The Landscape of Intersecting Brane Models

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Nikhef, Amsterdam

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Based on work in collaboration with Gabriele Honecker:

- *Mapping an Island in the Landscape*, JHEP 09 (2007) 128 [0708.2285].
- *Millions of Standard Models on $\mathbb{Z}_6'$?*, JHEP 07 (2008) 052 [0806.3039].
- *Complete Threshold Corrections for Intersecting Fractional D6-Branes*, [0905.xxxx].

Outline

Strings and the Real World

- One of the most important tasks of string theorists today is to make contact with particle physics.
- In particular in view of the LHC we have to try our best to explain signatures beyond the Standard model.
- Up to now there does not exist even one explicit construction that realizes the Standard Model (or one of the obvious extensions like the MSSM or simple GUTs) from a compactification of string theory.
- Many different approaches:
  - Heterotic compactifications (orbifolds, bundle constructions)
    [Nilles et al.; Ovrut et al.; Lukas et al.]
  - Gepner models
    [Gepner; Schellekens et al.]
  - Type II Intersecting Brane Models
    [Berkooz, Douglas, Leigh; Ibañez, Uranga et al.; Blumenhagen, Lüst et al.; Cvetic et al.]
  - F-theory
    [Vafa et al.]

The Landscape

- Up to now there is quite some evidence that (even after moduli stabilisation) string theory can lead to a huge[1] amount of vacua.

  [Susskind; Schellekens; Busso, Polchinski; Douglas et. al.]

- Information about the structure and actual content (of theories) of this landscape has been obtained only in particular cases (easy to calculate).

  [Dijkstra, Huiszoon, Schellekens; Blumenhagen et. al.; Dienes, Lennek; Douglas, Taylor; Honecker, FG]

- New techniques to analyse the large amount of vacua are needed, in particular a statistical approach has been advocated.

  [Denef, Douglas]

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[1] A popular number is 10^{500}, but the actual number is not even known to be finite (although there are arguments for that).

The Landscape

- String theory is unique...
  in 10 dimensions.
- Going from 10 to 4 dimensions introduces a lot of possibilities, due to "sizes" and "shapes" of the six-dimensional compact space.

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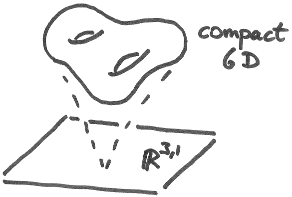

Questions

- Does the Landscape include the Standard Model?
- How does this Landscape look like? Which types of low energy effective theories are typical, which are rare?
- Are there common features and/or correlations between the properties of the low energy models?
- How can we make predictions for particle physics experiments?

Strategies

- Compute as many solutions as possible of low energy theories and look for common patterns.
- Look for correlations between properties of the low energy theories. This could even lead to predictions.
- Compare results of analyses at different “corners” of the landscape.

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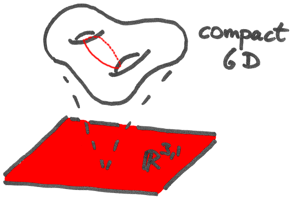
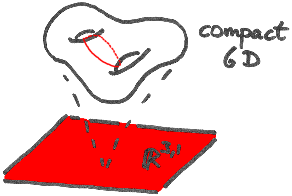
Intersecting Brane Models



- Type IIA string theory
- Use intersecting D6-branes to generate gauge groups and matter content.
- Branes fill space-time and wrap three–cycles in the internal compact space.
- Compactification on $\mathbb{R}^{3,1} \times M$ to $\mathcal{N} = 1$ supersymmetric solutions in four dimensions.
- M here toroidal orbifold T^6/G with $G = \mathbb{Z}_2 \times \mathbb{Z}_2$, $G = \mathbb{Z}_6$, $G = \mathbb{Z}'_6$.

