

Millions of Standard Models on Z'_6 ?

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Outline

Introduction

- Motivation

- Intersecting Brane Models

Setup

- Geometry

- Spectrum

Results

- General statistics

- Standard models

Conclusions

Motivation

The Landscape

- ▶ How does the landscape look like? Which models are typical, which are rare?
- ▶ Are there common features and/or correlations between the properties of different low energy models?
- ▶ How can we make predictions for particle physics experiments?

String Phenomenology

- ▶ Is it possible to build something close to the (supersymmetric) standard model from string theory?
- ▶ Many different approaches – here: [Intersecting D-branes](#).

Motivation

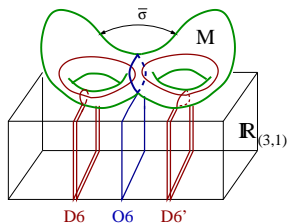
The Landscape

- ▶ How does the landscape look like? Which models are typical, which are rare?
- ▶ Are there common features and/or correlations between the properties of different low energy models?
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String Phenomenology

- ▶ Is it possible to build something close to the (supersymmetric) standard model from string theory?
- ▶ Many different approaches – here: **Intersecting D-branes**.

- ▶ Type IIA string theory on an orbifold background $\mathbb{R}^{3,1} \times T^6/(\Omega\mathcal{R} \times G)$, G being a discrete group.



- ▶ Orientifold projection \mathcal{R} leads to $O6$ -planes, wrapping 3-cycles Π_{O6} , RR charged.
- ▶ Introduce stacks of N_i $D6$ -branes wrapping cycles Π_i to cancel RR tadpoles.
- ▶ Matter arises at intersections of Π_i, Π'_i, Π_{O6} .

IBMs

Constraints

- ▶ Supersymmetry
 \rightsquigarrow Branes have to wrap calibrated cycles.
- ▶ Tadpole cancellation

$$\sum_i N_i (\Pi_i + \Pi'_i) = L \Pi_{O6}.$$

- ▶ K-theory

$$\sum_i N_i \Pi_i \circ \Pi_{Sp(2)} \equiv 0 \pmod{2}.$$

Spectrum

- ▶ Closed strings: $\mathcal{N} = 1$ sugra, axion-dilaton, $h_{1,1}^-$ Kähler + $h_{2,1}$ compl.str. moduli, $h_{1,1}^+$ vector multiplets
- ▶ Open strings: $U(N) / SO(2N) / Sp(N)$ gauge groups + charged matter

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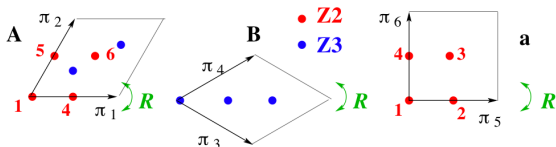
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$$T^6/\mathbb{Z}'_6$$

Geometry

- ▶ Orbifold action $\theta : z^i \rightarrow e^{2\pi i v_i} z^i$ with $v_i = \{1/6, 1/3, -1/2\}$.
- ▶ Two shapes of tori compatible with \mathcal{R} :



3-cycles

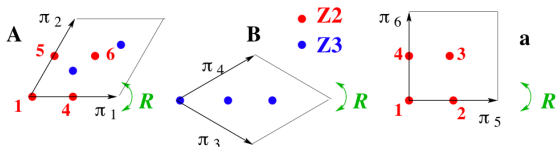
$$\Pi = \frac{1}{2} (\Pi_{torus} + \Pi_{exc}).$$

- ▶ 4-dim. basis of torus-cycles
- ▶ 8-dim. basis of cycles combined from two-cycles wrapping θ^3 fixed-points on $T_1 \times T_3$ and 1-cycles on T_2 .
- ▶ Tadpole conditions factorise, $O6$ planes contribute only to torus part.
- ▶ K-theory conditions always fulfilled - as in \mathbb{Z}_6 case.

