SUSY Model Building

Stuart Raby [a]

The Ohio State University, 191 W. Woodruff Ave, Columbus, OH 43210, USA

Abstract. I review some of the latest directions in supersymmetric model building, focusing on SUSY breaking mechanisms in the minimal supersymmetric standard model [MSSM], the "little" hierarchy and μ problems, etc. I then discuss SUSY GUTs and UV completions in string theory.

PACS. PACS-key describing text of that key – PACS-key describing text of that key

1 Introduction

The Supersymmetric Standard Model is motivated to solve the gauge hierarchy problem, i.e. to explain the small number $M_Z/M_{Pl} \sim 10^{-16}$. In the Standard Model this requires a fine-tuning of one part in 10^{32}. Supersymmetry makes this gauge hierarchy "technically natural" since scalar masses are tied to the value of their fermionic partners. And fermions have chiral symmetries which keep their masses only logarithmically sensitive to UV physics. Finally, if SUSY is spontaneously broken by some dynamical mechanism, we obtain a SUSY breaking scale M_{SUSY} of order $\approx e^{-\frac{8\pi^2}{g^2(M_{Pl})}} M_{Pl}$.

On the other hand, SUSY GUTs are motivated by the quest for understanding -

- charge quantization;
- family structure;
- gauge coupling unification, which works and defines a new scale of nature at $M_G \sim 10^{16}$ GeV, with $M_{SUSY} \sim 1$ TeV; and
- neutrino masses, with a See-Saw scale of order $(0.01 - 0.1) \times M_G$.

1.1 Minimal Supersymmetric Standard Model

The MSSM is defined by its minimal spectrum defined by the superfields -

- Q, U^c, D^c, L, E^c, N^c - fermions and sfermions;
- V^i, $(i = 1, 2, 3)$ - gauge bosons and gauginos;
- H_u, H_d - Higgs and Higgsinos.

And a $\mathbb{Z}_2$ symmetry defined by the operation -

$$F \longrightarrow -F, \quad H \longrightarrow H$$

where F, H are matter and Higgs multiplets, respectively. This symmetry is sometimes called R-parity (if it distinguishes particles and their superpartners), or

family reflection symmetry (matter parity) (if it does not distinguish particle and superpartner). This symmetry forbids the dangerous dimension 3 and 4 baryon and lepton number violating operators and guarantees that the lightest superpartner is stable and is a possible dark matter candidate.

1.2 SUSY Model Building

Perhaps before discussing the recent progress in SUSY model building, it may be worthwhile to put this whole program in context. There are several well-known problems, including the SUSY flavor problem, the μ problem, the "little" hierarchy problem, the SUSY CP problem, and the grand unified symmetry breaking and doublet-triplet splitting problems. In the first stage of model building, one searches for "mechanisms" which can solve these problems. Typically two or more "mechanisms" for solving a certain set of problems are mutually exclusive; meaning you have solved only one of these problems in the set and you can choose which problem you want to solve. It is of course much better to find one "mechanism" which solves more than one problem or a self-consistent set of "mechanisms" which simultaneously solve a set of problems. Finally, in the best case one would be able to solve all known problems in one self-consistent theory. This is clearly the goal of SUSY model building. With that said, let us now discuss some recent progress in SUSY model building.

2 Dynamical SUSY Breaking

There has been recent work on the subject of dynamical SUSY breaking in global supersymmetric theories by the following long list of authors - Intriligator, Seiberg & Shih; Dine, Feng & Silverstein; Kitano, Ooguri & Ookouchi; Argurio, Bertolini, Franco & Kachru; Murayama & Nomura; Dine & Mason; Brummer; Bai, Fan & Han; Dudas, Mourad & Nitti; Gomes-

Reino & Scrucca; Amariti, Girardello & Mariotto; Essig, Sinha & Torroba; Ahn; Serone & Westphal; Cho & Park; Abel, Dumford, Jaeckel & Khoze; Tatar & Wetenhall; van den Broek; Ferretti; Pastras; Ooguri, Ookouchi & Park; Kawano, Ooguri & Ookouchi. The bottom line of this work is that meta-stable SUSY breaking vacua in *global* SUSY are quite probable! In fact, in the talk by Murayama (this conference) it was argued that dynamical SUSY breaking is, in fact, no longer an obstacle to model building.

On the other hand, in another parallel series of recent articles by - Kachru, Kallosh, Linde & Trivedi; Choi, Falkowski, Nilles, Olechowski, Pokorski; Endo, Yamaguchi & Yoshioka; Choi, Jeong & Okumura; Falkowski, Lebedev & Mambrini; Kitano & Nomura; Lebedev, Nilles & Ratz; Lebedev, Loewen, Mambrini, Nilles & Ratz; Acharya, Bobkov, Kane, Kumar & Vaman (Shao); Randall & Sundrum; Giudice, Luty, Murayama & Rattazzi - it has been argued that meta-stable SUSY breaking vacua are generic in *local* SUSY /string theory vacua!