Intersecting Brane Models



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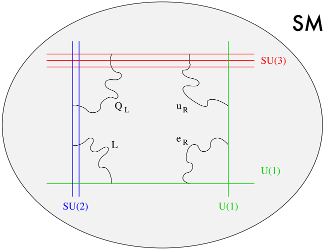
Standard model embedding

$U(3)_a \times U(2)_b/Sp(2)_b \times U(1)_c \times U(1)_d$

$U(3)_a = SU(3)_{QCD} \times U(1)_a$
$U(2)_b = SU(2)_w \times U(1)_b$
$U(1)_Y$: appropriate (massless) combination $Q_Y = \sum x_i \, Q_i$



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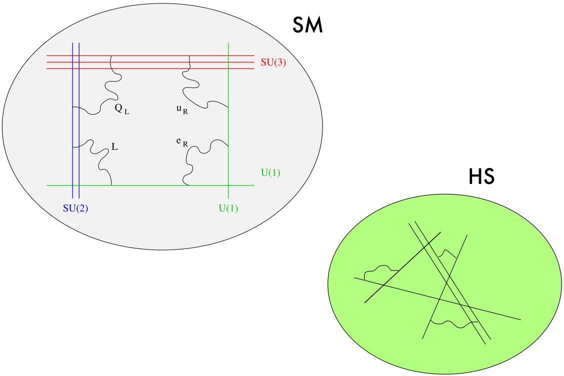

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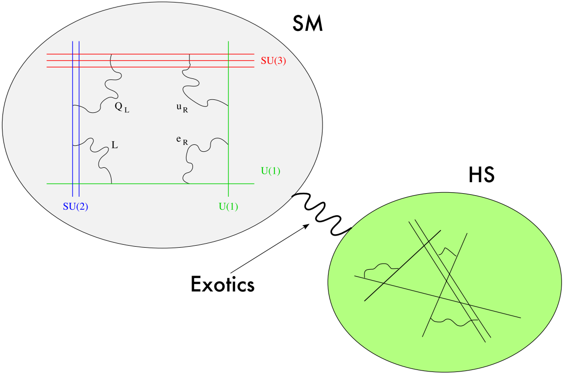

Methods to do statistics

Obtain statistical results about 4d properties in large sets of models by

- complete computation of all possible solutions (impossible) or
- choosing subsets in parameterspace, preferably completely at random. Due to computational complexity a random choice is not always possible.

Caveat

The choice of subsets (bias) could influence the result. These unwanted correlations have to be avoided.

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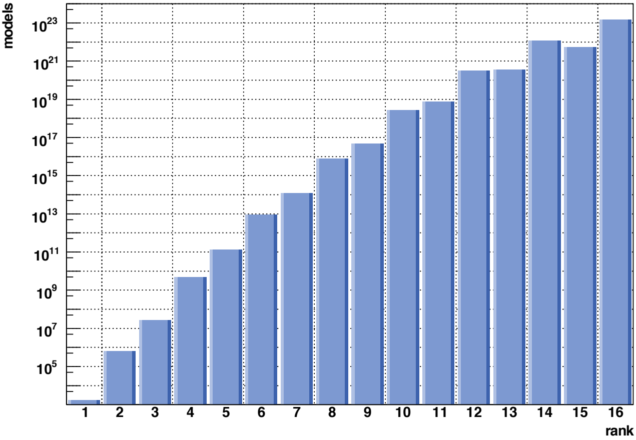

Frequency distribution of the total rank r of all models.

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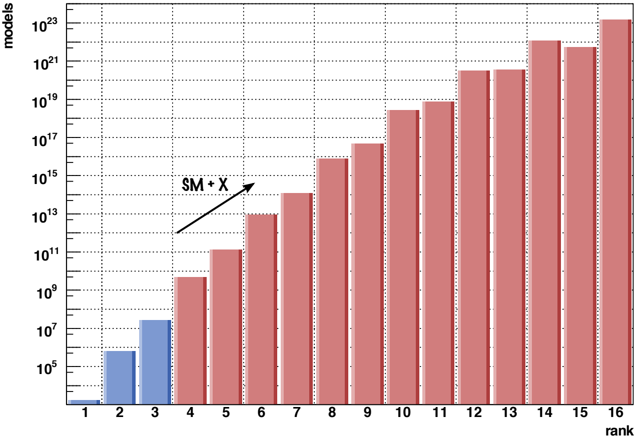

