SUSY/SUGRA/String phenomenology

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A review of the current status of SUSY/SUGRA/String phenomenology is given.

1. INTRODUCTION

The unification of gauge coupling constants observed in the extrapolation of the high precision LEP data points to the general validity of the ideas of supersymmetry/supergravity and grand unification. This apparent success also then validates the underlying field theoretic approach at least up to the scale $M_{\text{GUT}} \approx 10^{16}$ GeV. It is then entirely reasonable that one may extrapolate the grand unified theory to the post GUT region perhaps all the way up to the string scale $M_{\text{str}}\llbracket1\rrbracket$ where

$$M_{\text{str}} = \frac{e^{(1-\gamma)/2}3^{-\frac{4}{3}}}{4\pi}g_{\text{string}}M_{\text{Planck}} \approx 5 \times 10^{17}(1)$$

Thus $M_{\text{str}}$ appears to provide a natural cutoff above which one is in the domain of quantum gravity while below this scale physics may be described by an effective field theory based on the principle of gauge invariance and unified symmetry. Consistency of the two approaches is then ensured by matching the grand unified theory with the string at the string scale. In this sense the string serves to provide the boundary conditions for the field theoretic approach at the scale $M_{\text{str}}$.

Our objective of course is to eventually find the correct string model which will probe physics in a continuous fashion from the very low energy scales all the way up to the Planck scale. However, among the many problems to be overcome in string model building is the enormity of the number of possible vacua. For example, the ten dimensional $E_8 \times E_8$ heterotic string\textsuperscript{2} after compactification can generate models with rank up to 22. This yields many possibilities and a variety of phenomenological models such as those based on free field constructions, orbifolds, Calabi-Yau compatifications etc have been investigated\textsuperscript{3}.

2. String Models

One way to limit the number of possibilities in string model building is to use the constraint that a GUT model exist below the string scale. As mentioned in the Introduction the LEP data appears to give support to this picture. Thus it appears very appealing to build on the success of SUSY/SUGRA GUTS implied by the LEP data and try to deduce a GUT model from strings. Now the appearance of a gauge symmetry in strings is characterized by world sheet currents whose operator product expansion defines the Kac-Moody level $k$ of the algebra:

$$j_c(z)j_b(w) \sim \frac{if_{abc}}{z-w}j_a(w) + \frac{k}{2} \frac{\delta_{ab}}{(z-w)^2} + .. (2)$$

where $k$ is a positive integer for non-abelian groups while it is unconstrained for the abelian case.

The earliest attempts at string model building were all within the framework of level 1. Here while one can achieve a unified symmetry with a desirable gauge group such as SU(5), SO(10) or E(6), one has the problem of not having massless adjoint scalars which allow one to break the unified symmetry. While massless adjoint scalars can be gotten at level 2, there are presently no known models which have 3 massless generations at this level. For level 3 one can generate models with 3 massless generations as well as massless adjoint scalars.

\textsuperscript{*}This research is supported in part by NSF grant number PHY-9602074.
Over the last couple of years the construction of level 3 models has been energetically pursued and models of the type SU(5), SO(10), and E(6) have been constructed\[3\]. These models have many desirable features such as 3 chiral families, N=1 spacetime supersymmetry, massless scalars in the adjoint representation and a non-abelian hidden sector. The phenomenology of one of the E(6) models and of the related SO(10) model has also been partially examined\[8\]. With the assumption that a non-perturbative mechanism stabilizes the dilaton VEV, the gaugino condensation scale here is around $10^{13}$ GeV leading to a weak SUSY scale in the TeV region. However, the adjoint Higgs is flat modulus, and the mass matrix for the Higgs doublets is rank 6 requiring a fine tuning to get a pair of massless Higgs doublets. Similarly, the texture for the up quarks is rank 3 rather than rank 1 as is desirable for the mass hierarchy. Here again one needs a fine tuning for rank reduction. A satisfactory resolution to these may perhaps arise in other models of this generic type\[5\] whose phenomenology is not yet fully investigated.

Of course, it is not necessary to have a GUT for the unification of the gauge couplings $g_i$ in strings as the SM gauge group can emerge directly at the string scale. Here one has \[\text{(3)}\]

$$g_i^2 k_i = g_{\text{string}}^2 \left( \frac{8\pi G_N}{\alpha'} \right)$$

where $k_i$ are the Kac-Moody levels of the subgroups, $G_N$ is the Newtonian constant and $\alpha'$ is the Regge slope. One consequence of this possibility is that models of this type will in general possess fractionally charged neutral states unless the SM gauge group arises from an unbroken SU(5) at the string scale, or unless $k_i > 1$\[8\]. In models with fractionally charged states one must find a mechanism to either make them massive or confine them to produce bound states which carry integral charges.