The bottom line of this general analysis is that meta-stable SUSY breaking vacua are ubiquitous and they have cosmologically long life-times. Of course, the latter feature is a very satisfying prerequisite.

I do not have time to elaborate in this talk on this general and more formal aspect of SUSY model building. Instead I will now discuss some specific examples of SUSY breaking mechanisms within the context of solving some of the SUSY problems mentioned earlier. The most important aspect of SUSY breaking relevant for low energy phenomenology concerns the mechanism for transmitting SUSY breaking from the *SUSY breaking sector* to the *observable sector* of the theory. There are still three fundamental mechanisms for mediating SUSY breaking known as -

- gravity mediated SUSY breaking,
- gauge mediated SUSY breaking, and
- anomaly mediated SUSY breaking.

In addition there are also variations of the above, known as - eg. gaugino, moduli, and dilaton mediation.

3 Focus on solving problems of the MSSM

3.1 "Little" hierarchy problem

LEP II data excludes a Standard Model Higgs boson with mass less than 114.4 GeV. This lower bound has generated a great deal of angst among SUSY aficionados. The reason is that, as we will now argue, this requires a fine-tuning of parameters. This is known as the "little" hierarchy problem.

Consider the one loop corrected value of the Higgs mass in the MSSM. We have

$$m_h^2 \approx M_Z^2 + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right) \quad (1)$$

where $X_t^2 = |A_t|^2/m_{\tilde{t}}^2$. In order to satisfy the LEP bound, one needs either

1. $m_{\tilde{t}} \geq 1$ TeV, or
2. $X_t \approx \pm\sqrt{6}$.

The second possibility is known as the large mixing angle limit. Very special SUSY breaking scenarios are needed to obtain this. The first possibility is to have a heavy stop. If we now make the reasonable assumption that all scalar masses at the high energy scale are of the same order, we run into trouble. Consider the tree level Z mass given by (for moderate values of $\tan\beta \geq 5$) by

$$\frac{M_Z^2}{2} \approx -m_{H_u}^2(M_Z) - \mu^2. \quad (2)$$

Then for $-m_{H_u}^2(M_Z) \approx m_{\tilde{t}}^2 \approx \mathcal{O}(1 \text{ TeV})$, we need to fine-tune $\mu^2 = m_{\tilde{t}}^2(1 - \epsilon)$ such that

$$\epsilon \approx \frac{M_Z^2}{m_{\tilde{t}}^2} \leq 10^{-2}. \quad (3)$$

This argument can be made a bit more rigorous by defining the SUSY breaking parameters at the GUT scale and then using the renormalization group equations to find (for $\tan\beta = 10$)

$$M_Z^2 = -1.9\mu^2 + 5.9M_3^2 - 1.2m_{H_u}^2 + 1.5m_{\tilde{t}}^2 \quad (4)$$
$$-0.8A_t M_3 + 0.2A_t^2 + \ldots.$$

where the parameters on the RHS are evaluated at M_{GUT}. Thus we see that either way we need to fine-tune parameters by O $(10^{-2} - 10^{-3})$. Of course, this fine-tuning should be compared to one part in 10^{32} in the Standard Model. So perhaps it is NOT a huge problem. Note also that one can minimize the amount of fine-tuning by having $M_3 \ll 1$ TeV, i.e. with a light gluino.

3.2 Some suggested solutions to the "Little" Hierarchy problem

3.2.1 Gauge Messenger model

Dermisek and Kim [2] have shown that if one has soft SUSY breaking boundary conditions which are non-standard, and in particular, the stop mass squared starts out negative, then it is possible to solve the "little" hierarchy problem. In Fig. 1 it is shown that it is possible to obtain $X_t = \frac{A_t}{m_{\tilde{t}}}$ large and M_3 small, simultaneously.