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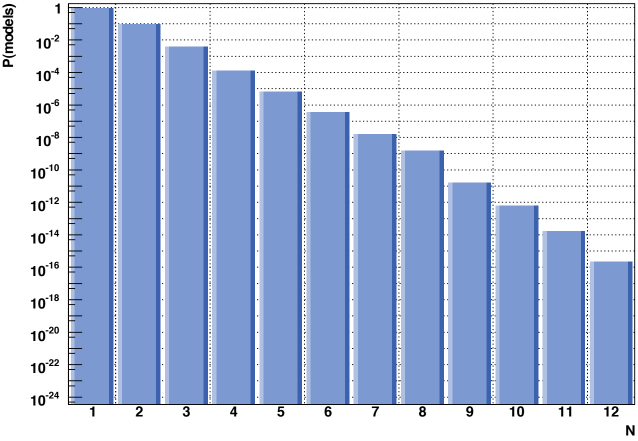
Gauge group factors



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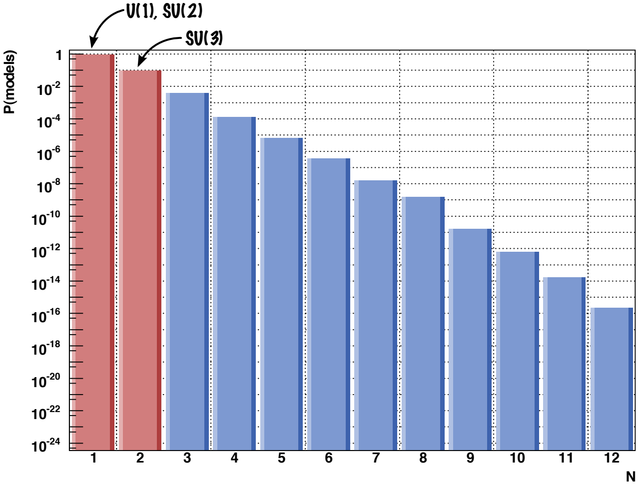
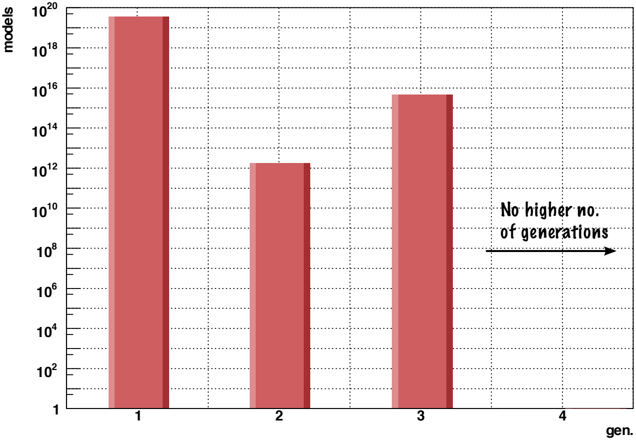


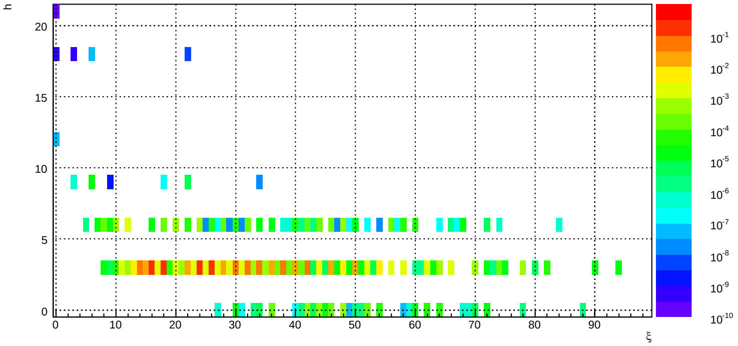
Frequency distribution of the rank of gauge group factors.

Number of generations



Frequency distribution of standard models with g generations.

Exotic matter vs. Higgs multiplets

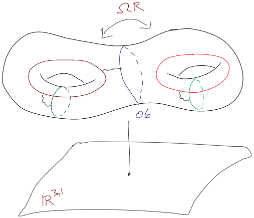


Correlation between exotic matter and Higgs multiplets.

to be continued...

IBMs, part II

- 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}.