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Spectrum

Chiral matter spectrum

(\mathbf{Anti}_a)	$\frac{1}{2}(I_{aa'} + I_{aO6})$
(\mathbf{Sym}_a)	$\frac{1}{2}(I_{aa'} - I_{aO6})$
$(\mathbf{N}_a, \overline{\mathbf{N}}_b)$	I_{ab}
$(\mathbf{N}_a, \overline{\mathbf{N}}_b)$	$I_{ab'}$

Full matter spectrum

(\mathbf{Adj}_a)	$1 + \frac{1}{4} \sum_{k=1}^{N-1} \left I_{a(\theta^k a)} + I_{a(\theta^k a)}^{\mathbb{Z}_2} \right $
(\mathbf{Anti}_a)	$\frac{1}{4} \sum_{k=0}^{N-1} \left I_{a(\theta^k a')} + I_{a(\theta^k a')}^{\mathbb{Z}_2} + I_a^{\Omega \mathcal{R} \theta^{-k}} + I_a^{\Omega \mathcal{R} \theta^{-k+N}} \right $
(\mathbf{Sym}_a)	$\frac{1}{4} \sum_{k=0}^{N-1} \left I_{a(\theta^k a')} + I_{a(\theta^k a')}^{\mathbb{Z}_2} - I_a^{\Omega \mathcal{R} \theta^{-k}} - I_a^{\Omega \mathcal{R} \theta^{-k+N}} \right $
$(\mathbf{N}_a, \overline{\mathbf{N}}_b)$	$\frac{1}{2} \sum_{k=0}^{N-1} \left I_{a(\theta^k b)} + I_{a(\theta^k b)}^{\mathbb{Z}_2} \right $
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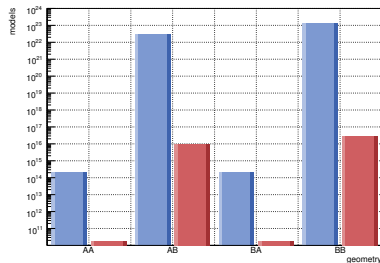
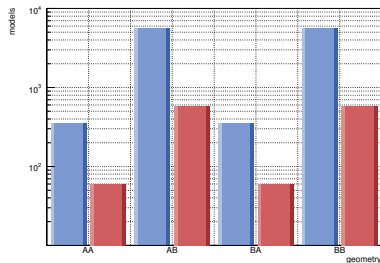
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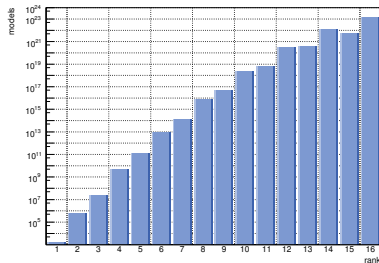
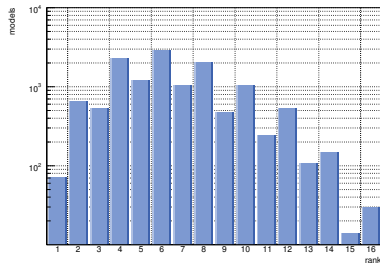
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General statistics



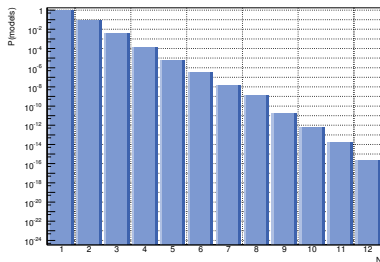
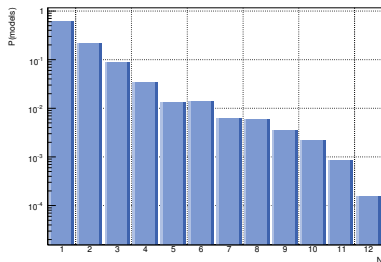
- ▶ Number of solutions to constraining equations depends on geometry.
- ▶ Inclusion of exceptional cycles increases the number solutions drastically.
- ▶ But **AA** / **BA** and **AB** / **BB** are **equivalent**.
- ▶ $\mathcal{O}(10^{23})$ inequivalent (?) solutions.