We discuss now briefly the coupling constant unification in string models and LEP data. Using renormalization group one has in general

$$\frac{16\pi^2}{g_i^2(M_Z)} = k_i \frac{16\pi^2}{g_{\text{string}}} + b_i ln \left( \frac{M_{\text{str}}^2}{M_Z^2} \right) + \Delta_i$$ \[\text{(4)}\]

where $\Delta_i$ contain both stringy and non-stringy effects. Firstly, one knows that if one uses the MSSM spectrum and runs the RG equations from the string scale down to $M_Z$, then values of $sin^2\theta_W$ will differ from experiment by many standard deviations. This situation can be corrected by either finding large threshold corrections, or using non-standard Kac-Moody levels or finding extra matter in vector like representations in the region between the string scale and the electroweak scale. The last possibility where one has extra matter at an intermediate scale currently appears to be the most promising one\[6\].

Finally, one may speculate as to what the future possibilities for string model building may be. Over the past two years we have seen what is being called the second string revolution. This development concerns the fact that one finds that the five string theories (Type 1, Type 2A, Type 2B, SO(32) heterotic and $E_8 \times E_8$ heterotic) are connected by dualities and it is conjectured that they all arise from a single eleven dimensional unified theory, the M theory, whose low energy limit is eleven dimensional supergravity. Thus, for example, it appears that the strongly coupled SO(32) heterotic string is the weakly coupled 10D typeI string\[11\], and that the dual of 10D $E_8 \times E_8$ heterotic string is the eleven dimensional theory compactified on $S^1/Z_2$\[12\].

We should see a new wave of model building which exploits the power of dualities. Already some work has appeared at the level of model building where the strong coupling limit of the $E_8 \times E_8$ heterotic string is exploited\[13\]. Another application is in black hole thermodynamics and the partial success in the deduction of the Bekenstein-Hawking entropy/area law\[14\] from a microscopic viewpoint\[4\]. The analysis here involves the new string (D-brane) degrees of freedom. Finally a remarkable new result concerns the appearance of additional massless modes that can arise even in the weak coupling limit of M theory resulting from an expansion of the gauge group at specific points in the moduli space\[11\]. This phenomenon may lead to yet new possibilities for model building.
3. Supergravity Unification

It is reasonable to conclude that while the string holds great many possibilities the correct string model still alludes us. For this reason one must continue with a bottom up approach as well, and an effective field theory is the correct framework for such an approach. The basic elements of this approach have been in place since the early eighties[18–21]. We recall briefly what this approach constitutes. One assumes that below the string scale one has an effective N=1 supergravity theory coupled to matter and gauge. The theory is defined in terms of three arbitrary functions. These are the gauge kinetic energy function $f_{a\beta}(Q_a, Q^\alpha)$, the superpotential $W(Q_a)$, and the Kahler potential $K(Q_a, Q^\alpha)$ where $Q_a$ are the matter fields and $Q^\alpha$ are their hermitian conjugates. The effective potential of this theory is given in terms of $G$ which depends on a combination of $W$ and $K$: $G=\kappa^2 K + \ln|\kappa^a|W|^2|$ where $\kappa \equiv 1/M_{\text{Planck}}$.

In the effective N=1 supergravity the simplest approach for the unification of the electro-weak and the strong interactions and gravity is supergravity grand unification. In such a model supergravity can break in the hidden sector and the breaking communicated to the visible sector by gravity[18]. Using the non-positive definite nature of the potential one can adjust the vacuum energy to be zero here. The model generates soft SUSY breaking in the visible sector and the $\mu$ term can also be generated in the Kahler potential and transferred to the superpotential via a Kahler transformation. Further, soft SUSY breaking induces breaking of the electro-weak symmetry[18] with the preferred mechanism being radiative breaking[22] which explains one of the long standing puzzles regarding how the electro-weak symmetry breaks in the Standard Model. In the minimal version of the model the soft SUSY breaking is specified by just 5 parameters[18–21] which reduce to four parameters and one sign after the radiative symmetry breaking of the electro-weak symmetry breaking occurs. One may choose these to be

$$m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu).$$

A great deal of SUGRA phenomenology has been carried out over the past few years based on this parameter space[28].(For a review see ref.[27]). An interesting aspect of supergravity grand unification is that with R parity invariance the lightest neutralino is the LSP over most of the parameter space of supergravity unified models and thus a candidate for cold dark matter (CDM)[28,29].