Constraints

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

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

- K-theory

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

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: $U(N)$ / $SO(2N)$ / $Sp(2N)$ gauge groups + charged matter

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Three-cycles

- Fractional cycles on $T^6/\mathbb{Z}_{2N}$: at $\mathbb{Z}_2$ fixed points on T^4. Continuous displacement and Wilson line on the remaining T^2 is described by chiral adjoints.

$$\Pi_{frac} = \frac{1}{2}\left(\Pi_{torus} + \Pi_{exc}\right)$$

- Rigid cycles on $T^6/(\mathbb{Z}_{2N} \times \mathbb{Z}_{2M})$: no displacement, only discrete Wilson lines, no adjoints.

$$\Pi_{rigid} = \frac{1}{4}\left(\Pi_{torus} + \Pi_{exc}\right)$$

Intersection numbers

The torus part of intersection numbers between two branes on $T^6/\mathbb{Z}_{2N}$ can be split into contributions from orientifold images:

$$\Pi^a_{torus} \circ \Pi^b_{torus} = 2 \sum_{k=0}^{N-1} I^{a(\theta^k b)}.$$

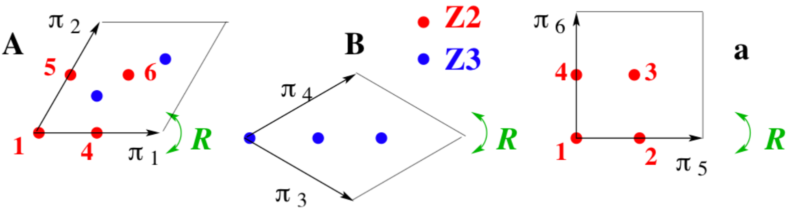
The $\mathbb{Z}_2$ invariant intersections of the exceptional branes are given by

$$\Pi^a_{exc} \circ \Pi^b_{exc} = 2 \sum_{k=0}^{N-1} I^{a(\theta^k b)}_{\mathbb{Z}_2}.$$

This allows to write down the full spectrum, including non-chiral matter.

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

- 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

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

- 4-dim. basis of torus-cycles:

$$\rho_1 = \sum_{k=0}^{5} \theta^k \pi_{135}, \ \rho_2 = \sum_{k=0}^{5} \theta^k \pi_{235}, \ \rho_3 = \sum_{k=0}^{5} \theta^k \pi_{136}, \ \rho_4 = \sum_{k=0}^{5} \theta^k \pi_{236},$$

which allows to expand

$$\Pi_{torus} = P\rho_1 + Q\rho_2 + U\rho_3 + V\rho_4.$$

3-cycles

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

- 8-dim. basis of exceptional cycles combined from two-cycles wrapping θ^3 fixed-points on $T_1 \times T_3$ and 1-cycles on T_2:

$$\delta_j = \sum_{k=0}^{2} \theta^k (e_{4j} \otimes \pi_3), \quad \tilde{\delta}_j = \sum_{k=2}^{2} \theta^k (e_{4j} \otimes \pi_4),$$

so a generic exceptional cycle is given by

$$\Pi_{exc} = \sum_{j=1}^{4} \left(d_j \delta_j + e_j \tilde{\delta}_j\right).$$

Tadpole conditions

- The conditions for torus and exceptional cyles factorise.
- The $O6$ planes contribute only to the torus part, which is geometry dependend. For **ABa** e.g.

$$\sum_a N_a \left(P_a + Q_a\right) = 8, \quad \sum_a N_a \left(U_a - V_a\right) = 24.$$

- All branes contribute $\geq 0 \rightsquigarrow$ finiteness of solutions.
- Exceptional part amounts to algebraic equations for d_a and e_a coefficients of all exceptional branes.

Supersymmetry conditions

- Toroidal part

$$\frac{R_1}{\sqrt{3}R_2}(P-Q)-(U+V)=0, \quad (P+Q)-\frac{R_2}{\sqrt{3}R_1}(V-U)>0.$$

- Exceptional part gives restriction on $\mathbb{Z}_2$ eigenvalues and Wilson lines on $T_1 \times T_3$.

K-theory conditions

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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

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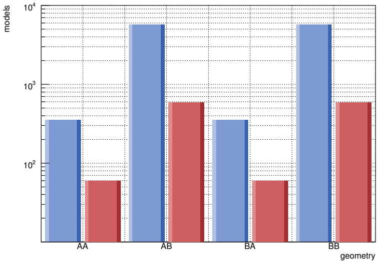
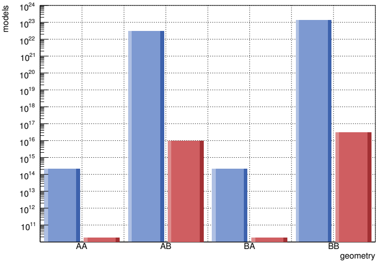
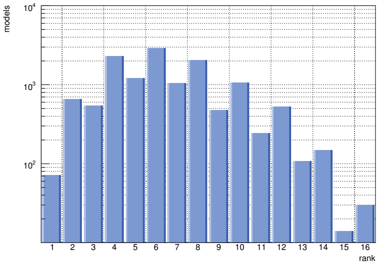
General statistics