Total rank



- Distribution shows same behaviour for torus cycles as $\mathbb{Z}_2 \times \mathbb{Z}_2$.
- Exceptional cycles enhance large ranks.

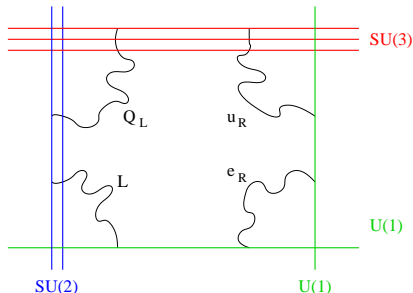
Single gauge group factors



- ▶ Distribution scales for bulk models $\sim (L + 1 - N) \frac{L^4}{N^2}$ - as found for $\mathbb{Z}_2 \times \mathbb{Z}_2$ by Douglas, Taylor.
- ▶ Inclusion of exceptional cycles gives $\sim n_e^{L+1-N} \frac{L^4}{N^2}$ - exponential fall-off.

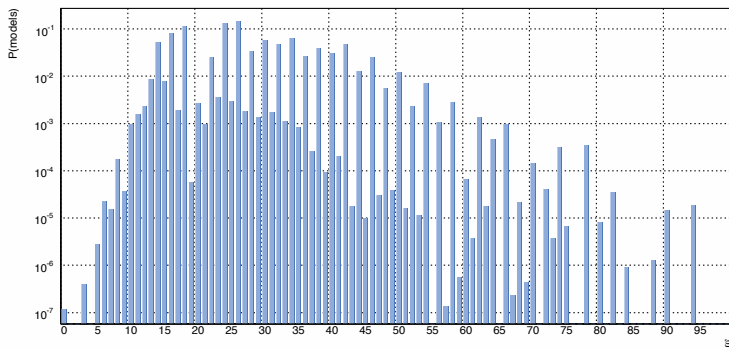
Standard models

$U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d$	
particle	n
Q_L	$\chi^{ab} + \chi^{ab'}$
u_R	$\chi^{a'c}$
d_R	$\chi^{a'c'}$
L	$\chi^{bd} + \chi^{b'd}$
e_R	$\chi^{cd'} + \chi^{\text{Sym}_d}$
$Q_Y = \frac{1}{6} Q_a + \frac{1}{2} Q_c + \frac{1}{2} Q_d$	



- ▶ Different constructions ($U(1)_Y$ assignments) have been searched for, but only these have been found.
- ▶ $\mathcal{O}(10^{15})$ three generation models.

Chiral exotics

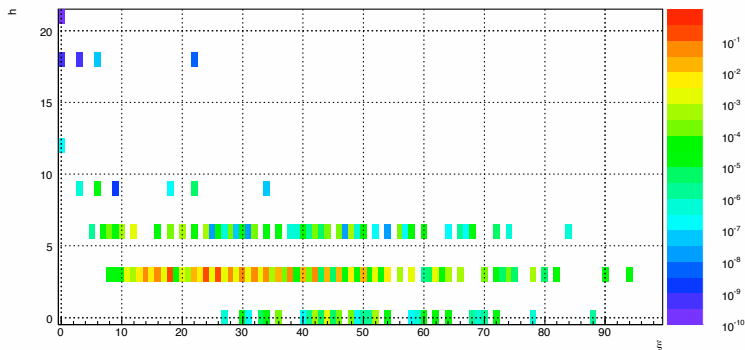


- Absolute number of chiral exotics

$$\xi = \sum_{v,h} \left| \chi^{vh} - \chi^{v'h} \right|.$$

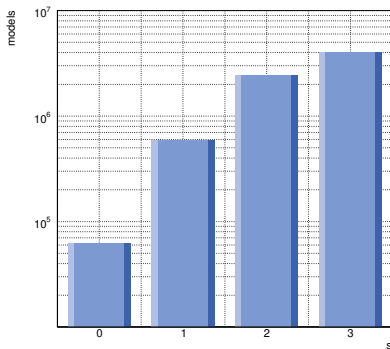
- $\mathcal{O}(10^7)$ three generation models without chiral exotics.

