EXPERIMENTAL SIGNATURES OF KÄHLER STABILIZATION OF THE DILATON

BRENT D. NELSON
Michigan Center for Theoretical Physics,
University of Michigan, Ann Arbor, MI 48109, USA

We investigate the collider signatures of modular invariant gaugino condensation, with Kähler stabilization of the dilaton, in the context of weakly coupled heterotic string-based models as an example of how supergravity can be used to build a meaningful string phenomenology.

1 Background of the Model

The dilaton is the only one of the various possible string moduli fields that always appears in the low-energy effective theory in a uniform way. It represents the tree-level value of the gauge kinetic function \( f_a \) and thus its vacuum expectation value determines the string coupling constant. In the chiral formulation of the dilaton we have

\[
\begin{align*}
\langle f_a^{(0)} \rangle & = S \\
\langle \text{Re } s \rangle & = \frac{1}{g_{\text{str}}^2}
\end{align*}
\]

where \( s = S|_{\theta = \bar{\theta} = 0} \) and \( g_{\text{str}} \) is the universal gauge coupling at the string scale.

It is clear that the low-energy phenomenology depends crucially on finding a dynamical mechanism that ensures a finite vacuum value for the dilaton at the observed coupling strength. However, the superpotential for the dilaton is vanishing at the classical level so only nonperturbative effects, of string and/or field-theoretic origin, can create a superpotential capable of stabilizing the dilaton. There are two commonly employed classes of solutions to this challenge. The first, sometimes referred to as the “racetrack” method, assumes only the tree level form of the dilaton Kähler potential

\[
K_{\text{tree}}(S, \bar{S}) = -\ln(S + \bar{S})
\]

and relies on at least two gaugino condensates in the hidden sector to generate the necessary dilaton superpotential. Generally the vacuum energy remains nonzero in such scenarios. This method requires correctly choosing the relative sizes of the beta-function coefficients for two different condensing gauge groups.

The second approach, sometimes referred to as “Kähler stabilization,” assumes that the tree level Kähler potential for the dilaton is augmented by nonperturbative corrections of a stringy or field-theoretic origin. Then in the presence of one or more gaugino condensates in the hidden sector the dilaton can be stabilized at

\[
g_{\text{str}}^2 = \frac{1}{2}
\]

with a vanishing vacuum energy. This method requires correctly choosing parameters in the postulated nonperturbative Kähler potential. This latter approach gives rise to a scenario that Casas referred to as the “generalized dilaton-dominated” scenario. The subject of this talk is to consider this well-defined and well-motivated model as a template for how supergravity effective theories can be used to bridge
the gap between string theory and experiment.

Consider the F-term scalar potential that arises from any generic supergravity theory \( V = K_{ij} F^i F^j - M M / 3 \), where \( F^i \) is the auxiliary field associated with the chiral superfield \( Z^i \) and \( M \) is the auxiliary field of supergravity. When only the dilaton auxiliary field \( F^S \) receives a vacuum expectation value the potential can be written

\[
V = K_{ss} |F^S|^2 - 3 e^K |W|^2 = e^K K^{s\bar{s}} |W_s + K_s W|^2 - 3 e^K |W|^2. \tag{1}
\]

Requiring that the potential \( \langle V \rangle \) be vanishing in the vacuum \( \langle V \rangle = 0 \) then implies (up to an overall phase)

\[
F^S = \sqrt{3} m_{3/2} (K_{ss})^{-1/2} = \sqrt{3} m_{3/2} a_{np} (K_{ss}^{\text{tree}})^{-1/2}, \tag{2}
\]

where we have introduced the parameter \( a_{np} \equiv (K_{ss}^{\text{tree}} / K_{ss}^{\text{true}})^{1/2} \) designed to measure the departure of the dilaton Kähler potential from its tree level value due to nonperturbative effects. Recall that \( \langle (K_{ss}^{\text{tree}})^{1/2} \rangle = (1/(s + \bar{s})) = g_{\text{str}}^2 / 2 \simeq 1/4 \).

To understand the likely magnitude of the phenomenological parameter \( a_{np} \) let us make the quite well-grounded assumption that the superpotential for the dilaton is generated by the phenomenon of gaugino condensation and that its dilaton dependence is given by \( W(S) \propto e^{-3S / 2b_+}. \) Here \( b_+ \) is the beta-function coefficient of a condensing gauge group \( G_\alpha \) of the hidden sector with \( b_\alpha = (1 / 16 \pi^2) (3 C_\alpha - \sum_i C_{i\alpha}^i) \) and \( C_\alpha, \ C_{i\alpha}^i \) are the quadratic Casimir operators for the gauge group \( G_\alpha \), respectively, in the adjoint representation and in the representation of the matter fields \( Z^i \) charged under that group. Let us assume a single condensing gauge group, which we will denote by \( G_+ \), so that we can write \( W_s = -(3 / 2 b_+) W(S) \).