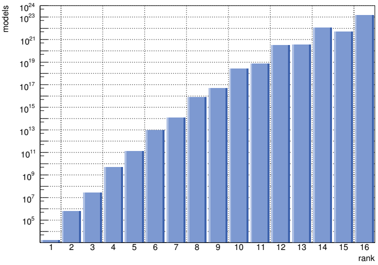




- Number of solutions to constraining equations depends on torus shapes (first two tori on horizontal axis, third torus color-coded: blue/red $= \mathbf{a}/\mathbf{b}$).
- Inclusion of exceptional cycles increases the number solutions exponentially – as in $\mathbb{Z}_6$ case.
- $\mathbf{AA}$ / $\mathbf{BA}$ and $\mathbf{AB}$ / $\mathbf{BB}$ are equivalent.
- $\mathcal{O}(10^{23})$ inequivalent (?) solutions.

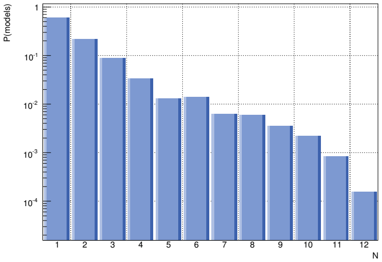
Total rank

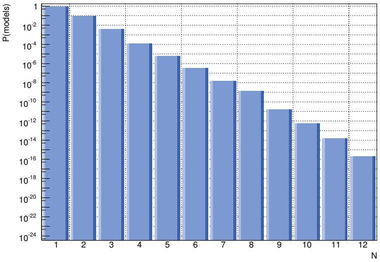




- Distribution shows same behaviour for torus cycles as $\mathbb{Z}_2 \times \mathbb{Z}_2$ – can be fitted to a Gaussian with maximum at $\approx \sum L_i/2$.
- Exceptional cycles enhance large ranks – due to the fact that large rank $\sim$ large number of branes – exponential enhancement.

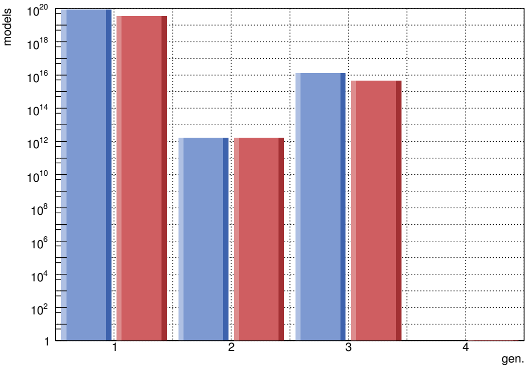
Single gauge group factors





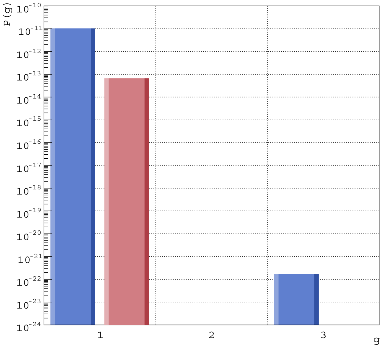
- Distribution scales for bulk models $\sim (L+1-N)\frac{L^4}{N^2}$ - as found for $\mathbb{Z}_2 \times \mathbb{Z}_2$ by Douglas, Taylor.
- Inclusion of exceptional cycles gives $\sim n_e^{L+1-N}\frac{L^4}{N^2}$ - exponential fall-off.

Standard models



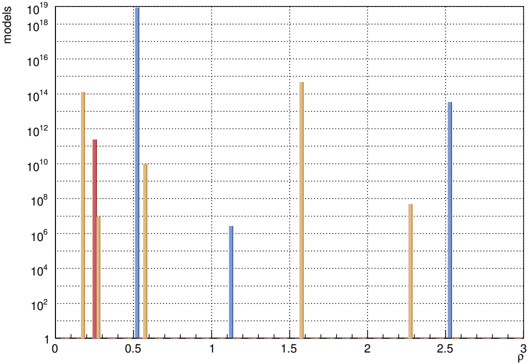
- Blue/red bars: massive/massless hypercharge.

