From Strings to the MSSM

Based on collaborations with:


Reviews:

H.P. Nilles, S. Ramos-Sánchez, M.R., P. Vaudrevange, “From Strings to the MSSM” (to appear)
MSSM gauge coupling unification @ $M_{\text{GUT}} \sim 10^{16} \text{ GeV}$
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One generation of observed matter fits into 16 of $SO(10)$

\[
SO(10) \rightarrow SU(3) \times SU(2) \times U(1)_Y = G_{\text{SM}} \\
16 \rightarrow (3, 2)_{1/6} \oplus (\bar{3}, 1)_{-2/3} \oplus (\bar{3}, 1)_{1/3} \\
\quad \oplus (1, 1)_{1} \oplus (1, 2)_{-1/2} \oplus (1, 1)_{0}
\]
MSSM gauge coupling unification @ $M_{\text{GUT}} \sim 10^{16}$ GeV

One generation of observed matter fits into $\mathbf{16}$ of $\text{SO}(10)$

However: Higgs only as doublet(s)

$$\mathbf{10} \to (\mathbf{1}, \mathbf{2})_{1/2} \oplus (\mathbf{1}, \mathbf{2})_{-1/2} \oplus (\mathbf{3}, \mathbf{1})_{-1/3} \oplus (\overline{\mathbf{3}}, \mathbf{1})_{1/3}$$

Doublets: needed

Triplets: excluded
MSSM gauge coupling unification @ $M_{\text{GUT}} \sim 10^{16} \text{ GeV}$

One generation of observed matter fits into $16$ of $\text{SO}(10)$

However: Higgs only as doublet(s)

Matter in complete multiplets

Higgs in split multiplets

convincing answer: ‘localized gauge groups’
Local grand unification (a specific realization)

**SO(10)**

16

$\mathbf{16}$


$\mathbf{E}_8 \times \mathbf{E}_8$

standard model
as an intersection of
$\text{SO}(10)$, $G'$ .

in $\mathbf{E}_8 \times \mathbf{E}_8$

'low-energy' effective theory

**Higgs doublets:**

live in the 'bulk'

**(2) SM generation(s):**

localized in region with
$\text{SO}(10)$ symmetry
Higher-dimensional GUTs vs. heterotic orbifolds

**top-down**
→ Orbifold compactifications of the heterotic string

- Dixon, Harvey, Vafa, Witten (1985-86)
- Ibáñez, Nilles, Quevedo (1987)
- Ibáñez, Kim, Nilles, Quevedo (1987)
- Font, Ibáñez, Nilles, Quevedo (1988)
- Font, Ibáñez, Quevedo, Sierra (1990)
- Katsuki, Kawamura, Kobayashi, Ohtsubo, Ono, Tanioka (1990)

- has UV completion
- automatically consistent
- explain representations

**bottom-up**
→ Orbifold GUTs

- Kawamura (1999-2001)
- Altarelli, Feruglio (2001)
- Hall, Nomura (2001)
- Hebecker, March-Russell (2001)
- Asaka, Buchmüller, Covi (2001)
- Hall, Nomura, Okui, Smith (2001)
- ... 

- simple geometrical interpretation
- shares many features with 4D GUTs

**combine both approaches**

- implement field-theoretic GUTs in non-prime orbifold compactifications of the heterotic string

- Faraggi, Förste, Tuminagziu (2006)
- Kim, Kyae (2006)
- ...
Orbifolds & Wilson lines

Motivation

‘Local grand unification’

Ibáñez, Nilles, Quevedo (1986)
Orbifolds & Wilson lines

Ibáñez, Nilles, Quevedo (1986)
Orbifolds & Wilson lines

G_{local} \rightarrow G_{bulk} \rightarrow G_{local}

Ibáñez, Nilles, Quevedo (1986)
We focus on the $\mathbb{Z}_6$-II orbifold based on the (factorizable) Lie-lattice $G_2 \times SU(3) \times SO(4)$.
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There are 2 shifts that produced local $SO(10)$ groups with localized $16$-plets

\[ V^{SO(10),1} = \frac{1}{6} (3, 3, 2, 0, 0, 0, 0, 0) (2, 0, 0, 0, 0, 0, 0, 0) \]
\[ V^{SO(10),2} = \frac{1}{6} (2, 2, 2, 0, 0, 0, 0, 0) (1, 1, 0, 0, 0, 0, 0, 0) \]

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There are 2 shifts that produced local SO(10) groups with localized $16$-plets

