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Measuring modular weights in mirage unification models at the LHC and ILC

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Abstract

String compactification with fluxes yields MSSM soft SUSY breaking terms that receive comparable contributions from modulus and anomaly mediation whose relative strength is governed by a phenomenological parameter α. Gaugino and first/second generation (and sometimes also Higgs and third generation) scalar mass parameters unify at a mirage unification scale $Q \neq M_{\mathrm{GUT}}$, determined by the value of α. The ratio of scalar to gaugino masses at this mirage unification scale depends directly on the scalar field modular weights, which are fixed in turn by the brane or brane intersections on which the MSSM fields are localized. We outline a program of measurements which can in principle be made at the CERN LHC and the International Linear e^+e^- Collider (ILC) which can lead to a determination of the modular weights.

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Superstring theory provides a consistent quantum theory of gravity, together with all the necessary ingredients for a theory that potentially unifies all four forces of nature. However, in order to make any contact with phenomenology, it is essential to understand how the degeneracy associated with the many flat directions in the space of scalar fields (the moduli) is lifted to yield the true ground state, since many quantities relevant for physics at accessible energies are determined by the ground state values of these moduli. The discovery of a new class of compactifications, where the extra spatial dimensions are curled up to small sizes with fluxes of additional fields trapped along these extra dimensions has been exploited by Kachru et al. (KKLT) [1] to construct a concrete model with a stable, calculable ground state with a positive cosmological constant and broken supersymmetry. This toy model is based on type-IIB superstrings including compactification with fluxes to a Calabi–Yau orientifold. While the background fluxes serve to stabilize the dilaton and the moduli that determine the shape of the compact manifold, it is necessary to invoke a non-perturbative mechanism such as gaugino condensation on a D7 brane to stabilize the size of the compact manifold. Finally, a non-supersymmetric anti-brane ($\overline{\mathrm{D3}}$) is included in order to break supersymmmetry and obtain a de Sitter universe as required by observations. The resulting low energy theory thus has no unwanted light moduli, has a broken supersymmetry, and a positive cosmological constant, but of course does not yield the Standard Model (SM). The existence of these flux compactifications with stable calculable minima having many desired properties may be viewed as a starting point for the program of discovering a string ground state that may lead to the (supersymmetric) Standard Model at low energies, and which is consistent with various constraints from cosmology.

These considerations have recently motivated several authors to analyze the structure of the soft SUSY breaking (SSB) terms in models based on a generalization of the KKLT

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set-up [2]. The key observation is that because of the mass hierarchy,

$$m_{\text{moduli}} \gg m_{3/2} \gg m_{\text{SUSY}}, \tag{1}$$

that develops in these models, these terms receive comparable contributions via both modulus (gravity) and anomaly mediation of SUSY breaking [3], with their relative size parametrized by one new parameter α. Moreover, the hierarchy (1) that leads to this mixed modulus-anomaly mediated SUSY breaking (MM-AMSB) automatically alleviates phenomenological problems from late decaying moduli and gravitinos that could disrupt, for instance, the predictions of light element abundances from Big Bang nucleosynthesis. Upon integrating out the heavy dilaton field and the shape moduli, we are left with an effective broken supergravity theory of the observable sector fields denoted by $\hat{Q}$ and the size modulus field $\hat{T}$. The Kähler potential depends on the location of matter and Higgs superfields in the extra dimensions via their modular weights $n_i = 0$ (1) for matter fields located on D7 (D3) branes, or $n_i = 1/2$ for chiral multiplets on brane intersections, while the gauge kinetic function $f_a = \hat{T}^{l_a}$, where a labels the gauge group, is determined by the corresponding location of the gauge supermultiplets, since the power $l_a = 1$ (0) for gauge fields on D7 (D3) branes [4].

Within the MM-AMSB model, the SSB gaugino mass parameters, trilinear SSB parameters and sfermion mass parameters, all renormalized just below the unification scale (taken to be $Q = M_{\text{GUT}}$), are given by,

$$M_a = M_s\left(l_a\alpha + b_a g_a^2\right), \tag{2}$$

$$A_{ijk} = M_s(-a_{ijk}\alpha + \gamma_i + \gamma_j + \gamma), \tag{3}$$

$$m_i^2 = M_s^2\left(c_i\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right), \tag{4}$$

where $M_s \equiv \frac{m_{3/2}}{16\pi^2}$, b_a are the gauge β function coefficients for gauge group a and g_a are the corresponding gauge couplings. The coefficients that appear in (2)–(4) are given by $c_i = 1 - n_i$, $a_{ijk} = 3 - n_i - n_j - n_k$ and $\xi_i = \sum_{j,k} a_{ijk}\frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_2^a(f_i)$. Finally, y_{ijk} are the superpotential Yukawa couplings, C_2^a is the quadratic Casimir for the ath gauge group corresponding to the representation to which the sfermion $\tilde{f}_i$ belongs, γ_i is the anomalous dimension and $\dot{\gamma}_i = 8\pi^2\frac{\partial\gamma_i}{\partial\log\mu}$. Expressions for the last two quantities involving the anomalous dimensions can be found in Appendix of Ref. [5].