Standard models



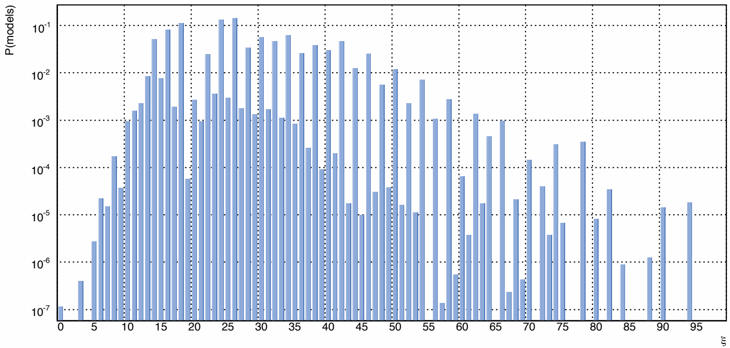
- Comparison with $\mathbb{Z}_6$: two- and three-generation models with massless hypercharge exist.
- Fundamentally different spectra.

Complex structure dependence



- Complex structure paramter: $\rho = \frac{\sqrt{3}R_2}{2R_1}$.
- One/two/three generation models = blue/red/yellow.

Chiral exotics

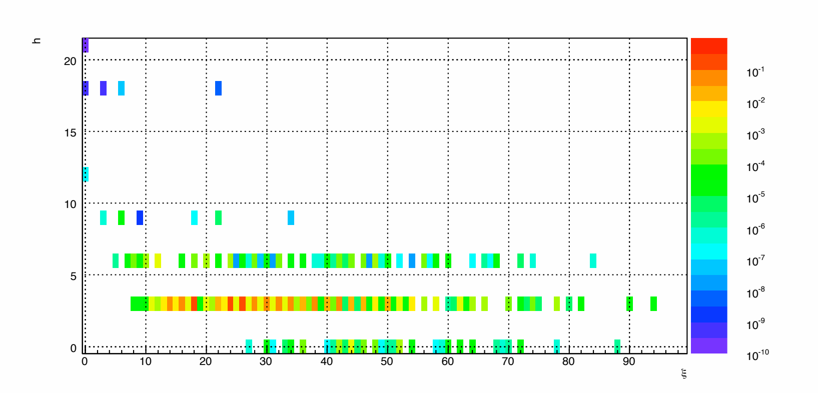


- Absolute number of chiral exotics

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

- $\mathcal{O}(10^7)$ 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 $(H_u + H_d)$.

Gauge couplings

The coupling g_a for a gauge group factor G_a at $\mu < M_{string}$ is given by

$$\frac{8\pi^2}{g_a^2(\mu)} = \frac{8\pi^2}{g_{a,\mathrm{string}}^2} + \frac{b_a}{2} \ln\left(\frac{M_{\mathrm{string}}^2}{\mu^2}\right) + \frac{\Delta_a}{2}.$$

Contributions:

- Tree level ($\kappa_a = 1$ for $SU(N)$, 2 for $SO/Sp(2N)$)

$$\frac{1}{\alpha_{a,\mathrm{string}}} = \frac{4\pi}{g_{a,\mathrm{string}}^2} = \frac{M_{\mathrm{Planck}}}{2\sqrt{2}\kappa_a M_{\mathrm{string}}} \frac{V_a}{\sqrt{V_6}},$$

At the orbifold point the volumes of the exceptional cycles are zero, so only toroidal contribution: $V_a = c\, L_1^a \cdot L_2^a \cdot L_3^a$.