Another very promising geometry is $\mathbb{Z}_{12}$-I

cf. talk by B. Kyae
100 MSSMs from heterotic orbifolds
Orbifold compactification with local SO(10) GUT

Cartoon of heterotic orbifold compactification with local SO(10) GUT structures

4D space-time
Orbifold compactification with local SO(10) GUT

Cartoon of heterotic orbifold compactification with local SO(10) GUT structures
Orbifold compactification with local SO(10) GUT

Cartoon of heterotic orbifold compactification with local SO(10) GUT structures

4D space-time

internal space

16

SO(10)
Construction of orbifold models: summary

10D theory

\( E_8 \times E_8 \)

specify:
- geometry
- gauge embedding

get:
- spectrum
- interactions

note: couplings are moduli-dependent
No-Go for three sequential families

**simplest implementation:** three ‘sequential’ 16-plets

Only possible in $\mathbb{Z}_3 \times \mathbb{Z}_2$

e tc. but not in $\mathbb{Z}_3$, $\mathbb{Z}_4$, $\mathbb{Z}_2 \times \mathbb{Z}_2$ etc.
simplest implementation: three ‘sequential’ 16-plets

Only possible in $\mathbb{Z}_3 \times \mathbb{Z}_2$ etc. but not in $\mathbb{Z}_3$, $\mathbb{Z}_4$, $\mathbb{Z}_2 \times \mathbb{Z}_2$ etc.

however: in all $\mathbb{Z}_3 \times \mathbb{Z}_2$ models there are chiral exotics (at least when hypercharge is correctly normalized)
No-Go for three sequential families

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- **however**: in all $\mathbb{Z}_3 \times \mathbb{Z}_2$ models there are chiral exotics (at least when hypercharge is correctly normalized)

**bottom-line**

not possible in $\mathbb{Z}_{N \leq 8}$ orbifolds
2+1 family models

We focus on models with the **Features:**

- Two families come from two equivalent fixed points
- 3rd family has to come from ‘somewhere else’ (untwisted sector, $T_{k>1}$)
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**Note:** this structure has been obtained in the context of string-derived Pati-Salam models

2+1 family models

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☞ 3rd family has to come from ‘somewhere else’ (untwisted sector, $T_{k>1}$)

☞ Note: this structure has been obtained in the context of string-derived Pati-Salam models

☞ This talk: discuss MSSM models with this structure


We construct $3 \times 10^4$ inequivalent models
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Out of those 218 have the chiral MSSM spectrum with $G_{SM} \subset SU(5) \subset SO(10)$ (such that hypercharge is in GUT normalization)
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The models have vector-like exotics which can, however, get large masses.
A Mini-Landscape of MSSM models


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☞ models publically available

http://www.th.physik.uni-bonn.de/nilles/Z6IIorbifold/
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What are their common properties?
Hidden sector strong dynamics

Supersymmetry breakdown through non-perturbative effects

e.g. gaugino condensation

Witten (1981)
Nilles (1982)
Ferrara, Girardello & Nilles (1983)
Derendinger, Ibáñez & Nilles (1985)
Dine, Rohm, Seiberg & Witten (1985)
Hidden sector strong dynamics

- Supersymmetry breakdown through non-perturbative effects

- Explanation of $m_{3/2} \ll M_P$ by dimensional transmutation

$$G = G_{\text{SM}} \times G_4$$

$$m_{3/2} \simeq \frac{\Lambda^3}{M_P^2}$$
Hidden sector strong dynamics

- **Supersymmetry** breakdown through non-perturbative effects

- Explanation of $m_{3/2} \ll M_P$ by dimensional transmutation

- We *estimate* the scale of hidden sector strong dynamics (i.e. calculate the $\beta$-function)

![Graph showing the dependence of $g_4(\mu)$ on $\log_{10}(\mu/\text{GeV})$]
Top–down motivation for low–energy SUSY

Distribution of the (naive) scale of gaugino condensation

![Histogram showing the distribution of the (naive) scale of gaugino condensation. The x-axis represents \( \log_{10}(\Lambda/\text{GeV}) \), and the y-axis represents the number of models. The histogram peaks around \( \log_{10}(\Lambda/\text{GeV}) = 12 \).]
Top–down motivation for low–energy SUSY

Distribution of the (naive) scale of gaugino condensation

\[ g_\text{vis/hid} = \text{Re} S \pm \varepsilon \text{Re} T + \cdots =: \text{Re} S \pm \Delta \]

Note: hidden sector usually stronger coupled

Ibáñez & Nilles (1986)
Dixon, Kaplunovsky & Louis (1991)
Mayr & Stieberger (1993)
Mayr & Stieberger (1993)
cf. talk by B. Kyae
Distribution of the (naive) scale of gaugino condensation

**bottom-line:**
statistical preference for intermediate scale supersymmetry breaking
Further requirements

A fully realistic string compactification has to fulfill further requirements

- realistic flavor structures,
- absence of rapid proton decay,
- ...
A fully realistic string compactification has to fulfill further requirements

- realistic flavor structures,
- absence of rapid proton decay,
- ...

