A Zip-code for Quarks, Leptons and Higgs Bosons

Paul-Konstantin Oehlmann

In collaboration with D. K. Mayorga and H. P. Nilles
Based on arXiv:1209.6041; arXiv:1305.0566

Planck 2013

May, 22, 2013

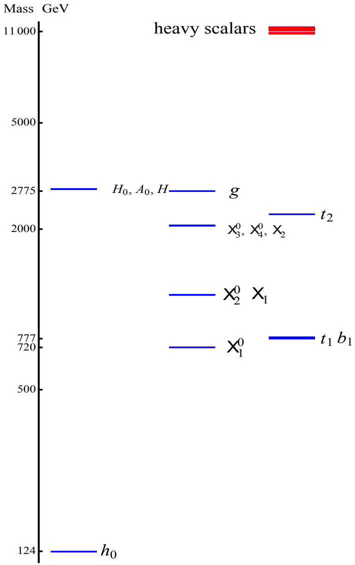
The $\mathbb{Z}_{6-\text{II}}$ Mini-Landscape

$\sim$ 200 realistic MSSM models based on the $\mathbb{Z}_{6-\text{II}}$ orbifold geometry have been constructed in computer based searches [Lebedev, Nilles, Raby, Ratz, *et al* '06]

Main features

1. The Higgs system
   - Higgs doublets are untwisted (Gauge-Higgs-Unification) [Fairlie, *et al*'79]
   - Shift symmetry in Kähler potential solves vacuum instability [Hebecker, *et al*'12]
   - μ-term forbidden by R-Symmetry [e.g. Raby, Ratz, Ross, Vaudrevange *et al*'11]
2. The Top-Quark
   - Top-Quark is untwisted with tree level Higgs Yukawa coupling
     $\hookrightarrow$ Gauge-Top-Unification [Hosteins, Kappl, Ratz, Schmidt-Hoberger *et al*'07]
   - Third family is a patchwork, completed by fields from different locations.
3. The light families
   - Twisted fields localized at fixed points
   - Form a complete **16** of SO(10)

SUSY Breaking Pattern



Dilaton stabilization needs:

1. Hidden sector gaugino condensation, favored [Lebedev *et al* '07]
2. Down-lifting of vacuum energy

$\Rightarrow m_{3/2}$ in multi-TeV range

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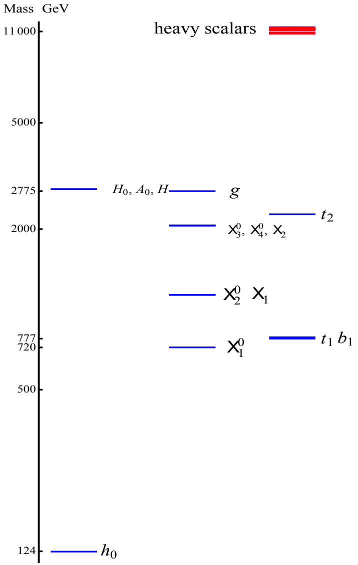

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$\Rightarrow m_{3/2}$ in multi-TeV range

- Fields at Fixed Points feel only $\mathcal{N} = 1$ SUSY
  $\rightarrow$ Scalar masses $\sim m_{3/2}$
- Fields in Bulk and Fixed Tori feel remnants of $\mathcal{N} = 4, 2$ SUSY
  $\rightarrow$ Superpartner masses suppressed by
  $\log(M_{\rm Pl}/m_{3/2})$

$\rightarrow$ **Natural SUSY** [Krippendorf *et al* '12]

Motivation

- How general are these results?
- What can be expected in different geometries?