Running

Due to massless string modes charged under $G_a = SU(N_a)$ is encoded in the beta function coefficient b_a with

$$b_{SU(N_a)} = -N_a \left(3 - \varphi^{\mathbf{Adj}_a}\right) + \sum_{b \neq a} \frac{N_b}{2} \left(\varphi^{ab} + \varphi^{ab'}\right) + \frac{N_a - 2}{2}\, \varphi^{\mathbf{Anti}_a} + \frac{N_a + 2}{2}\, \varphi^{\mathbf{Sym}_a}.$$

Threshold corrections

- Δ_a due to charged massive string modes.
- Can be computed using the background field method: Computation of one-loop vacuum energy of a string quantized in magnetic background B. The thresholds can then be obtained from B^2-term in expansion.
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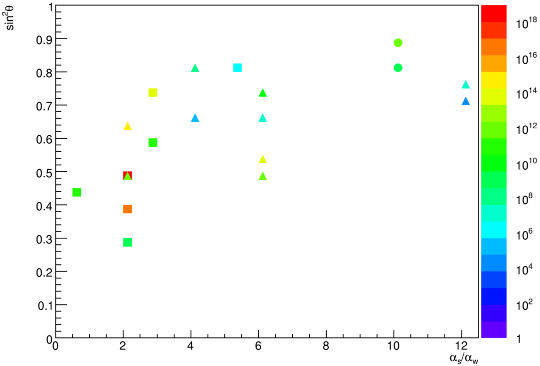
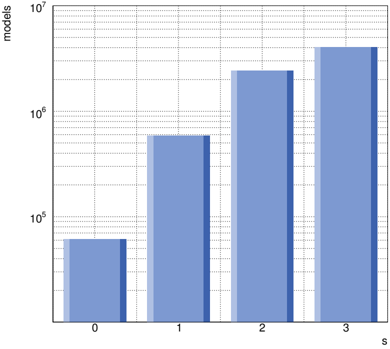
Gauge couplings



- Tree level coupling ratios α_s/α_w independent of scales.
- Very few different cases occur, always $\alpha_s \neq \alpha_w$.

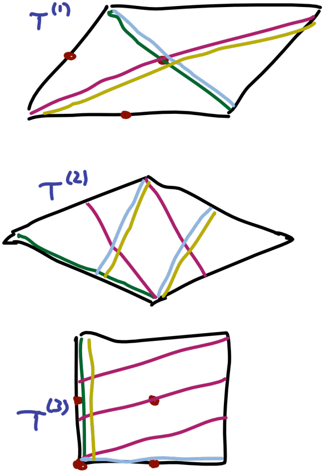
Hidden sector

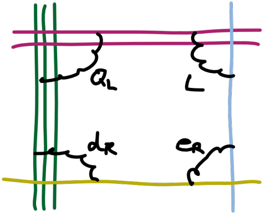


s	$\{N_i\}$	# models
0		61,440
1	1	147,456
	3	442,368
2	2,1	2,433,024
3	1,1,1	4,055,040

- 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





$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}\left(U(1)_b + U(1)_d\right)$$

Geometric setup of example model with MSSM spectrum.

Example

Chiral matter

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

Non-chiral matter

$$
\begin{aligned}
[V] = {} & 2 \times (\mathbf{8},\mathbf{1})^{(0,0)}_{\mathbf{0},\mathbf{0}} + 10 \times (\mathbf{1},\mathbf{3})^{(0,0)}_{\mathbf{0},\mathbf{0}} + 26 \times (\mathbf{1},\mathbf{1})^{(0,0)}_{\mathbf{0},\mathbf{0}} + \Big[(\mathbf{3},\mathbf{2})^{(0,0)}_{\mathbf{1/6},\mathbf{1/3}} \\
& + 3 \times (\overline{\mathbf{3}},\mathbf{1})^{(0,1)}_{\mathbf{1/3},\mathbf{2/3}} + 3 \times (\overline{\mathbf{3}},\mathbf{1})^{(0,-1)}_{\mathbf{-2/3},\mathbf{-4/3}} + (3 - x + 1_m) \times (\mathbf{1},\mathbf{1})^{(2,0)}_{\mathbf{1},\mathbf{0}} + (1 + 2_m) \times (\overline{\mathbf{3}}_A,\mathbf{1})^{(0,0)}_{\mathbf{1/3},\mathbf{2/3}} \\
& + (9 + 1_m) \times (\mathbf{1},\mathbf{3}_S)^{(0,0)}_{\mathbf{0},\mathbf{0}} + 2_m \times (\mathbf{1},\overline{\mathbf{2}})^{(-1,0)}_{\mathbf{-1/2},\mathbf{0}} + 2_m \times (\mathbf{1},\overline{\mathbf{2}})^{(1,0)}_{\mathbf{1/2},\mathbf{0}} + 2_m \times (\mathbf{1},\mathbf{2})^{(0,-1)}_{\mathbf{-1/2},\mathbf{-1}} \\
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\end{aligned}
$$

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 $U(1)_b$ aquires a mass absorbing a neutral closed string field, $(H_u + H_d)$, $(L + \bar{L})$ and S are vector-like.
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Observables for correlations

Number of bifundamental representations

$$\Delta^{\pm} := \#(\mathbf{N}_a, \overline{\mathbf{N}}_b) \pm \#(\mathbf{N}_a, \mathbf{N}_b)$$

and number of (Anti-)Symmetric representations $\chi^{Sym/Anti}$ for different constructions.

