 8$
  - $1 \in \Xi$
  - Even number of fermions
- One-Loop Phases
  - $C\begin{pmatrix} b_i \\ b_j \end{pmatrix} = \pm 1 \text{ or } \pm i$
- GSO Projection
  - $e^{i\pi b_i \cdot F_\alpha} |s\rangle_\alpha = \delta_\alpha C\begin{pmatrix} \alpha \\ b_i \end{pmatrix}^* |s\rangle_\alpha$
- Virasoro Condition
  - $M_L^2 = -\frac{1}{2} + \frac{\alpha_L^2}{8} + \sum v_L = -1 + \frac{\alpha_R^2}{8} + \sum v_R = M_R^2$

Pati-Salam Basis Vectors

Basis Vectors

- $v_1 \quad = 1 \quad = \{\psi^{1,2}, \chi^i, y^i, \omega^i | \bar{y}^i, \bar{\omega}^i, \bar{\psi}^{1,..,5}, \bar{\eta}^{1,2,3}, \bar{\phi}^{1,..,8}\}$
- $v_2 \quad = S \quad = \{\psi^\mu, \chi^{1,\dots,6}\}$
- $v_{2+i} = e_i \; = \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\} \qquad i = 1, \dots, 6$
- $v_9 \quad = b_1 = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}$
- $v_{10} \quad = b_2 = \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}$
- $v_{11} \quad = z_1 = \{\bar{\phi}^{1,\dots,4}\}$
- $v_{12} \quad = z_2 = \{\bar{\phi}^{5,\dots,8}\}$
- $v_{13} \quad = \alpha \; = \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\}$

Gauge Group

$$SU(4) \times SU(2)_L \times SU(2)_R \times U(1)_1 \times U(1)_2 \times U(1)_3 \times Hidden$$

Pati-Salam Enhancements

Depending on the choices of the projection coefficients, extra gauge bosons may arise. These arise with any linear combination of z_1, z_2 and α, which are massless. Such as

$$\mathbf{G} = \left\{ \begin{array}{ccccc} z_1, & z_2, & z_1 + z_2, & \alpha, & \alpha + z_1, \\ \alpha + z_2, & \alpha + z_1 + z_2, & \alpha + x, & \alpha + x + z_1, & x \end{array} \right\}$$

Where

$$x = 1 + S + \sum_{i=1}^{6} e_i + z_1 + z_2 = \{\bar{\psi}^{1,\cdots,5}, \bar{\eta}^{1,2,3}\}$$

Pati-Salam Observable Gauge Group Enhancements

$x = \{\bar{\eta}^{123}, \bar{\psi}^{12345}\}$ is the only sector which can enlarge the observable gauge group. Enhancement takes place when the following conditions are satisfied

Enhancement conditions	Resulting Enhancement
$(x\|e_i) = (x\|z_n) = 0$	$SU(4)_{obs} \times SU(2)_{L/R} \times U(1)' \to SU(6)$

The pre-stated conditions hold for all $i = 1, ..., 6$, $n = 1, 2$, and $U(1)'$ is a linear combination of the $U(1)_i$ where $i = 1, 2, 3$. In the case that any of the previous conditions is not satisfied, the enlargement of the gauge group is not possible.

$SU(6) \times SU(2)$ Gauge Group

$$SU(4) \times SU(2)_L \times SU(2)_R \times U(1)_1 \times U(1)_2 \times U(1)_3$$
$$\downarrow$$
$$SU(6) \times SU(2)_{L/R} \times U(1)_1^{'} \times U(1)_2^{'}$$