A Zip-code for Quarks, Leptons and Higgs Bosons

Outline:

1. $\mathbb{Z}_2 \times \mathbb{Z}_4$ Orbifold Geometry
2. $\mathbb{Z}_2 \times \mathbb{Z}_4$ Phenomenology and Examples
3. Conclusion

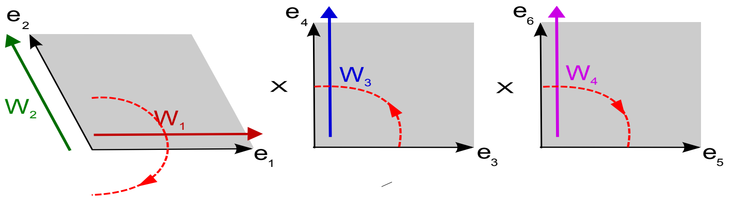
$\mathbb{Z}_2 \times \mathbb{Z}_4$ Geometry

Orbifold identification under twist $\theta(k_1, k_2)$

$$\theta(k_1, k_2) = \text{Diag}(e^{2\pi i\,(k_1 v_2^i + k_2 w^i)})$$

Geometric Definitions

- Choose factorizable lattice $SU(2)^2 \times SO(4) \times SO(4)$
- Choose the shifts $v_2 = (0, \frac{1}{2}, -\frac{1}{2}, 0) \quad v_4 = (0, 0, \frac{1}{4}, -\frac{1}{4})$
  - 8 sectors: $T_{(k_1,k_2)}$ $k_1 = 0, 1$ and $k_2 = 0, , 3$
  - 4 Wilson lines of order two: W_1, W_2, W_3, W_4



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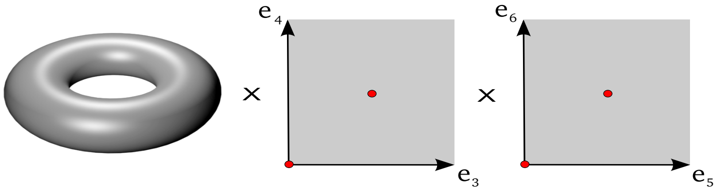
Twisted Sectors

- $T_{(0,1)}/T_{(0,3)}$ Twisted sector
  - 4 Fixed Tori



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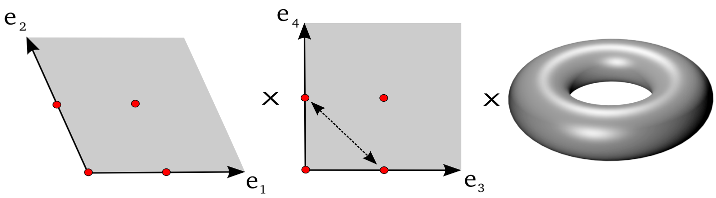
Twisted Sectors

- $T_{(1,0)}$ Twisted Sector
  - $\boxed{12} = 8 + 4$ Fixed Tori
  - $\mathbb{Z}_4$ identification: Gauge enhancement at special fixed tori
  - Broken degeneracy without Wilson lines



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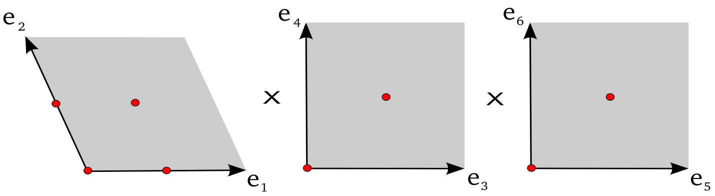
Twisted Sectors

- $T_{(1,1)} / T_{(1,3)}$ Twisted Sector
  - $\boxed{16}$ Fixed Points
  - Fixed points, high flexibility in breaking the degeneracy via Wilson lines



The Gauge Embedding

Modular invariance of the one-loop partition function
$\hookrightarrow$ Embedding of space group twist as translation in gauge lattice $\Lambda_{E_8 \times E_8}$

Construction of inequivalent Embeddings

Quotienting the automorphism group out of $\Lambda_{E_8 \times E_8}$, we classified all

$$144 \quad (61 \text{ in } \mathbb{Z}_{6-\text{II}})$$

inequivalent models and their brother model

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Gauge Spectrum

- 35 embeddings with SO(10) gauge factors (13 in $\mathbb{Z}_{6-\text{II}}$)
- 26 embeddings with E_6 gauge factors (16 in $\mathbb{Z}_{6-\text{II}}$)
- 25 embeddings with $SU(5)$ gauge factors (4 in $\mathbb{Z}_{6-\text{II}}$)
  $\hookrightarrow$ Seems more fertile for Model building