Moreover, they consider a scenario with a GUT group SU(5) and an adjoint Σ whose vev breaks SU(5) to the SM and at the same time breaks supersymmetry, such that the effective SUSY breaking scale $\Lambda = \frac{\alpha_{GUT}}{4\pi}\left|\frac{F_\Sigma}{M_{GUT}}\right|$. This sets the soft SUSY breaking boundary conditions. The stop mass squared is naturally negative and the gaugino masses satisfy: $M_3 = 4\Lambda$, $M_2 = 6\Lambda$, $M_1 = 10\Lambda$. The find a perfectly acceptable low energy spectrum with all squarks and sleptons with positive masses squared. Moreover, the "little" hierarchy problem is resolved with small M_3 and significant X_t as seen in Fig. 2 taken from [3]. The bottom line for the gauge messenger scenario is
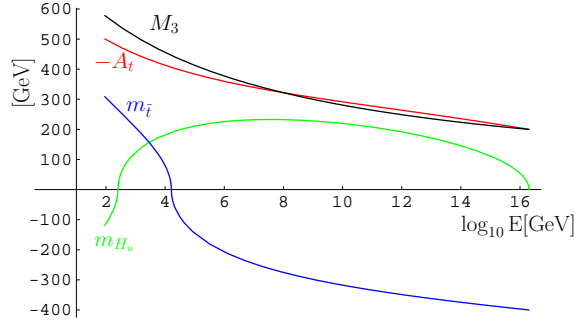
Fig. 1. Renormalization group running of relevant SSBs for $\tan\beta = 10$ and GUT scale boundary conditions: $-A_t = M_3 = 200$ GeV, $m_{\tilde{t}}^2 = -(400$ GeV$)^2$. Note, $m_{H_u} \equiv m_{H_u}^2/\sqrt{|m_{H_u}^2|}$ and $m_{\tilde{t}} \equiv m_{\tilde{t}}^2/\sqrt{|m_{\tilde{t}}^2|}$. Fig. from Ref. [2]
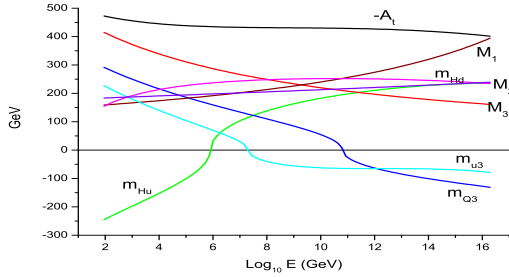

Fig. 2. Evolution of soft SUSY breaking parameters $-A_t$ (black), Q_3, U_3 mass ([dark, light] blue), H_u, H_d mass (green magenta) and gaugino masses starting with gauge messenger boundary conditions at M_{GUT}. Note, for example, $m_{H_u} \equiv m_{H_u}^2/\sqrt{|m_{H_u}^2|}$. Fig. from Ref. [3]

- gauge mediation with gauge messengers,
- it solves the flavor problem,
- 5% to 10 % fine tuning for electroweak symmetry breaking,
- gravitino LSP,
- stau NLSP, but
- on the downside, it lacks a UV completion, and
- it doesn't address the μ problem.

3.2.2 Sweet spot supersymmetry

Sweet spot supersymmetry (Ibe and Kitano [4]) combines gauge and gravity mediation with an effective messenger/ fundamental scale, $M_{mess} \sim 10^{-3}M_{GUT}$. The model solves the flavor problem, since scalar masses are predominantly due to gauge mediation, with $F/M_{mess} >> F/M_{Pl}$, and not gravity mediation. It solves the μ and $B\mu$ problems, a la Giudice-Masiero. The authors also discuss a possible UV completion with GUT breaking and Higgs double-triplet splitting. The one downside of this model is that it does not address the "little" hierarchy problem. The gravitino is the LSP with a mass of order 1 GeV.
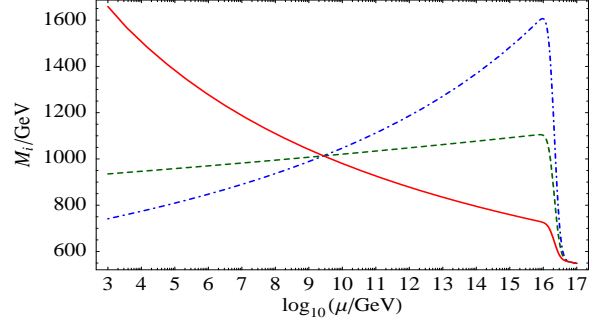

Fig. 3. For $\alpha = 1$ the gaugino masses meet at a scale of order 10^9 GeV. Fig. from Ref. [12]

3.2.3 Mirage mediation

Mirage mediation is based on the work of KKLT [1] demonstrating moduli stabilization and SUSY breaking in Type II superstrings. The initial analysis of the consequences of SUSY breaking in the observable sector is found in Ref. [5]. It was realized that the contributions of both gravity/moduli mediation and anomaly mediation are important [6,7,8,9,10]. If one defines the ratio α = anomaly : Modulus SUSY breaking, then one finds for $\alpha = 1$ that the gaugino masses unify at a "mirage" scale of order 10^9 GeV (see Fig. 3), while gauge couplings continue to unify at the GUT scale, $M_G \sim 2\times10^{16}$ GeV. As discussed in Refs. [11,12, 13,14], with a choice of $\alpha = 2$ one can have the gaugino masses unify at the electroweak scale (see Fig. 4). Moreover with light gauginos and sfermions one can now ameliorate the "little" hierarchy problem (see Fig. 5).