$U(1)$'s

The $U(1)$ embedded in $SU(6)$, which is anomaly free given by

$$U(1)_6 = U(1)_1 + U(1)_2 - U(1)_3$$

Additionally we have two orthogonal combinations, given by

$$U(1)_{1'} = 2U(1)_1 - U(1)_2 + U(1)_3$$
$$U(1)_{2'} = U(1)_2 + U(1)_3$$

$SU(6) \times SU(2)$ Matter States

- $SU(6) \times SU(2)$ is a maximal subgroup of E_6
- Matter states come from 27 rep of E_6
- The 27 rep of E_6 decomposed under the $SU(6) \times SU(2)$ subgroup is

$$27 = (15, 1) + (\bar{6}, 2)$$

$SU(6) \times SU(2)$ Matter State

If we choose the electroweak $SU(2)_L$ gauge group to be the one external to $SU(6)$, then the Standard Model matter and Higgs representations are embedded in

$$\mathcal{F}_L^i = (\bar{6}, 2)^i = F_L^i + \mathrm{h}^i = (Q + L + h^u + h^d)^i$$
$$\mathcal{F}_R^i = (15, 1)^i = F_R^i + \mathcal{D}^i + \mathcal{S}^i = (u + d + e + N + D + \bar{D} + \mathcal{S})^i$$

GGSO Coefficients

$$
(v_i|v_j) \quad = \quad
\begin{array}{c}
\\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ b_1 \\ b_2 \\ z_1 \\ z_2 \\ \alpha
\end{array}
\begin{array}{c}
\begin{array}{ccccccccccccc}
1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & b_1 & b_2 & z_1 & z_2 & \alpha
\end{array} \\
\left(\begin{array}{ccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 \\
1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 1
\end{array}\right)
\end{array}
$$

Where $C\binom{v_i}{v_j} = e^{i\pi(v_i|v_j)} \quad (b_i|b_j) \in \{0,1\}$

$SU(6) \times SU(2)$ Breaking

The heavy higgs is in

$$(15, 1) \text{ and } (\overline{15}, 1)$$

So we need the pair H and $\overline{H}$ to break to

$$SU(3) \times SU(2) \times U(1)_Y \times U(1)_{z'}$$

Similarly we require another pair $\mathcal{H}$ and $\overline{\mathcal{H}}$, to further break to the Standard Model.

