Exophobia, Leptophobia and Other Manias in Heterotic String Vacua

Progress Report:

- Exophobic String Vacua, NPB844 (2011) 365; PLB702 (2011) 81
- Leptophobic $U(1)$ in heterotic–string models, arXiv:1106:5422
- Spinor–Vector duality, NPB 848 (2011) 332

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DATA $\longrightarrow$ STANDARD MODEL

$SU(3) \times SU(2) \times U(1)_Y \longrightarrow SU(5) \longrightarrow SO(10)$

$$\left[\begin{pmatrix} \nu \\ e \end{pmatrix} + D^c_L \right] + \left[U^c_L + \begin{pmatrix} u \\ d \end{pmatrix} + E^c_L \right] + N^c_L$$

$$\bar{5} \quad + \quad 10 \quad\quad 1 \quad\quad \overline{} \quad 16$$

STANDARD MODEL -> UNIFICATION

ADDITIONAL EVIDENCE:

Logarithmic running, proton longevity, neutrino masses

PRIMARY GUIDES:

3 generations

SO(10) embedding

Realistic free fermionic models

'Phenomenology of the Standard Model and string unification'

- 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)
- Minimal Superstring Standard Model — PLB 455 (1999) 135 (with Cleaver & Nanopoulos)
- Moduli fixing — NPB 728 (2005) 83
- Exophobia — PLB 683 (2010) 306 (with Assel, Christodoulides, Kounnas & Rizos)

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

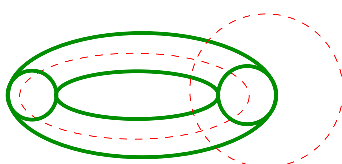
Cvetic, Shiu, Uranga (2001)
Ibanez, Marchesano, Rabadan (2001)
Kiristis, Schellekens, Tsulaia (2008)
....

Free Fermionic Construction

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

Right-Movers

$$\bar{\phi}_{A=1,\cdots,44} = \begin{cases} \bar{y}_i \ , \ \bar{\omega}_i & i = 1, \cdots, 6 \\ \\ \bar{\eta}_i & i = 1, 2, 3 \\ \bar{\psi}_{1,\cdots,5} & \\ \bar{\phi}_{1,\cdots,8} & \end{cases}$$



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

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

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

Classification of fermionic $Z_2 \times Z_2$ orbifolds

Basis vectors:

$$
\begin{aligned}
1 &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\} \\
S &= \{\psi^\mu, \chi^{1,\dots,6}\}, \\
z_1 &= \{\bar{\phi}^{1,\dots,4}\}, \\
z_2 &= \{\bar{\phi}^{5,\dots,8}\}, \\
e_i &= \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6, \qquad N = 4 \text{ Vacua}
\end{aligned}
$$

$$
\begin{aligned}
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}, \qquad N = 4 \to N = 2 \\
b_2 &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}, \qquad N = 2 \to N = 1
\end{aligned}
$$

$$
\alpha = \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\}
$$

& Gauge group $SO(6) \times SO(4) \times U(1)^3 \times \text{hidden}$

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

	1	S	e_1	e_2	e_3	e_4	e_5	e_6	z_1	z_2	b_1	b_2	α
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	$\pm$
α													

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

Pati–Salam models statistics with respect to phenomenological constraints

constraint	# of models	probability	# of models
None	100000000000	1	2.25×10^{15}
+ No gauge group enhancements.	78977078333	7.90×10^{-1}	1.78×10^{15}
+ Complete families	22497003372	2.25×10^{-1}	5.07×10^{14}
+ 3 generations	298140621	2.98×10^{-3}	6.71×10^{12}
+ PS breaking Higgs	23694017	2.37×10^{-4}	5.34×10^{11}
+ SM breaking Higgs	19191088	1.92×10^{-4}	4.32×10^{11}
+ No massless exotics	121669	1.22×10^{-6}	2.74×10^{9}

Constraints in second column act additionally.

Exotics -> fractionally charged states

Exemplary Model (Christodoulides, AEF, Rizos, PLB 702 (2011) 81)

- A specific choice of one–loop GSO phases
- Analysis of cubic level superpotential and flat directions
- Only one Yukawa coupling at cubic level -> heavy family
- All extra colour triplet -> massive
- One light Higgs bi–doublet
- Solely MSSM below PS breaking scale

Leptophobic Z' (PLB388 (1996) 524; arXiv:1106.5422 with Viraf Mehta)

CDF -> enhancement in di–jet data at $\sim 4\sigma$; D0 -> no enhancement

possible interpretation -> a leptophobic Z' -> in heterotic string?