The bottom line is that this model has a heavy gravitino with

$$m_{3/2} \approx \log(M_{Pl}/m_{3/2})m_{soft} \qquad (5)$$
$$\approx 4\pi^2 m_{soft} \approx 10 \text{ TeV}.$$

In addition

- it preserves gauge coupling unification at $M_{GUT} \sim 10^{16}$ GeV ;
- gaugino masses unify, BUT typically below the GUT scale;
- it cures the negative slepton mass squared problem of pure anomaly mediation;
- and it can address the little hierarchy problem;
- On the downside, the solution to the SUSY flavor problem is model dependent, i.e. it depends on the supposition that there exists a model in which all fermions reside on a $D7$ brane.

3.3 Gaugino Code

Choi and Nilles [15], after analyzing several different SUSY breaking mechanisms, suggest that gauginos are a sensitive window onto the fundamental SUSY breaking mechanism. In particular, they find the following gaugino spectra -

- mSugra and Gauge mediated SUSY breaking
    $M_1 : M_2 : M_3 \cong 1 : 2 : 6 \cong g_1^2 : g_2^2 : g_3^2;$
- anomaly pattern
    $M_1 : M_2 : M_3 \cong 3.3 : 1 : 9;$
- mirage pattern
    $M_1 : M_2 : M_3 \cong 1 : 1 : 1$ for $\alpha = 2$,
    $M_1 : M_2 : M_3 \cong 1 : 1.3 : 2.5$ for $\alpha \cong 1;$
- gauge messenger pattern
    $M_1 : M_2 : M_3 \cong 1 : 1.1 : 2.$

4 Higgs "portal" on physics beyond the MSSM

There are several indicators that the Higgs bosons are very special. In SUSY theories, the "little" hierarchy problem, the μ problem and fermion masses all point to the Higgs as being the "portal" onto new physics beyond the Standard Model. In the context of non-SUSY theories, this idea has been expressed in Refs. [16,17]. In SUSY theories, this idea has come up in several different contexts. For an effective field theory analysis in SUSY theories, see [18,19].

Consider, for example, the next to minimal SUSY model [NMSSM]. In the NMSSM [20,21,22,23,24,25,26,19] with an additional gauge singlet field S and superpotential of the form

$$W = SH_uH_d + S^3 \qquad (6)$$
$$\text{or}$$
$$= (\mu + \lambda_S \; S)H_uH_d + \frac{1}{2}M_SS^2$$

it has been shown that the Higgs may be heavier than the LEPII bound even with a light stop due to an additional shift in mass.

On the other hand, the Higgs may be lighter than the LEPII bound, BUT it has a new *invisible* decay mode into two light CP odd Higgs bosons, a [27,28]. If $m_a < 2m_b$, then the decay to two bottom quarks is forbidden. As a result a light Higgs with mass ~ 100 GeV would not have been seen at LEP. Moreover, if $m_a > 2m_\tau$ the decay $h \to 2a \to 4\tau$ might have been recorded at LEP (and might be seen, if only they re-analyze their data) [27,28].

5 MSSM at large $\tan\beta$

There were two interesting talks in this conference on the subject of the MSSM at large $\tan\beta \sim 50$ which I would like to briefly review. The first is a talk by Heinemeyer. He addresses the recent CDF data on an excess of Higgs to two τ events at a mass of 160 GeV. Heinemeyer and collaborators [29] show that it is possible to simultaneously fit the CDF data with the decay of the CP odd Higgs, A with $m_A = 160$ GeV, and have a light Higgs, h with $m_h = 115$ GeV. The region of soft SUSY breaking parameter space which accomplishes this feat has $A_0 \approx -2m_0 \sim 2$ TeV (note, their sign convention for A_0 differs from others), non-universal Higgs masses
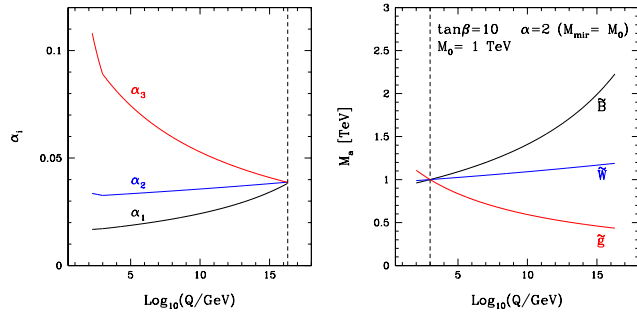