The Superpotential

$$
\begin{aligned}
\frac{W_{SM}}{g\sqrt{2}} = \;& F_1\, F_2\, F_4 + \bar{f}_1\, \bar{f}_2\, F_4 + \bar{f}_3\, \bar{f}_4\, F_1 + \bar{f}_4\, \bar{f}_1\, F_3 + F_1\, F_1\, F_5 + F_2\, F_2\, F_5 + F_4\, F_4\, F_7 \\
& + \bar{f}_1\, f_1\, F_5 + \bar{f}_2\, \bar{f}_2\, F_6 + \bar{f}_4\, \bar{f}_4\, F_7 + F_3\, F_3\, F_6 + \bar{f}_3\, \bar{f}_3\, F_5 + f_1\, f_1\, \bar{F}_5 + \bar{F}_4\, \bar{F}_4\, \bar{F}_7 \\
& + \bar{F}_5\, F_1\, \chi_1 + \bar{F}_6\, F_2\, \chi_2 + \bar{F}_6\, F_3\, \chi_3 + \bar{F}_7\, F_4\, \chi_4 + \bar{F}_7\, \bar{F}_4\, \chi_5 + \chi_1\, \chi_2\, \chi_4 \\
& + F_5\, F_6\, F_7 + \bar{F}_5\, \bar{F}_6\, \bar{F}_7 + \Phi_{12}\, \bar{\Phi}_{34}\, \Phi_{56} + \bar{\Phi}_{12}\, \Phi_{34}\, \bar{\Phi}_{56} + \bar{F}_5\, F_6\, \bar{\Phi}_{56} + \bar{F}_5\, F_7\, \bar{\Phi}_{34} \\
& + F_5\, \bar{F}_6\, \Phi_{56} + F_5\, \bar{F}_7\, \Phi_{34} + \bar{F}_6\, F_7\, \bar{\Phi}_{12} + \bar{F}_7\, F_6\, \Phi_{12} + \frac{1}{\sqrt{2}} \{ F_1\, \bar{F}_4\, \bar{\zeta}_{11} + \bar{f}_1\, f_1\, \bar{\zeta}_{12} \} \\
& + \{ \zeta_2\, \bar{\zeta}_7 + \zeta_1\, \bar{\zeta}_8 \}\, \chi_2 + \{ \bar{\zeta}_1\, \bar{\zeta}_3 + \bar{\zeta}_2\, \bar{\zeta}_4 \}\, \chi_4 + \{ \zeta_3\, \zeta_7 + \zeta_4\, \zeta_8 \}\, \chi_1 \\
& + \bar{\zeta}_{10}\, \zeta_{11}\, \chi_1 + \zeta_1\, \zeta_{11}\, \chi_5 + \frac{1}{\sqrt{2}} \{ \zeta_1\, \bar{\zeta}_{10}\, \bar{\zeta}_{11} + \zeta_2\, \bar{\zeta}_9\, \bar{\zeta}_{11} \} \\
& + \{ \zeta_1\, \zeta_1 + \zeta_2\, \zeta_2 \}\, \bar{\Phi}_1 + \{ \bar{\zeta}_1\, \bar{\zeta}_1 + \bar{\zeta}_2\, \bar{\zeta}_2 \}\, \Phi_1 \\
& + \{ \zeta_4\, \zeta_4 + \zeta_3\, \zeta_3 + \zeta_5\, \zeta_5 + \zeta_6\, \zeta_6 + \zeta_{11}\, \zeta_{11} + \zeta_{12}\, \zeta_{12} \}\, \bar{\Phi}_2 + \{ \bar{\zeta}_3\, \bar{\zeta}_3 + \bar{\zeta}_4\, \bar{\zeta}_4 \\
& + \bar{\zeta}_6\, \bar{\zeta}_6 + \bar{\zeta}_5\, \bar{\zeta}_5 + \bar{\zeta}_{11}\, \bar{\zeta}_{11} + \bar{\zeta}_{12}\, \bar{\zeta}_{12} \}\, \Phi_2 + \{ \zeta_8\, \zeta_8 + \zeta_7\, \zeta_7 + \bar{\zeta}_{10}\, \bar{\zeta}_{10} + \bar{\zeta}_9\, \bar{\zeta}_9 \}\, \bar{\Phi}_3 \\
& + \{ \bar{\zeta}_8\, \bar{\zeta}_8 + \bar{\zeta}_7\, \bar{\zeta}_7 + \zeta_9\, \zeta_9 + \zeta_{10}\, \zeta_{10} \}\, \Phi_3 + \{ \zeta_{11}\, \bar{\zeta}_{11} + \zeta_{12}\, \bar{\zeta}_{12} \}\, \bar{\Phi}_5 \\
& + \{ H_{11}\, H_{11} + H_{21}\, H_{21} + H_{121}\, H_{121} + H_{122}\, H_{122} + Z_1\, Z_1 + Z_4\, Z_4 + Z_5\, Z_5 \}\, \bar{\Phi}_{12} \\
& + \{ H_{12}\, H_{12} + H_{22}\, H_{22} + H_{13}\, H_{13} + H_{23}\, H_{23} \}\, \bar{\Phi}_{34} + Z_1\, Z_2\, \chi_3 + \frac{1}{\sqrt{2}} Z_1\, Z_3\, \bar{\zeta}_{12} \\
& + \{ H_{125}\, H_{125} + H_{126}\, H_{126} + H_{127}\, H_{127} + H_{128}\, H_{128} + Z_2\, Z_2 \}\, \Phi_{56} \\
& + \{ H_{123}\, H_{123} + H_{124}\, H_{124} \}\, \Phi_{12} + Z_3\, Z_3\, \bar{\Phi}_{56} + \{ H_{11}\, H_{12} + H_{21}\, H_{22} \}\, \chi_5 \;.
\end{aligned}
$$

Conclusion

We found

- 3 Generation model
- Heavy and light Higgs rep to break to SM
- Existence of F- and D-flat directions that produce a fermion mass term

Future work

- $SU(5) \times U(1) \times Hidden$
- $SU(3) \times SU(2) \times U(1)^n \times Hidden$

Thank You