One may ask what leads to the soft SUSY breaking scale of $m_s \sim 10^2$ GeV. It has been suggested recently that such a scale could arise from an anomaly free R symmetry. The idea here is that the requirement of anomaly cancellation requires 3 or 4 hidden sector fields and the U(1) quantum numbers of these fields are large. Minimization gives VEV’s to these fields which are $O(1/10)$ of the Planck mass. Thus this small number with a large power can reduce the Planck mass down to the scale of $O(10^2)$ GeV[29].

Our discussion above has focussed on the gravity mediated breaking of supersymmetry. Another possibility which has been discussed anew recently is the gauge mediated breaking of supersymmetry. Here one introduces messenger fields in vector like representations which are chosen to transform non-trivially under the Standard Model gauge group, and couple to the fields that break supersymmetry. The breaking of supersymmetry in the visible sector occurs at the one loop level for the gauginos and at the two loop level for the scalars[31]. However, one of the problems that emerges is that the Peccei-Quinn symmetry cannot be broken by gauge interactions, and one is forced to introduce non-gauge interactions to accomplish this breaking. Further, in models of this type it is the gravitino rather than the lightest neutralino which is the LSP. Now the gravitino mass must lie below $\sim 1$ KeV in order that the gravitinos do not overclose the universe[32]. With a mass in the above range the gravitino cannot be a candidate for cold dark matter (CDM). Thus unfortunately one of the most attractive features of supersymmetry, that it produces a candidate for cold dark matter for free, is lost in gauge mediated breaking of supersymmetry.

Phenomenologically there are some important
differences between the spectra of gravity mediated and gauge mediated breaking of supersymmetry. For a class of gauge mediated models one can write:

\[ M_i(M_m) = \frac{\alpha_i(M_m)}{4\pi} M_0 \]  

(6)

\[ m_a^2(M_m) = \eta C_{ia} M_i^2(M_m) \]  

(7)

where \( a \) is the matter field index, \( C_{ia} \) are the Casimir co-efficients for the field \( a \), \( M_m \) is the messenger scale, and \( \eta \) characterizes the various models. \( \eta < 1 \) for the minimal model where there is just one SUSY breaking singlet, but one can generate \( \eta > 1 \) for more general situations.

4. SUSY/SUGRA GUT and LEP Data

While the LEP data extrapolated to high scales with just the MSSM spectrum exhibits unification to a good accuracy, a closer look reveals that the theoretical results lie about 2 std higher for \( \alpha_s \) than the LEP data. The 2 std effect could arise from a variety of sources. One possibility is Planck scale corrections, since because of the proximity of the Planck scale to the GUT scale there could be corrections of \( O(M/M_P) \). Such effects could manifest via corrections to the gauge kinetic energy function. Thus inclusion of the Planck corrections brings in a field dependence in \( f_{a\beta} \) and for SU(5) one may write

\[ f_{a\beta} = (A \delta_{a\beta} + c \frac{1}{2M_P^2} d_{a\beta} \gamma \Sigma^\dagger) \]  

(8)

Here \( c \) parameterizes Planck physics and \( c \sim 1 \) gives the desired 2 std correction in the gauge coupling constant unification to achieve full agreement with experiment. One can also understand a 2 std effect from extensions of the minimal SU(5) model such as, for example, in some versions of the missing doublet model.

Next we discuss the issue of baryon instability and show that this is a general problem in SUSY and string models alike. First, all unified models have p instability via lepto-quark exchange. In addition SUSY theories may have rapid p decay via lepton and baryon number violating dimension 4 operators. This type of p decay can be suppressed by the imposition of R parity invariance. However, p decay can occur via dimension 5 operators which is mediated by the Higgs triplet exchange. Thus, for example, in a model with \( n \) Higgs triplets and anti-triplets one has in general an interaction such as

\[ \bar{H}_1 J + \bar{K} H_1 + \bar{H}_i M_{ij} H_j \]  

(9)

The condition for the suppression of p decay from dimension 5 operators then is that

\[ (M^{-1})_{11} = 0 \]  

(10)