Other desired features include

- solution to the $\mu$ problem,
- solution to the strong CP problem,
- ...
A heterotic ‘benchmark’ model
Input = geometry, shift & Wilson lines

\[ V = \begin{pmatrix} \frac{1}{3}, & -\frac{1}{2}, & -\frac{1}{2}, & 0, & 0, & 0, & 0 \end{pmatrix} \begin{pmatrix} \frac{1}{2}, & -\frac{1}{6}, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2}, & \frac{1}{2} \end{pmatrix} \]

\[ W_2 = \begin{pmatrix} 0, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2}, & \frac{1}{2}, & 0, & 0, & 0 \end{pmatrix} \begin{pmatrix} 4, & -3, & -\frac{7}{2}, & -4, & -3, & -\frac{7}{2}, & -\frac{9}{2}, & \frac{7}{2} \end{pmatrix} \]

\[ W_3 = \begin{pmatrix} -\frac{1}{2}, & -\frac{1}{2}, & \frac{1}{6}, & \frac{1}{6}, & \frac{1}{6}, & \frac{1}{6}, & \frac{1}{6}, & \frac{1}{6} \end{pmatrix} \begin{pmatrix} \frac{1}{3}, & 0, & 0, & \frac{2}{3}, & 0, & \frac{5}{3}, & -2, & 0 \end{pmatrix} \]
Input = geometry, shift & Wilson lines

Gauge group

\[ G = [\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times \text{U}(1)_{B-L}] \times [\text{SU}(4) \times \text{SU}(2)'] \times \text{U}(1)^7 \]

GUT normalization \[ \Rightarrow \] gauge coupling unification

normalization not as in $\text{SO}(10)$
Model definition and spectrum


- Input = geometry, shift & Wilson lines
- **Gauge group**
  
  \[ G \subset SU(5) \subset SO(10) \]

  \[ G = [SU(3) \times SU(2) \times U(1)_Y \times U(1)_{B-L}] \times [SU(4) \times SU(2)'] \times U(1)^7 \]

- **Spectrum**

  \[ \text{spectrum} = 3 \times \text{generation} + \text{vector-like w.r.t.} \ G_{SM} \times U(1)_{B-L} \]
### Spectrum @ orbifold point

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>3</td>
<td>$(\overline{3}, 1; 1, 1)_{(1/6,1/3)}$</td>
<td>$q_i$</td>
<td>3</td>
<td>$(\overline{3}, 1; 1, 1)_{(-2/3,-1/3)}$</td>
<td>$ar{u}_i$</td>
</tr>
<tr>
<td>3</td>
<td>$(1, 1; 1, 1)_{(1,1)}$</td>
<td>$\bar{e}_i$</td>
<td>8</td>
<td>$(1, 2; 1, 1)_{(0,*)}$</td>
<td>$m_i$</td>
</tr>
<tr>
<td>$3+1$</td>
<td>$(\overline{3}, 1; 1, 1)_{(1/3,-1/3)}$</td>
<td>$\tilde{d}_i$</td>
<td>1</td>
<td>$(3, 1; 1, 1)_{(-1/3,1/3)}$</td>
<td>$d_i$</td>
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<td>1</td>
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<td>$\tilde{\ell}_i$</td>
</tr>
<tr>
<td>1</td>
<td>$(1, 2; 1, 1)_{(-1/2,0)}$</td>
<td>$h_d$</td>
<td>1</td>
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<td>$h_u$</td>
</tr>
<tr>
<td>6</td>
<td>$(\overline{3}, 1; 1, 1)_{(1/3,2/3)}$</td>
<td>$\tilde{\delta}_i$</td>
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<tr>
<td>14</td>
<td>$(1, 1; 1, 1)_{(1/2,*)}$</td>
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<tr>
<td>5</td>
<td>$(1, 1; 1, 2)_{(0,1)}$</td>
<td>$\bar{\eta}_i$</td>
<td>5</td>
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<td>$\eta_i$</td>
</tr>
<tr>
<td>10</td>
<td>$(1, 1; 1, 2)_{(0,0)}$</td>
<td>$h_i$</td>
<td>2</td>
<td>$(1, 2; 1, 2)_{(0,0)}$</td>
<td>$y_i$</td>
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<tr>
<td>6</td>
<td>$(1, 1; 4, 1)_{(0,*)}$</td>
<td>$f_i$</td>
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<tr>
<td>2</td>
<td>$(\overline{3}, 1; 1, 1)_{(-1/6,2/3)}$</td>
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<td>spectrum = 3 generations + vector-like</td>
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<tr>
<td>2</td>
<td>$(\bar{3}, 1; 1, 1)_{(-1/6, 2/3)}$</td>
<td>$\bar{v}_i$</td>
<td>2</td>
<td>$(3, 1; 1, 1)_{(1/6, -2/3)}$</td>
<td>$v_i$</td>
</tr>
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</table>