Choice of samples

Different strategies to obtain statistical results are used:

- $T^6/\mathbb{Z}_2\times\mathbb{Z}_2$ ($\mathcal{O}(10^{10})$ models): explicit cutoff in the parameter space.
- $T^6/\mathbb{Z}_6$ ($\mathcal{O}(10^{28})$) and $T^6/\mathbb{Z}_6'$ ($\mathcal{O}(10^{23})$ models): random samples of different sizes.
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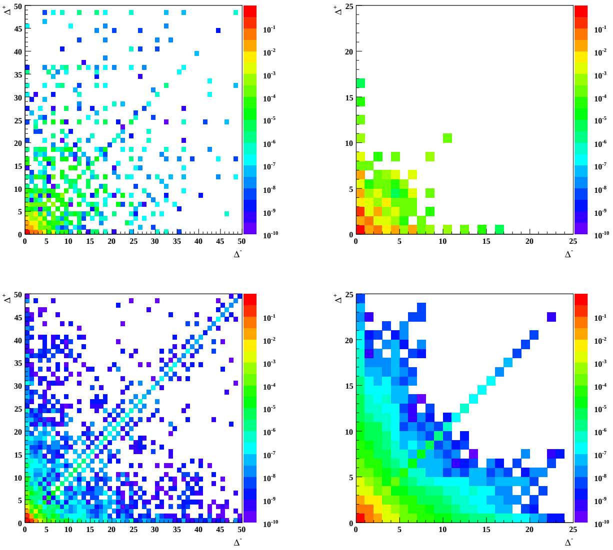
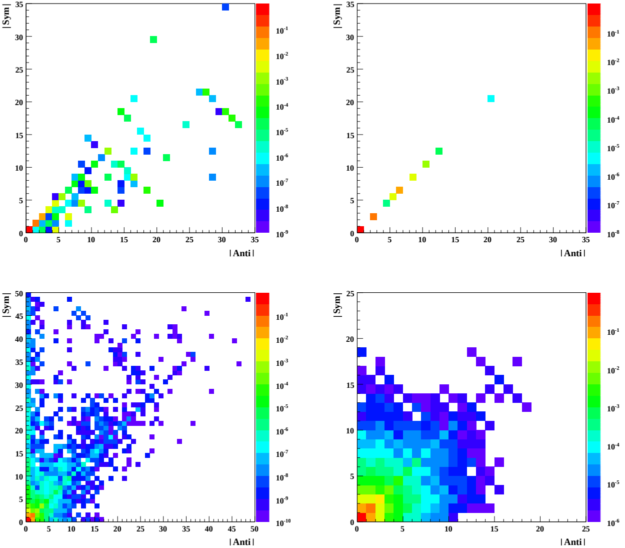
Δ^+ vs Δ^-



Correlation between number of bifundamental matter representations on.
Top left to down right: $T^6/\mathbb{Z}_2\times\mathbb{Z}_2$, $T^6/\mathbb{Z}_6$, $T^6/\mathbb{Z}_6'$, Gepner models.

χ^{Sym} vs. χ^{Anti}



Correlation between number of symmetric and antisymmetric representations.
Top left to down right: $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$, $T^6/\mathbb{Z}_6$, $T^6/\mathbb{Z}_6'$, Gepner models.

Conclusions

- Within this (very limited) study an explicit realisation of just the MSSM is very unlikely.
- Including a hidden sector (interesting for susy breaking) allows for MSSM constructions, however all with large number of Higgs multiplets.
- Many unsolved issues: Complete moduli stabilization, SUSY breaking, Yukawa couplings, ...
- Statistically three generations are less likely than one - exponential falloff in the number of generations that has also been observed in other constructions..
- Correlations in the matter content and couplings do occur, but how generic these are is unclear - better comparison to other constructions is needed.