Fig. 4. With $\alpha = 2$ gaugino masses unify at the weak scale, while gauge couplings still unify at $M_G \sim 2 \times 10^{16}$ GeV. Fig. from Ref. [14]
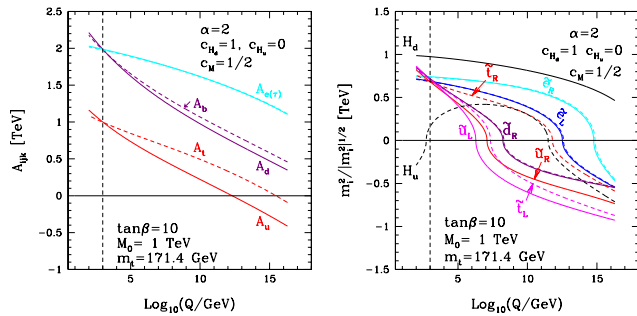

Fig. 5. Evolution of soft SUSY breaking parameters in mirage mediation with $\alpha = 2$. Fig. from Ref. [14]

and $\tan\beta \sim 50$. It is important to emphasize that at the same time they are consistent with data on $b \to s\gamma$ and the bounds on the decay $B_s \to \mu^+ \; \mu^-$.

In the second talk by Belyaev it was shown that there are regions of MSSM parameter space with $\tan\beta \sim 35$ and a very light Higgs with mass $m_h = 60$ GeV. The Higgs would have escaped the LEP bounds since the branching ratio for the decay $h \to bb$ is suppressed, while the branching ratio for $h \to \tau\tau$ is enhanced [30].

6 SUSY GUTs

Supersymmetric grand unified theories explain charge quantization of quarks and leptons and give hope of explaining, or at least providing an organizing principle to explain, the hierarchy of fermion masses. The gauge group SO(10) is very special in this regard, since one family of quarks and leptons (including a right-handed neutrino necessary for a See-Saw mechanism) are contained in the spinor representation, i.e.

$$16 : Q, U^c, D^c, L, E^c, N^c,$$

where I listed the Weyl spinors in one family. And the two Higgs doublets needed in the MSSM are contained in the 10 dimensional representation, i.e.

$$10 : H_u, H_d, T, T^c,$$

where T, T^c are color triplet Higgs. The color triplets must necessarily have mass of order the GUT scale,

while the Higgs doublets are effectively massless at this scale.

Thus ordinary 4 dimensional SUSY GUTs have three inherent problems. The first is the doublet-triplet splitting problem as discussed above. The second is inventing a GUT symmetry breaking sector which spontaneously breaks the GUT symmetry and leaves only the MSSM states below the GUT scale. And the third problem is the suppression of the nucleon decay rate below the experimental bounds. None of these problems is insurmountable. However, the examples which exist in the literature are far from being pretty and it is even more difficult to imagine them coming from a more fundamental theory, such as string theory.

6.1 Fermion masses in SO(10)

If the standard electroweak Higgs boson is solely contained in a **10** dimensional representation and quarks and leptons are in **16**s, there is only one Yukawa coupling that is allowed at the renormalizable level, i.e.

$$\lambda 16\ 10\ 16$$

with

$$\lambda_t = \lambda_b = \lambda_\tau = \lambda_{\nu_\tau} \equiv \lambda.$$

We assume that this is only valid for the third family.

Within the context of SUSY SO(10) there are two different versions in the literature of a so-called "minimal" SO(10) SUSY model including all three families.

1.

$$W \supset 16\ 10\ 16 + 16\ \overline{126}\ 16 + 16\ 120\ 16. \quad (7)$$

This version of "minimal SO(10)" has been discussed by Aulakh, Babu, Bajc, Chen, Fukuyama, Mahanthappa, Mohapatra, Senjanovic, etc. It is the minimal *renormalizable* SO(10) SUSY model.

2.

$$W \supset 16\ 10\ 16 + 16\ 10\ \frac{45}{M}\ 16 + \cdots \quad (8)$$

In this version of "minimal SO(10)" the fermion hierarchy derives from a hierarchy of effective nonrenormalizable operators suppressed by some fundamental scale, M. This version has been discussed by Albright, Anderson, Babu, Barr, Barbieri, Berezhiani, Blazek, Carena, Dermisek, Dimopoulos, Hall, Pati, Raby, Romanino, Rossi, Starkman, Wagner, Wilczek, Wiesenfeldt, Willenbrock, etc.

Note, only the latter version has a possible UV completion to string theory.

Consider a particular "minimal" SO(10)$\times(D_3 \times U(1)$ family symmetry) model [DR] [31,32].[1] This model

Table 1. Parameters in the DR model.