**spectrum = 3 generations + vector-like**
### Spectrum @ orbifold point

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<thead>
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<td>$q_i$</td>
<td>3</td>
<td>$(\bar{3}, 1; 1, 1)_{(-2/3, -1/3)}$</td>
<td>$\bar{u}_i$</td>
</tr>
<tr>
<td>3</td>
<td>$(1, 1; 1, 1)_{(1,1)}$</td>
<td>$\bar{e}_i$</td>
<td>8</td>
<td>$(1, 2; 1, 1)_{(0,*)}$</td>
<td>$m_i$</td>
</tr>
<tr>
<td>3 + 1</td>
<td>$(\bar{3}, 1; 1, 1)_{(1/3,-1/3)}$</td>
<td>$\bar{d}_i$</td>
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<td>$(3, 1; 1, 1)_{(-1/3,1/3)}$</td>
<td>$d_i$</td>
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<td>$h_d$</td>
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<td>14</td>
<td>$(1, 1; 1, 1)_{(-1/2,*)}$</td>
<td>$s_i^-$</td>
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<tr>
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<td>$n_i$</td>
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<td>$(1, 1; \bar{4}, 1)_{(0,*)}$</td>
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<td>2</td>
<td>$(3, 1; 1, 1)_{(1/6,-2/3)}$</td>
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**spectrum = 3 generations + vector-like**
### Spectrum @ orbifold point

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<tr>
<td>3</td>
<td>(3,2;1,1) (1/6,1/3)</td>
<td>(q_i)</td>
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<td>(3,1;1,1) (-2/3,-1/3)</td>
<td>(\bar{u}_i)</td>
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<td>(m_i)</td>
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<td>3 + 1</td>
<td>(\bar{3},1;1,1) (-1/3,-1/3)</td>
<td>(\bar{d}_i)</td>
<td>1</td>
<td>(3,1;1,1) (-1/3,1/3)</td>
<td>(d_i)</td>
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<tr>
<td>3 + 1</td>
<td>(1,2;1,1) (-1/2,-1)</td>
<td>(\ell_i)</td>
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<tr>
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<td>(1,2;1,1) (-1/2,0)</td>
<td>(h_d)</td>
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<td>(1,2;1,1) (1/2,0)</td>
<td>(h_u)</td>
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<td>6</td>
<td>(\bar{3},1;1,1) (1/3,2/3)</td>
<td>(\bar{\delta}_i)</td>
<td>6</td>
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<td>(n_i)</td>
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<td>(1,1;4,1) (-1/2,-1)</td>
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<td>(3,1;1,1) (1/6,-2/3)</td>
<td>(v_i)</td>
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**B−L** allows to discriminate
- between lepton and Higgs fields
- between neutrinos and other singlets
## Spectrum @ orbifold point

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<td>3</td>
<td>$\left( 3, 1; 1, 1 \right)_{(-2/3, -1/3)}$</td>
<td>$\bar{u}_i$</td>
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<td>$\bar{e}_i$</td>
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<td>$\left( 1, 2; 1, 1 \right)_{(0, *)}$</td>
<td>$m_i$</td>
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<td>3 + 1</td>
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<td>$\left( 3, 1; 1, 1 \right)_{(1/3, 2/3)}$</td>
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<td>$\left( 1, 1; 1, 4 \right)_{(0, *)}$</td>
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<td>32</td>
<td>$\left( 1, 1; 1, 1 \right)_{(0, 0)}$</td>
<td>$s_i^0$</td>
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<tr>
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<td>2</td>
<td>$\left( 3, 1; 1, 1 \right)_{(1/6, -2/3)}$</td>
<td>$v_i$</td>
</tr>
</tbody>
</table>