Phenomenological Input and Constraints

Goal: Want to judge the fertility of this geometry and find preferred field localizations

Focus on SO(10) breaking via Wilson lines to SM

1. Renormalizable Top-Yukawa from $\mathbf{16} \cdot \mathbf{16} \cdot \mathbf{10}$
2. Achieve doublet-triplet splitting via Wilson lines
3. Break the fixed point degeneracy via Wilson lines
   $\hookrightarrow$ Get three families as complete as possible

Which models are compatible with those constraints?

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   String selection rules constrain field locations
2. Achieve doublet-triplet splitting via Wilson lines
   Constraints Higgs location to be Wilson line affected
3. Break the fixed point degeneracy via Wilson lines
   $\hookrightarrow$ Get three families as complete as possible
   Fixes Wilson configuration and family locations

Which models are compatible with those constraints?

Example Model

Given by shifts

$$V_2 = (1, -\tfrac{1}{2}, 0, 0, 0, -\tfrac{1}{2}, 0, 0)(\tfrac{5}{4}, -\tfrac{1}{4}, \tfrac{3}{4}, \tfrac{3}{4}, \tfrac{3}{4}, \tfrac{3}{4}, -\tfrac{1}{4}, \tfrac{1}{4})$$
$$V_4 = (\tfrac{1}{2}, 0, 0, 0, 0, 0, 0, 0)(\tfrac{5}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, \tfrac{1}{2}, -\tfrac{1}{2})$$

Leading to $SO(10) \times SU(2) \times SU(2) \times SU(8) \times U(1)^2$ with spectrum

U	1 $(\mathbf{16}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{0,-1}$
	1 $(\mathbf{16}, \mathbf{1}, \mathbf{2}, \mathbf{1})_{0,1}$
	1 $(\mathbf{10}, \mathbf{2}, \mathbf{2}, \mathbf{1})_{0,0}$
	1 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-12,0}$
	1 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{12,0}$
	1 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{28})_{6,0}$
	1 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \overline{\mathbf{28}})_{6,0}$

$T(0,1)$	4 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{8})_{6,1}$
	4 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \overline{\mathbf{8}})_{0,1}$
$T(0,2)$	10 $(\mathbf{1}, \mathbf{2}, \mathbf{2}, \mathbf{1})_{6,0}$
	10 $(\mathbf{10}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-6,0}$
	6 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-6,-2}$
	6 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-6,2}$

$T(0,3)$	4 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \overline{\mathbf{8}})_{6,-1}$
	4 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{8})_{0,-1}$
$T(1,0)$	4 $(\mathbf{1}, \mathbf{1}, \mathbf{2}, \mathbf{8})_{-3,0}$
$T(1,1)$	Empty
$T(1,2)$	4 $(\mathbf{1}, \mathbf{2}, \mathbf{1}, \overline{\mathbf{8}})_{-3,0}$
$T(1,3)$	16 $(\mathbf{16}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{3,0}$
	16 $(\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{3,1}$
	16 $(\mathbf{1}, \mathbf{1}, \mathbf{2}, \mathbf{1})_{3,-1}$

Example Model

Given by shifts

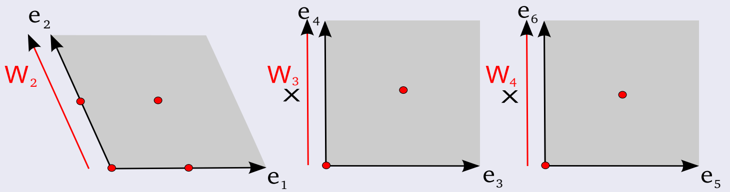
$$V_2 = (1, -\tfrac{1}{2}, 0, 0, 0, -\tfrac{1}{2}, 0, 0)(\tfrac{5}{4}, -\tfrac{1}{4}, \tfrac{3}{4}, \tfrac{3}{4}, \tfrac{3}{4}, \tfrac{3}{4}, -\tfrac{1}{4}, \tfrac{1}{4})$$
$$V_4 = (\tfrac{1}{2}, 0, 0, 0, 0, 0, 0, 0)(\tfrac{5}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, \tfrac{1}{2}, -\tfrac{1}{2})$$