Returning for a moment to the tree level case, it is not difficult to see that requiring \( \langle V \rangle = 0 \) would require a dilaton vev such that \( g_{\text{str}}^2 \sim 1 / b_+ \sim 16 \pi^2 \). In fact, no such minimum exists and the dilaton has a runaway solution to zero coupling. However, if we do not insist on the tree level dilaton Kähler potential then the vanishing of the vacuum energy implies

\[
(K_{ss})^{-1} \left| K_s - \frac{3}{2 b_+} \right|^2 = 3 \rightarrow (K_{ss})^{-1/2} = \sqrt{3} \frac{3 b_+}{1 - \frac{2}{3} b_+ K_s}. \tag{3}
\]

So provided \( K_s \sim O(1) \) so that \( K_s b_+ \ll 1 \) we can immediately see that a Kähler potential which stabilizes the dilaton while simultaneously providing zero vacuum energy will necessarily result in a suppressed dilaton contribution to soft supersymmetry breaking. Indeed, from the definition of \( a_{np} \) we have

\[
a_{np} = \sqrt{3} \frac{3 b_+}{1 - \frac{2}{3} K_s b_+} \ll 1. \tag{4}
\]
2 Soft terms and benchmark choices

From (2) we see that $|F^S/M| \approx 4a/M^{1/2} \ll 1$, so one-loop corrections can be important for those soft supersymmetry-breaking terms that receive their tree level contributions solely from the dilaton auxiliary field. In particular, loop-corrections arising from the conformal anomaly are proportional to $M$ itself and receive no suppression, so they can be competitive with the tree level contributions in the presence of a nontrivial Kähler potential for the dilaton. If we assume that the Kähler metric for the observable sector matter fields is independent of the dilaton then the leading order expressions for the soft supersymmetry-breaking terms for canonically normalized fields are

$$M_a \approx \frac{g_a^2(\mu)}{2} \left[ \langle F^S \rangle - 2b_am_{3/2} \right]$$

$$A_{ijk} \approx -\langle K_aF^S \rangle + m_{3/2} [\gamma_i + \gamma_j + \gamma_k]$$

$$m_0^2 \approx m_{3/2}^2,$$

(5)

where $\gamma_i$ is the anomalous dimension of field $Z^i$. While we have presented only the leading terms in the one-loop parameters in (5), the complete expressions for soft terms at one loop were used in the calculations.

From (5) it is clear that the dominant signature of a “generalized” dilaton-domination scenario is the hierarchy between gaugino and scalar masses. On top of this gross feature it is also clear that the loop effects will produce a “fine-structure” of nonuniversalities among the gaugino masses and $A$-terms. With the phase choice represented in (5), and the definition of $b_a$, the effect of the loop corrections will be to lower the gluino mass $M_3$ while increasing the bino mass $M_1$ relative to the wino $M_2$. It is important to note that the significant splitting experienced by the gaugino masses is not also seen in the gauge couplings themselves. Tree level gaugino masses are still universal, but are suppressed, so that nonuniversal loop contributions are comparable, while loop contributions to the gauge couplings themselves are always small in comparison to the large tree level value.

In previous studies of this class of models it was found that requiring $m_{3/2} \approx 1$ TeV to within an order of magnitude typically required $b_+ \leq 0.15$. We are thus led to consider the cases where $b_+ = 15/16\pi^2 \approx 0.095$ and $b_+ = 9/16\pi^2 \approx 0.057$. The former could result from a condensation of pure $SU(5)$ Yang-Mills fields in the hidden sector; the latter from a similar condensation of pure $SU(3)$ Yang-Mills fields or from the condensation of an $E_6$ hidden sector gauge group with 9 27’s condensing in the hidden sector as well. To serve as a baseline we will also consider a much larger value of $b_+ = 36/16\pi^2 \approx 0.228$. This could result from a hidden sector condensation of pure $E_6$ Yang-Mills fields.