### crucial:

**existence of SM singlets with** $q_{B-L} = \pm 2$
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

$$X_i \overline{X}_j \underbrace{s_{i_1} \ldots s_{i_n}}_{\text{vev} \rightarrow \text{mass term}}$$
Decoupling of exotics vs. $\mu$ term

- Decoupling of exotics

\[ X_i \bar{X}_j \underbrace{s_{i_1} \ldots s_{i_n}}_{\text{vev} \rightarrow \text{mass term}} \]

We have checked that:

1. exotics’ mass matrices have full rank with

\[ s_i = G_{\text{SM}} \times SU(4) \text{ singlets with } q_{B-L} = 0 \text{ or } \pm 2 \]
Decoupling of exotics vs. $\mu$ term

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   \[ s_i = G_{\text{SM}} \times SU(4) \text{ singlets with } q_{B-L} = 0 \text{ or } \pm 2 \]

2. $s_i$ vevs are consistent with **supersymmetry**

Note that giving vevs to (localized) fields corresponds to blowing up the orbifold singularities
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

$$X_i \overline{X}_j \begin{pmatrix} s_1 & \cdots & s_n \end{pmatrix}$$

vev $\rightarrow$ mass term

We have checked that:

1. exotics’ mass matrices have full rank with

   $$s_i = G_{SM} \times SU(4)$$
   singlets with $q_{B-L} = 0$ or $\pm 2$

2. $s_i$ vevs are consistent with supersymmetry

$\Rightarrow$ Have obtained an MSSM vacuum with $R$-parity
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

\[ X_i \overline{X}_j \underbrace{s_{i_1} \ldots s_{i_n}} \text{vev} \rightarrow \text{mass term} \]

We have checked that:

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   \[ s_i = G_{\text{SM}} \times SU(4) \text{ singlets with } q_{B-L} = 0 \text{ or } \pm 2 \]

2. $s_i$ vevs are consistent with supersymmetry

⇒ Have obtained an MSSM vacuum with $R$-parity

Questions:

☞ Is there a reason why the Higgs doublets’ mass is much smaller than the exotics’ masses?

☞ Is there a reason why the Higgs mass is of the order of the weak scale?
A stringy solution to the $\mu$ problem

The pair $h_u - h_d$ are the only fields from $U_3$
A stringy solution to the $\mu$ problem

- The pair $h_u - h_d$ are the only fields from $U_3$

- $h_u h_d$ is ‘neutral’ w.r.t. to the selection rules:
  - gauge invariant
  - correspond to space group element $(1, 0)$
  - total $R$-charges are $(0, 0, -2) = (0, 0, 0) \mod (6, 3, 2)$
The pair $h_u - h_d$ are the only fields from $U_3$.

$h_u h_d$ is ‘neutral’ w.r.t. to the selection rules:

As a consequence: for any monomial $\mathcal{M} = s_{i_1} \ldots s_{i_N}$

$$\mathcal{M} h_u h_d \in \mathcal{W}, \quad \mathcal{M} \in \mathcal{W}$$
A stringy solution to the $\mu$ problem

- The pair $h_u - h_d$ are the only fields from $U_3$

- $h_u h_d$ is ‘neutral’ w.r.t. to the selection rules:

  ➝ As a consequence: for any monomial $M = s_{i_1} \ldots s_{i_N}$

  $$M h_u h_d \in W \leadsto M \in W$$

- We find (empirically, at order $s^6$)

  $$F_i = 0 \leadsto \langle M \rangle = 0 \ \forall \text{monomials } M \in W$$
A stringy solution to the $\mu$ problem

- The pair $h_u - h_d$ are the only fields from $U_3$

- $h_u h_d$ is ‘neutral’ w.r.t. to the selection rules:

  - As a consequence: for any monomial $M = s_{i_1} \ldots s_{i_N}$

    $$M h_u h_d \in W \Leftrightarrow M \in W$$

- We find (empirically, at order $s^6$)

  $$F_i = 0 \quad \Leftrightarrow \quad \langle M \rangle = 0 \quad \forall \text{ monomials } M \in W$$

- At the perturbative level

  $$\langle W \rangle = 0 \quad \text{and} \quad \mu = \frac{\partial^2 W}{\partial h_u \partial h_d} = 0$$

  $$\ldots \text{and all exotics are massive} \left( m_{\text{exotics}} \sim \sqrt{\text{FI-term}} \sim M_{\text{GUT}} \right)$$
A stringy solution to the $\mu$ problem