and Wilson lines

$$W_2 = (-\tfrac{1}{2}, \tfrac{1}{2}, -\tfrac{3}{2}, -\tfrac{1}{2}, 0, -1, -1, 2)(-\tfrac{3}{4}, -\tfrac{7}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, \tfrac{7}{4}, \tfrac{3}{4}, \tfrac{3}{4})$$
$$W_3 = (-1, \tfrac{3}{2}, -\tfrac{1}{2}, \tfrac{1}{2}, 0, \tfrac{1}{2}, 0, 2)(-\tfrac{1}{2}, 1, -2, 0, \tfrac{3}{2}, -1, -\tfrac{3}{2}, -\tfrac{3}{2})$$
$$W_4 = (-\tfrac{5}{4}, \tfrac{5}{4}, \tfrac{1}{4}, -\tfrac{1}{4}, \tfrac{3}{4}, -\tfrac{1}{4}, \tfrac{5}{4}, \tfrac{9}{4})(0, 1, 1, 2, -1, -\tfrac{1}{2}, 2, \tfrac{3}{2})$$

Wilson line breaking

$$SO(10) \times SU(2) \times SU(2) \times SU(8) \times U(1)^2 \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(3) \times SU(2) \times U(1)^9$$



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Break the degeneracy

Lower the degeneracy by factor of 8

Two local **16**-plets unaffected

$\rightarrow$ Two light families

$T(0,3)$	$4\ (\mathbf{1},\mathbf{1},\mathbf{1},\bar{\mathbf{8}})_{6,-1}$ $4\ (\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{8})_{0,-1}$
$T(1,0)$	$4\ (\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{8})_{-3,0}$
$T(1,1)$	Empty
$T(1,2)$	$4\ (\mathbf{1},\mathbf{2},\mathbf{1},\bar{\mathbf{8}})_{-3,0}$
$T(1,3)$	$16(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{3,0}$ $16\ (\mathbf{1},\mathbf{2},\mathbf{1},\mathbf{1})_{3,1}$ $16\ (\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1})_{3,-1}$

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Project out unwanted tripletts

U	1 $(\mathbf{16}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{0,-1}$
	1 $(\mathbf{16}, \mathbf{1}, \mathbf{2}, \mathbf{1})_{0,1}$
	1 $(\mathbf{10}, \mathbf{2}, \mathbf{2}, \mathbf{1})_{0,0}$
	1 $(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-12,0}$
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$$(\mathbf{16}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{0,-1} \rightarrow (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-1,\dots} + \underbrace{(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{1/3,\dots}}_{\overline{u}}$$
$$(\mathbf{16}, \mathbf{1}, \mathbf{2}, \mathbf{1})_{0,1} \rightarrow \underbrace{(\mathbf{3}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{-1/6,\dots}}_{Q}$$
$$(\mathbf{10}, \mathbf{2}, \mathbf{2}, \mathbf{1})_{0,0} \rightarrow \underbrace{(\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{-1/2,\dots}}_{H_u} + \underbrace{(\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{1/2,\dots}}_{H_d}$$

Example Model

Yukawa Couplings

U	$1\ (\mathbf{16},\mathbf{2},\mathbf{1},\mathbf{1})_{0,-1}$
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	$1\ (\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{28})_{6,0}$
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Trilinear Top-Yukawa:

$\hookrightarrow (\mathbf{10},\mathbf{2},\mathbf{2},\mathbf{1}) \cdot (\mathbf{16},\mathbf{1},\mathbf{2},\mathbf{1}) \cdot (\mathbf{16},\mathbf{2},\mathbf{1},\mathbf{1}) \xrightarrow{W_2, W_3, W_4} H_u Q \overline{U}$