Sector	#	Parameters
gauge	3	$\alpha_G,\ M_G,\ \epsilon_3,$
SUSY (GUT scale)	5	$m_{16},\ M_{1/2},\ A_0,\ m_{H_u},\ m_{H_d},$
textures	11	$\epsilon,\ \epsilon',\ \lambda,\ \rho,\ \sigma,\ \tilde{\epsilon},\ \xi,$
neutrino	3	$M_{R_1},\ M_{R_2},\ M_{R_3},$
SUSY (EW scale)	2	$\tan\beta,\ \mu$

predicts Yukawa coupling unification for the third family. The full set of 3×3 Yukawa matrices is very simple and very much constrained by symmetry. It is given by

$$Y_u = \begin{pmatrix} 0 & \epsilon'\ \rho & -\epsilon\ \xi \\ -\epsilon'\ \rho & \tilde{\epsilon}\ \rho & -\epsilon \\ \epsilon\ \xi & \epsilon & 1 \end{pmatrix} \lambda \quad (9)$$

$$Y_d = \begin{pmatrix} 0 & \epsilon' & -\epsilon\ \xi\ \sigma \\ -\epsilon' & \tilde{\epsilon} & -\epsilon\ \sigma \\ \epsilon\ \xi & \epsilon & 1 \end{pmatrix} \lambda$$

$$Y_e = \begin{pmatrix} 0 & -\epsilon' & 3\ \epsilon\ \xi \\ \epsilon' & 3\ \tilde{\epsilon} & 3\ \epsilon \\ -3\ \epsilon\ \xi\ \sigma & -3\ \epsilon\ \sigma & 1 \end{pmatrix} \lambda$$

$$Y_\nu = \begin{pmatrix} 0 & -\epsilon'\ \omega & \frac{3}{2}\ \epsilon\ \xi\ \omega \\ \epsilon'\ \omega & 3\ \tilde{\epsilon}\ \omega & \frac{3}{2}\ \epsilon\ \omega \\ -3\ \epsilon\ \xi\ \sigma & -3\ \epsilon\ \sigma & 1 \end{pmatrix} \lambda.$$

where all the arbitrary order one coefficients are explicitly listed. The model fits all fermion masses and mixing angles very well, including neutrinos. Good fits require the soft SUSY breaking parameters to satisfy

$$-A_0 \approx 2m_{16} \gg M_{1/2} \sim \mu, \quad (10)$$

non-universal Higgs masses and $\tan\beta \approx 50$ [33]. At first sight, this is apparently the same region of parameter space discussed in the talk by Heinemeyer. However, recently I have learned that the sign of A_0 (here) is opposite to that of Heinemeyer et al. [29].[2] So there is no direct comparison between the results. Nevertheless, there has been a recent analysis of this SO(10) model whose results were presented at this conference by Altmannshofer, see "Challenging SO(10) SUSY GUTs with family symmetries through FCNC processes" [34]. They perform a global χ^2 analysis of the DR model [31,32]. The model has a total of 24 parameters at the GUT scale, which must be varied to compare to low energy data (see Table 1). This should be compared to the 27 parameters in the Standard Model or 32 in the MSSM. Their analysis confirms previous results, but they now extend the analysis to include b flavor physics such as $b \to s\gamma$, $b \to sl^+l^-$, $B \to \tau\nu$, $B - \bar{B}$ mixing and $B_s \to \mu^+\mu^-$. The bottom line is that the model has some difficulty fitting the processes $b \to sl^+l^-$ and $B \to \tau\nu$. Good fits require heavy scalars with mass greater than 10 TeV. More models need to be tested as rigorously in order to eventually find a Standard GUT model.

---

[1] This is an example of the second type of minimal SO(10) SUSY model.

[2] Private communication, W. Altmannshofer, D. Guadagnoli, and D. M. Straub.

Fig. 6. E(6) orbifold GUT in $M_4 \times S^1/(Z_2 \times Z_2')$. Fig. from Ref. [36]
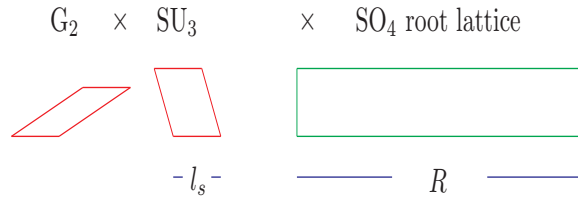

Fig. 7. $(T^2)^3$ defined in terms of two dimensional planes mod translations along the vectors of the $G_2 \times SU(3) \times SO(4)$ root lattices. Note, we assume one direction is much larger than the others.

7 UV completion of effective field theories

Orbifold GUTs in 5 or 6 dimensions can solve some of the problems of 4 dimensional GUTs. One starts with a GUT in higher dimensions and then uses boundary conditions at the orbifold fixed points to break the GUT symmetry, without a complicated GUT symmetry breaking sector, and also split Higgs doublets and triplets, by projecting the triplets out of the theory. In many cases this has the added effect of eliminating the baryon number violating operators in SUSY GUTs. See for example the work of Kawamura; Hall & Nomura; Contino, Pilo, Rattazzi & Trincherini; Altarelli, Feruglio & Masina; Dermisek & Mafi; H.D. Kim & Raby; Asaka, Buchmuller & Covi; Lee; and Hebecker & March-Russell. Of course, the inherent problem with orbifold GUT field theories is that they are not renormalizable. Thus they are effective field theories defined below some cut-off scale M^*. The penultimate UV completion would be to embed orbifold GUTs into 10 dimensional string theory. Then $M^* = M_s$, the string scale. The first steps in this program have already been taken.