**Note:** these features are not ‘put in by hand’, but just happen to arise in vacua with unbroken standard model gauge symmetry and $R$-parity

There are several comparable models in the Mini-Landscape

We find (empirically, at order $s^6$)

$$ F_i = 0 \quad \Leftrightarrow \quad \langle M \rangle = 0 \quad \forall \text{ monomials } M \in W $$

At the perturbative level

$$ \langle W \rangle = 0 \quad \text{and} \quad \mu = \frac{\partial^2 W}{\partial h_u \partial h_d} = 0 $$

... and all exotics are massive ($m_{\text{exotics}} \sim \sqrt{\text{FI-term}} \sim M_{\text{GUT}}$)
Stringy solutions to the $\mu$ problem - literature

There exist proposals for precisely this situation
There exist proposals for precisely this situation

1. $\mu$ from $\mathcal{W}$

...the relation $\mathcal{W} \supset \mathcal{W}_0 h_u h_d$ has been assumed

$\sim$ non-perturbative effects induced by hidden sector strong dynamics lead to $\langle \mathcal{W} \rangle \neq 0$ so that

$$\mu \sim \langle \mathcal{W} \rangle \sim m_{3/2}$$

...this is a stringy version of the Kim-Nilles mechanism

Casas, Muñoz (1993)
Kim, Nilles (1984)
Stringy solutions to the $\mu$ problem - literature

There exist proposals for precisely this situation

1. $\mu$ from $W$

   Casas, Muñoz (1993)

2. $\mu$ from $K$

   Antoniadis, Gava, Narain, Taylor (1994)

   see also the recent similar discussion by Hebecker, March-Russell, Ziegler

\[ K \supset - \log \left[ (T_3 + \overline{T}_3) \left( Z_3 + \overline{Z}_3 \right) - (h_u + \overline{h}_d) \left( \overline{h}_u + h_d \right) \right] \]

Kähler modulus complex structure modulus

\ldots leads effectively to the Giudice-Masiero mechanism

Giudice, Masiero (1988)
Stringy solutions to the $\mu$ problem - literature

There exist proposals for precisely this situation

1. $\mu$ from $W$
   - Casas, Muñoz (1993)

2. $\mu$ from $K$
   - Antoniadis, Gava, Narain, Taylor (1994)

Model allows to use both mechanisms (simultaneously)

$\sim \text{expect } \mu \sim m_{3/2}$
There exist proposals for precisely this situation

1. $\mu$ from $W$
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2. $\mu$ from $K$
   Antoniadis, Gava, Narain, Taylor (1994)

Model allows to use both mechanisms (simultaneously)

\[ \sim \text{ expect } \mu \sim m_{3/2} \]

‘Combination’ of both mechanisms appears phenomenologically viable

Brümmer et al. (in preparation)
Untwisted sector (internal components of the gauge bosons)

<table>
<thead>
<tr>
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<th>field-theoretic description</th>
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<td>$U_1$</td>
<td>$\sim A_5 + iA_6$</td>
<td>$\overline{u}_1 + \ldots$</td>
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<tr>
<td>$U_2$</td>
<td>$\sim A_7 + iA_8$</td>
<td>$q_1 + \ldots$</td>
</tr>
<tr>
<td>$U_3$</td>
<td>$\sim A_9 + iA_{10}$</td>
<td>$h_u + \ldots$</td>
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Renormalizable coupling

$y_t \, u_1 \, q_1 \, h_u$

$y_t \approx g \, @ \, M_{\text{comp}}$

- all other Yukawa couplings are suppressed (i.e. appear at higher order in $s_i$)
Flavor structure

Yukawa couplings in the configuration discussed so far up to $s^6$

$$Y_u = \begin{pmatrix} 1 & s^6 & s^6 \\ s^6 & s^5 & s^5 \\ s^5 & s^5 & s^5 \end{pmatrix}, \quad Y_d = \begin{pmatrix} s^6 & 0 & 0 \\ 0 & s^5 & 0 \\ s^5 & 0 & 0 \end{pmatrix}, \quad Y_e = \begin{pmatrix} 0 & 0 & s^5 \\ s^6 & s^5 & 0 \\ 0 & s^6 & s^6 \end{pmatrix}$$