Vector-like Higgs pair protected by R-Symmetry:

$\hookrightarrow (\mathbf{10},\mathbf{2},\mathbf{2},\mathbf{1}) \cdot (\mathbf{10},\mathbf{2},\mathbf{2},\mathbf{1}) \xrightarrow{W_2, W_3, W_4} H_u H_d$

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Specific Model Details

- Net MSSM spectrum
- Non-Anomalous Hypercharge
- One unique pair of Higgs doublets
- All MSSM Exotics are vector-like
- Find realistic VEV configuration hard

The General Story

The Higgs System

1. Untwisted Higgs seems favored due to high flexibility to couple trilinearly
2. Same solution for μ-problem as in the $\mathbb{Z}_{6-\mathrm{II}}$ orbifold due to $\mathbb{Z}_2$ twist

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The Three Families

1. Models with three all local **16**-plets, NOT incompatible with heavy top
2. Models with 2 local **16**-plets favored
3. A Heavy Top Quarks suggests its location in bulk as well.

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Properties of Untwisted Sector crucial ingredient

Untwisted sectors with these features are frequent: $\sim$ 75% of all embeddings

Conclusion

We investigated the MSSM matter properties found in the $\mathbb{Z}_{6-\mathrm{II}}$ and extended them to $\mathbb{Z}_2 \times \mathbb{Z}_4$

What we did

- Considered the factorisable $\mathbb{Z}_2 \times \mathbb{Z}_4$ geometry
- Constructed all gauge embeddings
- Strategy to construct good models

Our findings

The $\mathbb{Z}_2 \times \mathbb{Z}_4$ confirms the picture of the $\mathbb{Z}_{6-\mathrm{II}}$ Mini-Landscape

- Higgs and Top Quark are favorably untwisted fields
- $\mathbb{Z}_2$ twist induces a vector-like Higgs pair, μ-term absent by its R-Symmetry
- Light families originating from localized **16**-plets

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Thank you!

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Example Model: Full Spectrum

$$SU(3)_C \times SU(2)_L \times U(1)_Y \underbrace{\times SU(3) \times SU(2) \times U(1)^9}_{Hidden}$$

#	Rep.	label	#	Rep.	label
3	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{\frac{2}{3}}$	$\overline{u}$	69	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_0$	n
3	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-1}$	$\overline{e}$	32	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-\frac{1}{2}}$	r
3	$(\mathbf{3}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{-\frac{1}{6}}$	q	4	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$	b
4	$(\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{\frac{1}{2}}$	l	30	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{\frac{1}{2}}$	$\overline{r}$
1	$(\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{1})_{-\frac{1}{2}}$	$\overline{l}$	4	$(\mathbf{1}, \mathbf{1}, \overline{\mathbf{3}}, \mathbf{1})_0$	s
9	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-\frac{1}{3}}$	$\overline{d}$	10	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2})_0$	$\tilde{v}$
6	$(\mathbf{3}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{\frac{1}{3}}$	d	8	$(\mathbf{1}, \mathbf{1}, \mathbf{3}, \mathbf{1})_0$	$\overline{s}$
6	$(\mathbf{3}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-\frac{1}{6}}$	f	2	$(\mathbf{1}, \mathbf{1}, \overline{\mathbf{3}}, \mathbf{1})_{\frac{1}{2}}$	χ
8	$(\mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{1})_0$	v	5	$(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2})_{\frac{1}{2}}$	$\overline{b}$
1	$(\mathbf{3}, \mathbf{1}, \mathbf{1}, \mathbf{2})_{-\frac{1}{6}}$	m	2	$(\mathbf{1}, \mathbf{1}, \overline{\mathbf{3}}, \mathbf{1})_{-\frac{1}{2}}$	$\tilde{\chi}$
8	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{\frac{1}{6}}$	$\overline{f}$			