Gauge Coupling Unification in Heterotic String Models with Gauge Mediated SUSY Breaking

Phys. Rev. D83 (2011) 075008;
Work with Prof. Stuart Raby

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August 28, 2011

SUSY 2011, Fermilab, IL.
Motivation

In string theories with compactified extra-dimensions, there generically exist extra non-standard model particles, usually called “exotics”.

To mediate SUSY breaking with vector-like “exotic” particles arising from heterotic string theory, and produce a “consistent” low-energy spectrum.
Mini-Landscape Search\(^1\)

- Search for MSSM spectrum at low energies starting with \(E_8 \times E_8\) heterotic string models compactified on the orbifold, \(T^6/\mathbb{Z}_6\)
- Look for GUTS with the Standard Model Gauge group embedded

\[ E_8 \supset E_6 \supset SO(10) \supset SU(5) \supset G_{SM} \]

- Spectrum: Three families + Vector-like “exotics”
- 15 models with promising phenomenology.

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Gauge Coupling Unification

- Gauge Coupling Unification was studied in 2 of these 15 models in the current work and earlier\(^2\).

**Model 1 and Model 2A**

- This required some of the vector-like exotics to be massive at less than \(10^{15}\) GeV.
- Solutions were constrained by the value of proton lifetime in these models.

\[
\tau(p \rightarrow \pi^0 e^+) \gtrsim 10^{34} \text{ yr}^*
\]

* Current bound from Super Kamiokande.

Matter Content and Energy scales

• \( \tilde{n} = (n_3, n_2, (n_1, n'_1)) \) defines the ‘light’ exotic matter content of the theory.

\[
\begin{align*}
n_3 \times [(3, 1)_{1/3} + (\bar{3}, 1)_{-1/3}] + n_2 \times [(1, 2)_0 + (1, 2)_0] + \\
n_1 \times [(1, 1)_1 + (1, 1)_{-1}]
\end{align*}
\]

• \( M_{EX1} \) - Mass scale of the triplet exotics.

• \( M_{EX2} \) - Mass scale of the doublet exotics.

• \( M_C \) - The compactification scale of the extra-dimensions.

The singlets are allowed to be massive either at \( M_{EX1} \) or \( M_{EX2} \).
Heterotic Theory on Orbifold

*Figure not drawn to scale.
*Figure not drawn to scale.
4D MSSM

The two theories match until this scale.

*Figure not drawn to scale.*
Gauge Coupling Unification
Gaugino Masses

- The gauginos obtain mass at one loop from the exotics:

\[ M_i = b_i^{EX3} \frac{\alpha_i}{4\pi} \frac{F_\phi}{M_{EX1}} + b_i^{EX2} \frac{\alpha_i}{4\pi} \frac{F_\phi}{M_{EX2}} \]

The two exotic scales give rise to non-universal gaugino masses.

The gravitino contribution is sub-dominant when:

\[ \frac{F_\phi}{M_{EX}} >> \frac{m_3^*}{2} \]

\[ b^{EX3} = (n_3, 0, \frac{n_3 + 3n_1}{10}) \quad b^{EX2} = (0, n_2, \frac{3n_1'}{10}) \]

* Anomaly contributions to gaugino masses were considered in a recent analysis.
Scalar Masses

- The scalars obtain mass at two-loops:

\[
m_{\phi_i}^2 = m_{3/2}^2 + 2 \left( b_3^{EX3} \frac{\alpha_3}{4\pi} \frac{F\phi}{M_{EX1}} \right)^2 C_3(i) + 2 \left( b_2^{EX2} \frac{\alpha_2}{4\pi} \frac{F\phi}{M_{EX2}} \right)^2 C_2(i) \\
+ 2 \left( \frac{\alpha_1}{4\pi} \left( b_1^{EX3} \frac{F\phi}{M_{EX1}} + b_1^{EX2} \frac{F\phi}{M_{EX2}} \right) \right)^2 C_1(i) + dQ_a^X M_2^2
\]

- \( dQ_a^X M_2^2 \) is a possible D - term contribution from an anomalous \( U(1)_X \) that is proportional to GMSB.