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

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

beyond the NAHE set Add $\{\alpha, \beta, \gamma\}$ $\rightarrow$ 3 generations

$$SO(10) \longrightarrow \text{subgroup}$$

$$e.g.\ \ SU(3) \times SU(2) \times U(1)_{T_{3_R}} \times U(1)_{B-L}$$

Patterns of $SO(10)$ symmetry breaking

The $SO(10) \rightarrow$ subgroup $\quad b(\bar{\psi}^{1\cdots5}_{\frac{1}{2}})$:

1. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\ \bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \Rightarrow\ SU(5)\times U(1)\ \ U(1)\ U(1)\ U(1)$
2. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\ \bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\ 11100\ 000\ \} \Rightarrow SO(6)\times SO(4)\ U(1)\ U(1)\ U(1)$

$$(1. + 2.) \ \Rightarrow\ SO(10) \ \ \rightarrow SU(3)_C \times SU(2)_L \times U(1)_C \times U(1)_L$$

$$SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

2. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\ 11100000\ \} \Rightarrow SO(6)\times SO(4)\ U(1)\ U(1)\ U(1)$
3. $b\{\bar{\psi}^{1\cdots5}_{\frac{1}{2}}\ \bar{\eta}^1\ \bar{\eta}^2\ \bar{\eta}^3\} = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}00\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \Rightarrow$

$$SU(\ 3\ )_C \times U(1)_C \times SU(2)_L \times SU(2)_R\ U(1)\ U(1)\ U(1)$$

$U(1)$ matter charges

in cases 1. 2.

$$\Longrightarrow \qquad Q_{U(1)_j}(16 = \{Q, L, U, D, E, N\}) \;=\; +\frac{1}{2}$$

$\Longrightarrow$ the $U(1)_{1,2,3}$ are anomalous

In the LRS model of case 3.

$$\Longrightarrow \qquad Q_{U(1)_j}(Q_L, L_L) \;=\; -\frac{1}{2}$$

$$Q_{U(1)_j}(Q_R = \{U, D\}, L_R = \{E, N\}) \;=\; +\frac{1}{2}$$

$\Longrightarrow$ the $U(1)_{1,2,3}$ are anomaly free

In the LRS models

$$U(1)_{B'} = \frac{1}{3}U_C - U_1 - U_2 - U_3$$

$$Q_{B'}(L_L) \quad = \quad -\frac{1}{2} + \frac{1}{2} = \ 0 \qquad Q_{B'}(L_R) \quad = \quad +\frac{1}{2} - \frac{1}{2} = \ 0$$

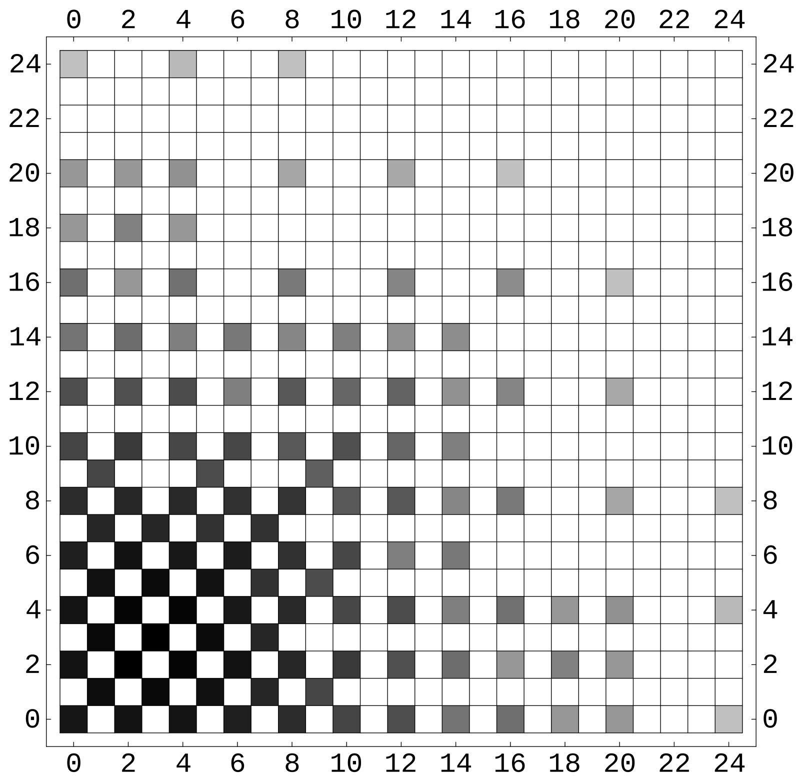
$$Q_{B'}(Q_L) \quad = \quad +\frac{1}{2} + \frac{1}{2} = +1 \qquad Q_{B'}(Q_R) \quad = \quad -\frac{1}{2} - \frac{1}{2} = -1$$

$$\longrightarrow$$

A Family Universal Anomaly Free Leptophobic $U(1)$

Spinor–vector duality:

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



Symmetric under exchange of rows and columns

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

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

Spinor–Vector duality in Orbifolds:

Using the level-one $\mathrm{SO}(2n)$ characters

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

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

where

$$\theta_3 \equiv Z_f\binom{0}{0} \quad \theta_4 \equiv Z_f\binom{0}{1}$$

$$\theta_2 \equiv Z_f\binom{1}{0} \quad \theta_1 \equiv Z_f\binom{1}{1}$$

Starting from:

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

where as usual, for each circle,

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

and

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

apply $\quad Z_2 \times Z_2' : g \times g'$

$$g \; : \; (-1)^{(F_1+F_2)}\delta$$

$$F_{1,2} \; : \; (\, \overline{O}^{1,2}_{16},\, \overline{V}^{1,2}_{16},\, \overline{S}^{1,2}_{16},\, \overline{C}^{1,2}_{16} \,) \longrightarrow (\, \overline{O}^{1,2}_{16},\, \overline{V}^{1,2}_{16},\, -\overline{S}^{1,2}_{16},\, -\overline{C}^{1,2}_{16} \,)$$

with $\quad \delta X_9 = X_9 + \pi R_9 \; ,$

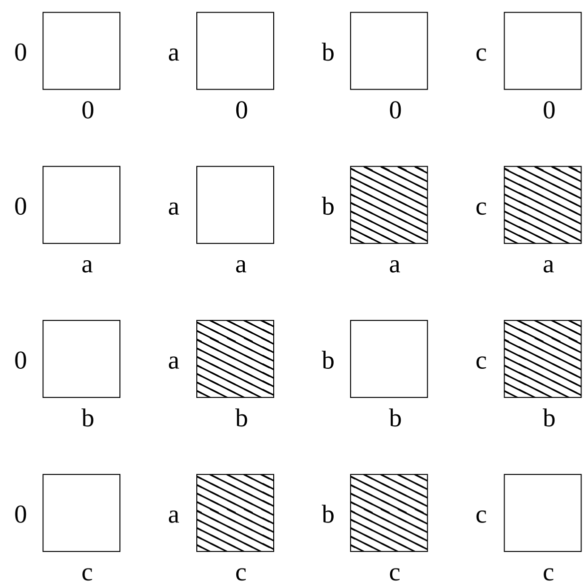
$$\delta \; : \; \Lambda^9_{m,n} \longrightarrow (-1)^m \Lambda^9_{m,n}$$

$$g' \; : \; (x_4, x_5, x_6, x_7, x_8, x_9) \longrightarrow (-x_4, -x_5, -x_6, -x_7, +x_8, +x_9)$$

Note: A single space twisting Z_2' $\quad \Rightarrow \quad N = 4 \to N = 2$

$$E_7 \to SO(12) \times SU(2)$$

$\Rightarrow$ Analyze $\quad Z = \left(\dfrac{Z_+}{Z_g \times Z_{g'}} \right) = \left[\dfrac{(1+g)}{2} \dfrac{(1+g')}{2} \right] Z_+$



a = g ; b = g' ; c = gg'

P.F. = (□ + ε ▨) = $\Lambda_{m,n}$ • ( ) + $\Lambda_{m,n+1/2}$ • ( )

ε = ± 1

massless massive

• sector b

$$\Lambda_{p,q}\left\{\frac{1}{2}\left(\left|\frac{2\eta}{\theta_4}\right|^4+\left|\frac{2\eta}{\theta_3}\right|^4\right)\left[P_\epsilon^+ Q_s \overline{V}_{12}\overline{C}_4\overline{O}_{16}+P_\epsilon^- Q_s \overline{S}_{12}\overline{O}_4\overline{O}_{16}\right]+\frac{1}{2}\left(\left|\frac{2\eta}{\theta_4}\right|^4-\left|\frac{2\eta}{\theta_3}\right|^4\right)\left[P_\epsilon^+ Q_s \overline{O}_{12}\overline{S}_4\overline{O}_{16}\right]\right\} + \text{massive}$$

where

$$P_\epsilon^+ = \left(\frac{1+\epsilon(-1)^m}{2}\right)\Lambda_{m,n} \qquad P_\epsilon^- = \left(\frac{1-\epsilon(-1)^m}{2}\right)\Lambda_{m}$$

$$\epsilon = +1 \Rightarrow P_\epsilon^+ = \Lambda_{2m,n} \qquad P_\epsilon^- = \Lambda_{2m+1,n}$$

$$\epsilon = -1 \Rightarrow P_\epsilon^+ = \Lambda_{2m+1,n} \qquad P_\epsilon^- = \Lambda_{2m,n}$$

and $12\cdot 2 + 4\cdot 2 = 32$

Further :

- The spinor–vector duality in this model is realised in terms of a continuous interpolation between two discrete Wilson lines.

- The spinor-vector duality is realised in terms of a spectral flow operator that operates in the bosonic side of the heterotic string. In the case of enhanced E_6 symmetry, the spectral flow operator acts as an internal E_6 generator. When E_6 is broken the spectral flow operator induces the spinor–vector duality map.

Conclusions

Exophobia $\longrightarrow$ existence proof. Detailed model.

Leptophobia $\longrightarrow$ CDF vs D0 $\rightarrow$ experimental issue $\rightarrow$ exclusive models

spinor–vector duality $\rightarrow$ Physics & Geometry