The MM-AMSB model is completely specified by the parameter set,

$$m_{3/2},\ \alpha,\ \tan\beta,\ \text{sign}(\mu),\ n_i,\ l_a. \tag{5}$$

The mass scale for the SSB parameters is dictated by the gravitino mass $m_{3/2}$. The phenomenological parameter α, which could be of either sign, determines the relative contributions of anomaly mediation and gravity mediation to the soft terms, and as mentioned above $|\alpha| \sim \mathcal{O}(1)$ is the hallmark of this scenario. Non-observation of large flavor changing neutral currents implies common modular weights of particles with the same gauge quantum numbers. Grand unification implies matter particles within the same GUT multiplet have common modular weights, and that the l_a are universal. We will assume that all

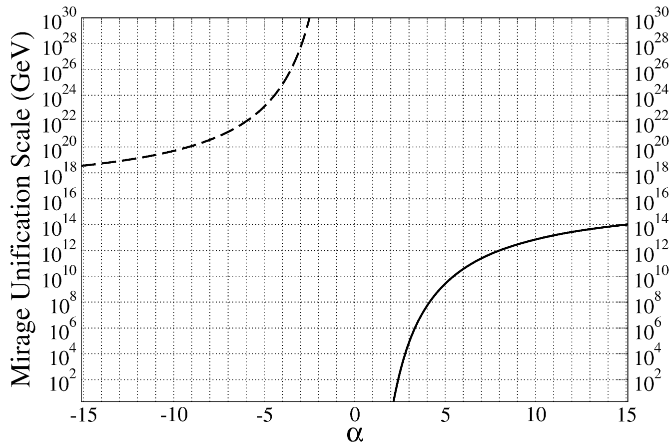

Fig. 1. A plot of the mirage unification scale versus modulus-AMSB mixing parameter α, assuming $l = 1$.

$l_a = l$ and, for simplicity, a common modular weight for all matter particles, but allow a different (common) one for the two Higgs doublets of the MSSM. The main purpose of this analysis is to see to what extent it will be possible to confirm our assumptions and deduce the value of l and the modular weights, assuming that SUSY is discovered at the LHC and is further studied at a TeV e^+e^- linear collider. Other aspects of MM-AMSB phenomenology have been examined in the literature [4–8].

The universality of the l_a leads to the phenomenon of *mirage unification* [4,5] of gaugino masses. In other words, gaugino mass parameters M_i (assuming that these can be extracted from the data) when extrapolated using one loop renormalization group equations (RGEs) would unify at a scale $Q = \mu_{\text{mir}} \neq M_{\text{GUT}}$, the scale of unification of gauge couplings. Indeed, the observation of gaugino unification at the mirage unification scale,

$$\mu_{\text{mir}} = M_{\text{GUT}} e^{-8\pi^2/(l\alpha)}, \tag{6}$$

would strikingly point to such a scenario. If $\alpha < 0$, $\mu_{\text{mir}} > M_{\text{GUT}}$, though one would have to continue extrapolation using MSSM RGEs to discover this! We assume here that $l \neq 0$, since this would be distinguished by a gaugino mass pattern as in the AMSB framework. While μ_{mir} determines $l\alpha$, the (unified) value of the gaugino masses extrapolated to $Q = \mu_{\text{mir}}$ is $M_a(\mu_{\text{mir}}) = M_s \times (l\alpha)$, and so gives the value of M_s (and so $m_{3/2}$).

We show the mirage unification scale versus $l\alpha$ in Fig. 1 for $l = 1$. The existence of a mirage unification scale is taken to be a "smoking gun" signature for MM-AMSB models. If supersymmetry is discovered and the various soft parameters are precisely measured at the weak scale, then extrapolation of the soft parameters via the RGEs to a point of unification [9] at a scale $\mu_{\text{mir}} \neq M_{\text{GUT}}$ would indicate that nature is in fact described by a MM-AMSB model with mirage unification! In the process, the scale μ_{mir}, or equivalently $l\alpha$, would be measured.

In the MM-AMSB framework with universal matter modular weights (for the first two generations whose Yukawa couplings are negligible), the SSB matter mass parameters also unify at