- The large gravity contribution makes the scalar masses universal at the GUT scale.
The road to MSSM

1. Heterotic string model compactified on an anisotropic orbifold.

2. Match with effective 4D theory

3. Require gauge coupling unification at the 4D GUT scale

4. Fix exotic masses

5. Calculate SOFT TERMS at the messenger scale.

   - Use RGE (SOFTSUSY)

6. Weak scale SUSY spectrum!

7. Match threshold corrections at the GUT scale.
Effect of $\epsilon_3$

- We study the effect of threshold corrections on the spectrum of exotics as well as the low energy spectrum.

The figure represents the correlation for one particular model with $\vec{n} = (4, 2, (2, 1))$
### Two Cases

<table>
<thead>
<tr>
<th>Observable</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{3/2}$</td>
<td>$4 \text{ TeV}$</td>
<td>$10 \text{ TeV}$</td>
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<tr>
<td>$d$</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>$M_S$</td>
<td>$6.04 \times 10^{17}$</td>
<td>$6.05 \times 10^{17}$</td>
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<tr>
<td>$M_C$</td>
<td>$1.2 \times 10^{16}$</td>
<td>$1.2 \times 10^{16}$</td>
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<tr>
<td>$M_{EX1}$</td>
<td>$5.03 \times 10^{13}$</td>
<td>$1.10 \times 10^{14}$</td>
</tr>
<tr>
<td>$M_{EX2}$</td>
<td>$1.69 \times 10^{13}$</td>
<td>$8.54 \times 10^{13}$</td>
</tr>
<tr>
<td>$M_{GUT}$</td>
<td>$2.5 \times 10^{16}$</td>
<td>$2.0 \times 10^{16}$</td>
</tr>
<tr>
<td>$\epsilon_3$</td>
<td>-2.5 %</td>
<td>0 %</td>
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<tr>
<td>$\tan \beta$</td>
<td>7</td>
<td>4</td>
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<tr>
<td>$\mu$</td>
<td>-206.217</td>
<td>-1932.930</td>
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</tbody>
</table>
MSSM Spectrum - Case 1

\[ m_{3/2} = 4 \text{ TeV}, \; d = 0, \; \varepsilon_3 = -2.5\% \]
MSSM Spectrum - Case 2

$m_{3/2} = 10$ TeV, $d = 5$, $\epsilon_3 = 0 \%$
The main difference between the spectrum discussed here and CMSSM is the non-universality of gaugino masses.

Kinematically, the signatures from this spectrum would be similar to CMSSM with heavy scalars.

Results presented at EPS 2011 from ATLAS: Gluino masses of 200 GeV - 660 GeV ruled out for neutralino masses up to 160 GeV.

These results heavily constrain the parameter space discussed here.
Summary

• We have a self-consistent spectrum generated from heterotic string theory with vector-like “exotic” particles mediating SUSY breaking.

• The threshold corrections at the GUT scale depend on the gaugino masses.

• A large region of the parameter space discussed here is ruled out by the latest results from LHC.
<table>
<thead>
<tr>
<th>Model</th>
<th>Hidden Sector</th>
<th>Exotic Matter Irrep</th>
<th>Name</th>
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<tbody>
<tr>
<td>1 A/B</td>
<td>$SU(4) \times SU(2)$</td>
<td>brane exotics</td>
<td>$2 \times [(3, 1; 1, 1)<em>{1/3,2/3} + (\bar{3}, 1; 1, 1)</em>{-1/3,-2/3}]$</td>
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<td>2</td>
<td>$SO(8) \times SU(2)$</td>
<td>brane exotics</td>
<td>$4 \times [(3, 1; 1, 1)<em>{1/3,*} + (\bar{3}, 1; 1, 1)</em>{-1/3,*}]$</td>
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Anomaly Contributions

M3/M2 vs Threshold Corrections

- Black circles: At M_{3u} without anomaly contribution
- Red squares: At M_{3u} with anomaly contribution
- Green circles: At M_{3d} without anomaly contribution
- Orange squares: At M_{3d} with anomaly contribution

Threshold Corrections, $\xi^3$

M3/M2
$m_{\tilde{\chi}^0}$ vs $m_{\tilde{g}}$