Consider the following E(6) orbifold GUT in 5 dimensions [35,36]. The theory is initially defined on Minkowski space times a circle. The $Z_2 \times Z_2'$ orbifold leaves a line segment with two boundaries. At the left boundary E(6) is broken to SO(10) while at the right boundary it is broken to $SU(6) \times SU(2)_R$. The unbroken gauge symmetry is the intersection of the two, i.e. Pati-Salam - $SU(4)_c \times SU(2)_L \times SU(2)_R$. The bulk modes include an effective N=2 gauge sector and 4 $(27 + 27^c)$ hypermultiplets.[3] In addition there are two families localized on the SO(10) fixed point (see Fig. 6).

This model was obtained as the low energy limit of the $E(8) \times E(8)$ heterotic string in 10D [35,36]. Six of the ten dimensions are compactified on the product of 3 two tori (Fig. 7) defined in terms of the given root lattices. The tori are then orbifolded by a $Z_6 = Z_3 \times Z_2$ symmetry with Wilson lines in the SU(3) and SO(4) torus. The Z_6 symmetry is also embedded into the $E(8) \times E(8)$ root lattice in terms of a shift vector V_6, consistent with modular invariance constraints.

Upon orbifolding the first two tori by Z_3 with a Wilson line in the SU(3) torus one obtains the effective 5 dimensional orbifold (see Fig. 8). The bulk modes, gauge and hypermultiplets, are the massless string states from the untwisted or Z_3 twisted sectors. All of these string states move freely in Minkowski space $\times$ the SO(4) torus. In recent years several groups have discussed orbifold GUTs from the heterotic string - Kobayashi, Raby & Zhang; Forste, Nilles, Vaudrevange & Wingerter; Buchmuller, Hamaguchi, Lebedev & Ratz; JE Kim, JH Kim & Kyae; and Buchmuller, Ludeling & Schmidt.

Heterotic strings in 10 dimensions compactified on a 6 dimensional compact space have been used to obtain 3 family models with the MSSM spectrum in 4 dimensions. See the work of Bouchard, Braun, Buchmuller, Cleaver, Donagi, Faraggi, Hamaguchi, He, Kobayashi, Lebedev, Ludeling, Nanopoulos, Nilles, Ovrut, Pantev, Pokorski, Raby, Ramos-Sanchez, Ratz, Reinbacher, Ross, Vaudrevange, Waldram, Wingerter, and Zhang. Also see the talks by Nilles, Kyae, Luedeling, Lebedev & Wingerter in this conference. For a recent paper on constructing 3 family MSSM models from the heterotic string see [37] and references therein.

8 Conclusions

In recent years, SUSY model building has focused on the "little hierarchy, μ and $B\mu$ problems. There is still no Standard Model of SUSY breaking. BUT metastable vacua appear to be generic and easy to obtain. Higgs and gauginos are portals on to new physics beyond the MSSM. Finally, the search for a UV completion of the MSSM through SUSY GUTs to orbifold GUTs and ultimately to the heterotic string is now very much in progress.

---

[3] I am using 4D superfield notation.

$$G_2 \qquad SU_3 \qquad\qquad SO_4$$

$$V,\ \Sigma\ \in \mathbf{E_6}$$

$$(\mathbf{27} + \overline{\mathbf{27}})$$
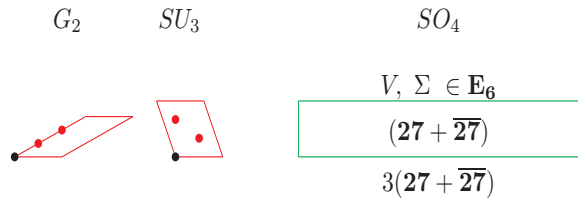
$$3(\mathbf{27} + \overline{\mathbf{27}})$$

Fig. 8. These are the massless components of the heterotic string on $(T^2)^3/Z_3$ plus one Wilson line in the SU(3) torus. The massless states come from the untwisted sector, or twisted states sitting on the pictured fixed points. All are free to move around in the SO(4) torus.