Higgs families



- ▶ This gives an upper limit on Higgs families, it could also be non-chiral lepton pairs (can be differentiated by B-L charge, if $U(1)_{B-L}$ is massless).
- ▶ Correlation between number of exotics and number of Higgs.
- ▶ Example with 9 ($H_u + H_d$).

Hidden sector



s	{N _i }	# models
0		61,440
1	1	147,456
	3	442,368
2	2,1	2,433,024
3	1,1,1	4,055,040

- ▶ Models without hidden sector exist with 18 or 21 Higgs families.
- ▶ All of them have a massless $B - L$, chiral spectra look identical - are these really independent models?

Example

Chiral matter

$$\begin{aligned}
 [C] &= 3 \times \left[(\mathbf{3}, \mathbf{2})_{1/6, 1/3}^{(0,0)} + (\overline{\mathbf{3}}, \mathbf{1})_{1/3, -1/3}^{(1,0)} + (\overline{\mathbf{3}}, \mathbf{1})_{-2/3, -1/3}^{(-1,0)} + (\mathbf{1}, \mathbf{1})_{1,1}^{(1,1)} + (\mathbf{1}, \mathbf{1})_{0,1}^{(-1,1)} \right. \\
 &\quad \left. + 2 \times (\mathbf{1}, \mathbf{2})_{-1/2, -1}^{(0,-1)} + (\mathbf{1}, \mathbf{2})_{1/2, 1}^{(0,1)} + 6 \times (\mathbf{1}, \overline{\mathbf{2}})_{-1/2, 0}^{(-1,0)} + 6 \times (\mathbf{1}, \overline{\mathbf{2}})_{1/2, 0}^{(1,0)} + 3 \times (\mathbf{1}, \mathbf{1}_{\overline{A}})_{0,0}^{(0,0)} \right] \\
 &\equiv 3 \times \left[Q_L + d_R + u_R + e_R + \nu_R + 2 \times L + \overline{L} \right] + 18 \times \left[H_d + H_u \right] + 9 \times S,
 \end{aligned}$$

Non-chiral matter

$$\begin{aligned}
 [V] &= 2 \times (\mathbf{8}, \mathbf{1})_{0,0}^{(0,0)} + 10 \times (\mathbf{1}, \mathbf{3})_{0,0}^{(0,0)} + 26 \times (\mathbf{1}, \mathbf{1})_{0,0}^{(0,0)} + \left[(\mathbf{3}, \mathbf{2})_{1/6, 1/3}^{(0,0)} \right. \\
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 &\quad + (9+1_m) \times (\mathbf{1}, \mathbf{3}_S)_{0,0}^{(0,0)} + 2_m \times (\mathbf{1}, \overline{\mathbf{2}})_{-1/2, 0}^{(-1,0)} + 2_m \times (\mathbf{1}, \overline{\mathbf{2}})_{1/2, 0}^{(1,0)} + 2_m \times (\mathbf{1}, \mathbf{2})_{-1/2, -1}^{(0,-1)} \\
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Remarks

- ▶ Massless $U(1)_Y$ and $U(1)_{B-L} = \frac{1}{3} U(1)_a + U(1)_d$.
- ▶ "m" reps. become massive after brane displacement.
- ▶ Since $U(1)_b$ acquires a mass absorbing a neutral closed string field, $(H_u + H_d)$, $(L + \overline{L})$ and S are vector-like.
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- ▶ Complete matter spectra are computable algebraically (chiral and **non-chiral**).
- ▶ Out of $\mathcal{O}(10^{23})$ models we found $\mathcal{O}(10^{15})$ with a sm gauge group, out of which $\mathcal{O}(10^7)$ have **no chiral exotics**.

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- ▶ It is not clear if all models are truly independent solutions or connected by further symmetries. The fact that many have identical chiral properties suggests strongly that this is the case.
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