Each $s$ entry represents a monomial of singlets with the indicated order.
Yukawa couplings in the configuration discussed so far up to $s^6$

\[
Y_u = \begin{pmatrix}
1 & s^6 & s^6 \\
s^6 & s^5 & s^5 \\
s^5 & s^5 & s^5
\end{pmatrix}, \quad Y_d = \begin{pmatrix}
s^6 & 0 & 0 \\
0 & s^5 & 0 \\
s^5 & 0 & 0
\end{pmatrix}, \quad Y_e = \begin{pmatrix}
0 & 0 & s^5 \\
s^6 & s^5 & 0 \\
0 & s^6 & s^6
\end{pmatrix}
\]

We find many other configurations with the same characteristics ($\mu \sim m_{3/2}$, all exotics decouple, etc.) but different Yukawa couplings

\[
Y_u = \begin{pmatrix}
1 & s^6 & s^6 \\
s^5 & s^5 & s^5 \\
s^5 & s^5 & s^5
\end{pmatrix}, \quad Y_d = \begin{pmatrix}
s^6 & s^6 & 0 \\
s^5 & s^5 & 0 \\
s^5 & s^5 & 0
\end{pmatrix}, \quad Y_e = \begin{pmatrix}
s^6 & s^5 & s^5 \\
s^6 & s^5 & s^5 \\
0 & s^6 & s^6
\end{pmatrix}
\]

Effective Yukawa couplings are vacuum/moduli dependent
Yukawa couplings in the configuration discussed so far up to $s^6$

$$Y_u = \begin{pmatrix} 1 & s^6 & s^6 \\ s^6 & s^5 & s^5 \\ s^5 & s^5 & s^5 \end{pmatrix}, \quad Y_d = \begin{pmatrix} s^6 & 0 & 0 \\ 0 & s^5 & 0 \\ s^5 & 0 & 0 \end{pmatrix}, \quad Y_e = \begin{pmatrix} 0 & 0 & s^5 \\ s^6 & s^5 & 0 \\ 0 & s^6 & s^6 \end{pmatrix}$$

We find many other configurations with the same characteristics ($\mu \sim m_{3/2}$, all exotics decouple, etc.) but different Yukawa couplings

Effective Yukawa couplings $\sim s^n$ vanish @ orbifold point

\[
\begin{cases}
\text{hierarchical Yukawa couplings in Nature} & \leftrightarrow \\
do we live close to an orbifold point & \text{??}
\end{cases}
\]
See-saw couplings: $W_{\text{see-saw}} = Y_{ij} h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j$
See-saw couplings:

\[ \mathbf{W}_{\text{see-saw}} = Y_{ij} h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j \]

In string models, \( M, Y_\nu \sim \langle s^n \rangle \text{ singlet} \)
See-saw couplings

see-saw couplings: $W_{\text{see-saw}} = Y_{ij}^h h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j$

in string models $M, \ Y_\nu \sim \langle s^n \rangle$

see-saw mass matrix

$W_{\text{see-saw}} \xrightarrow{h_u \rightarrow v} (\nu, \bar{\nu}) \begin{pmatrix} 0 & y_\nu v \\ y_\nu v & M \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} \approx \frac{y_\nu^2 v^2}{M} \nu \nu + M \bar{\nu} \bar{\nu}$
see-saw couplings: \( W_{\text{see-saw}} = Y_{ij} h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j \)

in string models \( M, Y_\nu \sim \langle s^n \rangle \)

see-saw mass matrix

\[
W_{\text{see-saw}} \xrightarrow{h_u \rightarrow \nu} (\nu, \bar{\nu}) \begin{pmatrix} 0 & y_\nu \nu \\ y_\nu \nu & M \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} \simeq \frac{y_\nu^2 \nu^2}{M} \nu \nu + M \bar{\nu} \bar{\nu}
\]

naive GUT expectation:

\( m_\nu \sim (100 \text{ GeV})^2 / 10^{16} \text{ GeV} \sim 10^{-3} \text{ eV} \)
See-saw couplings

- see-saw couplings: \( W_{\text{see-saw}} = Y_{ij} h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j \)
- in string models \( M, Y_{\nu} \sim \langle s^n \rangle \)
- see-saw mass matrix

\[
W_{\text{see-saw}} \xrightarrow{h_u \rightarrow \nu} (\nu, \bar{\nu}) \begin{pmatrix} 0 & y_{\nu} v \\ y_{\nu} v & M \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} \approx \frac{y_{\nu}^2 v^2}{M} \nu \nu + M \bar{\nu} \bar{\nu}
\]

- naive GUT expectation:
  \( m_{\nu} \sim (100 \text{ GeV})^2 / 10^{16} \text{ GeV} \sim 10^{-3} \text{ eV} \)