References

1. S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi, Phys. Rev. D **68** (2003) 046005 [arXiv:hep-th/0301240].
2. R. Dermisek and H. D. Kim, Phys. Rev. Lett. **96**, (2006) 211803. [arXiv:hep-ph/0601036].
3. R. Dermisek, H. D. Kim and I. W. Kim, JHEP **0610** (2006) 001 [arXiv:hep-ph/0607169].
4. M. Ibe and R. Kitano, arXiv:0705.3686 [hep-ph].
5. K. Choi, A. Falkowski, H. P. Nilles, M. Olechowski and S. Pokorski, JHEP **0411** (2004) 076 [arXiv:hep-th/0411066].
6. M. Endo, M. Yamaguchi and K. Yoshioka, Phys. Rev. D **72** (2005) 015004 [arXiv:hep-ph/0504036].
7. K. Choi, K. S. Jeong and K. i. Okumura, JHEP **0509** (2005) 039 [arXiv:hep-ph/0504037].
8. A. Falkowski, O. Lebedev and Y. Mambrini, JHEP **0511** (2005) 034 [arXiv:hep-ph/0507110].
9. O. Loaiza-Brito, J. Martin, H. P. Nilles and M. Ratz, AIP Conf. Proc. **805** (2006) 198 [arXiv:hep-th/0509158].
10. O. Lebedev, V. Lowen, Y. Mambrini, H. P. Nilles and M. Ratz, JHEP **0702** (2007) 063 [arXiv:hep-ph/0612035].
11. K. Choi, K. S. Jeong, T. Kobayashi and K. i. Okumura, Phys. Lett. B **633** (2006) 355 [arXiv:hep-ph/0508029].
12. O. Lebedev, H. P. Nilles and M. Ratz, arXiv:hep-ph/0511320.
13. R. Kitano and Y. Nomura, Phys. Lett. B **631** (2005) 58 [arXiv:hep-ph/0509039].
14. K. Choi, K. S. Jeong, T. Kobayashi and K. i. Okumura, Phys. Rev. D **75** (2007) 095012 [arXiv:hep-ph/0612258].
15. K. Choi and H. P. Nilles, JHEP **0704** (2007) 006 [arXiv:hep-ph/0702146].
16. B. Patt and F. Wilczek, arXiv:hep-ph/0605188.
17. D. O'Connell, M. J. Ramsey-Musolf and M. B. Wise, Phys. Rev. D **75** (2007) 037701 [arXiv:hep-ph/0611014].
18. A. Brignole, J. A. Casas, J. R. Espinosa and I. Navarro, Nucl. Phys. B **666** (2003) 105 [arXiv:hep-ph/0301121].
19. M. Dine, N. Seiberg and S. Thomas, arXiv:0707.0005 [hep-ph].
20. J. R. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski and F. Zwirner, Phys. Rev. D **39** (1989) 844.
21. M. Drees, Int. J. Mod. Phys. A **4** (1989) 3635.
22. U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Phys. Lett. B **315** (1993) 331 [arXiv:hep-ph/9307322].
23. P. N. Pandita, Z. Phys. C **59** (1993) 575.
24. F. Franke and H. Fraas, Phys. Lett. B **353** (1995) 234 [arXiv:hep-ph/9504279].
25. S. F. King and P. L. White, Phys. Rev. D **53** (1996) 4049 [arXiv:hep-ph/9508346].
26. U. Ellwanger, M. Rausch de Traubenberg and C. A. Savoy, Nucl. Phys. B **492** (1997) 21 [arXiv:hep-ph/9611251].
27. R. Dermisek and J. F. Gunion, Phys. Rev. Lett. **95** (2005) 041801 [arXiv:hep-ph/0502105].
28. R. Dermisek and J. F. Gunion, arXiv:0709.2269 [hep-ph].
29. J. R. Ellis, S. Heinemeyer, K. A. Olive and G. Weiglein, Phys. Lett. B **653** (2007) 292 [arXiv:0706.0977 [hep-ph]].
30. A. Belyaev, Q. H. Cao, D. Nomura, K. Tobe and C. P. Yuan, arXiv:hep-ph/0609079.
31. R. Dermisek and S. Raby, Phys. Rev. D **62** (2000) 015007 [arXiv:hep-ph/9911275].
32. R. Dermisek, M. Harada and S. Raby, Phys. Rev. D **74** (2006) 035011 [arXiv:hep-ph/0606055].
33. T. Blazek, R. Dermisek and S. Raby, Phys. Rev. Lett. **88** (2002) 111804 [arXiv:hep-ph/0107097].
34. M. Albrecht, W. Altmannshofer, A. J. Buras, D. Guadagnoli and D. M. Straub, arXiv:0707.3954 [hep-ph].
35. T. Kobayashi, S. Raby and R. J. Zhang, Phys. Lett. B **593** (2004) 262 [arXiv:hep-ph/0403065].
36. T. Kobayashi, S. Raby and R. J. Zhang, Nucl. Phys. B **704** (2005) 3 [arXiv:hep-ph/0409098].
37. O. Lebedev, H. P. Nilles, S. Raby, S. Ramos-Sanchez, M. Ratz, P. K. S. Vaudrevange and A. Wingerter, arXiv:0708.2691 [hep-th].