\(^{a}\)The appropriate input values for the PYTHIA event generator can be obtained at http://www-pat.fnal.gov/personal/mrenna/benchmarks/
3 Phenomenological Features

The resulting low-energy spectrum for the three benchmark models is summarized in Table 1. Here the model labeled “mSUGRA” is the cMSSM Point B of Battaglia et al. The key feature of Kähler stabilization is likely to be a small mass splitting between $\tilde{N}_1$ and $\tilde{C}_1$ characteristic of anomaly mediation in the gaugino sector. The LSP is not overwhelming bino-like nor is it a pure wino state as in anomaly mediation. Thus adequate neutralino relic density can be obtained. The relatively small $\mu$ term values for such large scalar masses is a manifestation of the focus point effect.

Table 1. Selected physical masses and parameters for benchmark models.

| Point | A | B | C | mSUGRA |
|-------|---|---|---|--------|
| $\tan \beta$ | 10 | 5 | 5 | 10 |
| $m_{3/2}$ | 1500 | 3200 | 4300 | NA |
| $\alpha_{NP}$ | 1/15.77 | 1/37.05 | 1/61.36 | NA |
| $m_{\tilde{N}_1}$ | 77.9 | 93.1 | 90.6 | 98 |
| $m_{\tilde{N}_2}$ | 122.3 | 132.2 | 110.0 | 182 |
| $m_{\tilde{C}_1}$ | 119.8 | 131.9 | 109.8 | 181 |
| $m_{\tilde{g}}$ | 471 | 427 | 329 | 582 |
| $\tilde{B} \%|_{LSP}$ | 89.8 $\%$ | 98.7 $\%$ | 93.4 $\%$ | 99.9$\%$ |
| $\tilde{W}_3 \%|_{LSP}$ | 2.5 $\%$ | 0.6 $\%$ | 4.6 $\%$ | 0.01$\%$ |
| $m_{\tilde{t}_1}$ | 947 | 1909 | 2570 | 392 |
| $m_{\tilde{b}_1}$ | 1282 | 2681 | 3614 | 501 |
| $m_{\tilde{t}_2}$ | 1491 | 3199 | 4298 | 137 |
| $m_{h}$ | 114.3 | 114.5 | 116.4 | 112 |
| $m_{A}$ | 1507 | 3318 | 4400 | 381 |
| $\mu$ | 245 | 631 | 481 | 332 |

Figure shows naive estimates of numbers of events in 2 fb$^{-1}$ integrated luminosity for various models and various inclusive signatures. The signature of these models are calculated using PYTHIA, but only at the generator level: no geometric or kinematic cuts or triggering efficiencies are applied, no jet clustering is performed, tau leptons are not decayed, etc. The event numbers are only meant to illustrate the generic features of each model and demonstrate the experimental challenges. Every signature has missing energy. From left to right, the signatures are: (1) inclusive multi-jets $n_{jets} \geq 3$, (2) one lepton plus $n_{jets} \geq 2$, (3) opposite sign dileptons plus $n_{jets} \geq 2$, (4) same-sign dileptons, (5) trilepton, and (6) 3 taus plus jets [before decaying the taus]. For signatures (4)-(6), no requirement is made on the number of jets. A background analysis must of course be done to be sure any given channel is detectable, but models with hundreds of events are presumably detectable for the first two signatures, and models with tens of events for the rest. The same-sign dilepton channel has smaller backgrounds: even a handful of clean events may constitute a signal.
These models, which are better motivated from the string theory point of view than mSUGRA, offer far better prospects for interesting physics at the Tevatron than even the most optimistic unified scenario. This is in large part due to the much lighter gluino in these models for the same value of the Higgs mass. Considering these models in the context to supergravity was essential to recognizing this result – only supergravity can truly take us from compactification to calorimeter.

References

1. T. Banks and M. Dine, Phys. Rev. D50 (1994) 7454.
2. M. Dine and Y. Shirman, Phys. Rev. D63 (2001) 046005.
3. J. A. Casas, Phys. Lett. B384 (1996) 103.
4. B. D. Nelson, [hep-ph/0211087](https://arxiv.org/abs/hep-ph/0211087).
5. G. L. Kane, J. Lykken, S. Mrenna, B. D. Nelson, L. Wang and T. T. Wang, Phys. Rev. D67 (2003) 045008.
6. P. Binetruy, M. K. Gaillard and B. D. Nelson, Nucl. Phys. B604 (2001) 32.
7. B. D. Nelson, [hep-ph/0009277](https://arxiv.org/abs/hep-ph/0009277).
8. M. Battaglia, A. De Roeck, J. Ellis, F. Gianotti, K. T. Matchev, K. A. Olive, L. Pape, G. Wilson, Eur. Phys. J. C22 (2001) 535.
9. A. Birkedal-Hansen and B. D. Nelson, Phys. Rev. D64 (2001) 015008.