... suspiciously close to observed values

\[
\sqrt{\Delta m_{\text{atm}}^2} \approx 0.04 \text{ eV} \quad \& \quad \sqrt{\Delta m_{\text{sol}}^2} \approx 0.008 \text{ eV}
\]
Heterotic see-saw


there are $O(100)$ neutrinos (= $R$-parity odd SM singlets)
there are $\mathcal{O}(100)$ neutrinos ($= R$-parity odd SM singlets)

$\mathcal{O}(100)$ contributions to the (effective) neutrino mass operator

\[
m_\nu = \sum \bar{\nu} \phi \phi \nu + \bar{\nu} \nu
\]
there are $\mathcal{O}(100)$ neutrinos ($= R$-parity odd SM singlets)

$\mathcal{O}(100)$ contributions to the (effective) neutrino mass operator

effective suppression of the see-saw scale

$$m_\nu \sim \frac{v^2}{M_*}$$

$M_* \sim \frac{M_{GUT}}{10\ldots100}$

... seems consistent with observation

$$\left( \sqrt{\Delta m^2_{atm}} \simeq 0.04 \text{ eV} \ & \ & \sqrt{\Delta m^2_{sol}} \simeq 0.008 \text{ eV} \right)$$
there are $\mathcal{O}(100)$ neutrinos ($= R$-parity odd SM singlets)

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$\sqrt{\Delta m_{\text{atm}}^2} \simeq 0.04 \text{ eV} \ & \ \sqrt{\Delta m_{\text{sol}}^2} \simeq 0.008 \text{ eV}$

Main conclusion:

See-saw is a generic feature in heterotic MSSM vacua
there are $O(100)$ neutrinos (= $R$-parity odd SM singlets)

$O(100)$ contributions to the (effective) neutrino mass operator

effective suppression of the see-saw scale

... seems consistent with observation

\[
\left( \sqrt{\Delta m^2_{\text{atm}}} \simeq 0.04 \text{ eV} \; \& \; \sqrt{\Delta m^2_{\text{sol}}} \simeq 0.008 \text{ eV} \right)
\]

Main conclusion:

See-saw is a generic feature in heterotic MSSM vacua

Note: in $\mathbb{Z}_3$ orbifolds one arrives at a different conclusion

cf. Giedt, Kane, Langacker, Nelson (2005)
Summary of search strategy

We started analyzing the heterotic orbifold landscape
Summary of search strategy

☞ We started analyzing the heterotic orbifold landscape

16

\text{SO}(10)

☞ The concept of \textit{`local grand unification`} has led us to beautiful spots
Summary of features

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

No exotics
Summary of features

1. $3 \times 16 + \text{Higgs} + \text{nothing}$

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$

- gravity
- strong force
- weak force
- electromagnetism
Summary of features

1. $3 \times 16 + \text{Higgs} + \text{nothing}$
2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$
3. unification

![Graph showing $\alpha_i$ vs. $\log_{10}(\mu/\text{GeV})$]
Summary of features

1. \(3 \times 16 + \text{Higgs} + \text{nothing}\)
2. \(\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}\)
3. unification
4. \(R\)-parity
   ... but potential problems with dimension 5 proton decay
Summary of features

1. $3 \times 16 + \text{Higgs} + \text{nothing}$
2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$
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6. $y_t \simeq g @ M_{\text{GUT}}$ & potentially realistic flavor structures à la Froggatt-Nielsen
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6. \(y_t \simeq g @ M_{\text{GUT}}\) & potentially realistic flavor structures à la Froggatt-Nielsen

7. dynamical supersymmetry breaking

\[ \log_{10}(\Lambda/\text{GeV}) \]

- spontaneously broken SUSY with TeV scale soft masses
Summary of features

1. \(3 \times 16 + \text{Higgs} + \text{nothing}\)

2. \(\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}\)

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4. \(R\)-parity

5. see-saw

6. \(y_t \simeq g @ M_{\text{GUT}}\) & potentially realistic flavor structures à la Froggatt-Nielsen

7. dynamical supersymmetry breaking

8. solution to the \(\mu\)-problem

\[\mu \sim \langle W \rangle\]
Summary of features

1. $3 \times 16 + \text{Higgs} + \text{nothing}$
2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times \text{G}_{\text{hid}}$
3. unification
4. $R$-parity
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6. $y_t \simeq g @ M_{\text{GUT}}$ & potentially realistic flavor structures à la Froggatt-Nielsen
7. dynamical supersymmetry breaking
8. solution to the $\mu$-problem

that's what we searched for...

\dots that's what we got 'for free'

"stringy surprises"
LHC let’s have coffee!