Such a suppression can arise either from discrete symmetries or from non standard embeddings. However, aside from these possibilities one finds that normally in SUSY/string models one will in general have p instability and one must suppress dim 5 p decay by making the Higgs triplet superheavy, which of course leads to the question of doublet-triplet splitting. One of the interesting ideas in doublet-triplet splitting is the use of a sliding singlet. It was shown some time ago that the sliding singlet idea can be made to work in SU(5). However, in the analysis of ref. one has the breaking of SU(6) to SU(3) x SU(2) x U(1) occurring in two steps which involves an intermediate scale of \( \sim 10^{10} \) GeV and leads to a value of \( \sin^2 \theta_W \) smaller than the current experimental value. A recent analysis accomplishes the breaking in one step eliminating the need for an intermediate scale. Recent theoretical analyses of p decay show that the expected Superkamiokande (Super-K) and Icarus limit of \( 2 \times 10^{32} \) yrs for the \( p \to \bar{\nu} K^+ \) mode can almost exhaust the maximum life time limits for this mode in the minimal SU(5) SUGRA models within the naturalness constraints of \( m_0 \leq 1 \) TeV, \( m_{3/2} \leq 1 \) TeV. Including the constraints of dark matter one finds that the gluino mass must lie below 500 GeV if Super-K reaches its expected sensitivity and no p decay mode is seen.

The situation regarding SO(10) is more severe. In SO(10) models one has a large \( \tan \beta \), i.e., \( \tan \beta \sim 50 \) to get \( b - t - \tau \) unification. However, in the effective proton decay scale \( M_{PD} \equiv (M^{-1})_{11} \) to stabilize the proton is given by

\[ M_{PD} > \tan \beta (0.57 \times 10^{16}) GeV \]  

(11)
Figure 1. The maximum $p \rightarrow \bar{\nu}K^+$ lifetime in minimal supergravity model under the constraint $m_0 \leq 1$ TeV. The solid curve is for the case when no relic density constraint is imposed. The dashed curve is with the constraint $\Omega h^2 < 1$. The dashed horizontal line is the current experimental limit and the solid horizontal line is the limit expected at Super-K and Icarus.

which is $\sim 2.5 \times 10^{17}$ GeV. It is shown by Urano and Arnowitt that such a large scale upsets the $\alpha_s$ prediction of the minimal SUSY model\cite{48} and one needs large threshold corrections as in the work of Lucas and Raby to restore agreement with experiment\cite{49}.

5. GUTS, Strings and Textures

We discuss now very briefly textures and their effects on proton stability As is well known in unified theories one normally gets poor predictions for the quark-lepton mass ratios. Thus, for example, in SU(5) $m_u/m_e$ is in good agreement with experiment\cite{50,56} but $m_d/m_\mu$ and $m_s/m_\tau$ are not in agreement and to get the correct mass ratios one needs textures\cite{51,52}. In the Higgs doublet sector one may write

$$W_d = H_1 A^E e^c + H_1 d^c A^D q + H_2 u^c A^U q$$

where $A^E$, $A^D$ and $A^U$ are the textures matrices. The simplest example of textures are those by Georgi and Jarlskog where $A^E$ and $A^D$ are given by

$$\begin{pmatrix} 0 & F & 0 \\ F & -3E & 0 \\ 0 & 0 & D \end{pmatrix}, \begin{pmatrix} 0 & F e^{-\phi} & 0 \\ F e^{\phi} & E & 0 \\ 0 & 0 & D \end{pmatrix}$$

respectively and $A^U$ is given by

$$\begin{pmatrix} 0 & C & 0 \\ C & 0 & B \\ 0 & B & A \end{pmatrix}$$

where the entries A,B,C,... possess a hierarchy, i.e., A is O(1), B and D are O($\epsilon$), C and E are O($\epsilon^2$), and F is of order ($\epsilon^3$) where $\epsilon << 1$. There are several interesting features regarding these textures. One of these concerns the origin of $\epsilon$ and several possibilities have been discussed as to how a small number such as this can naturally arise. For example, it is suggested that the smallness of $\epsilon$ arises from the ratio $M_{str}/M_{Pl}$, or in the context of anomalous U(1) horizontal symmetries it is suggested that the ratio could be $\theta/M_{Pl}$ where $\theta$ is a dynamical field which develops a VEV below the string scale\cite{54}. There is another possibility and that is that $\epsilon$ could be the ratio $M_{GUT}/M_{Pl}$. The last possibility is the one we will focus on here. Such a possibility arises naturally if one generates textures via Planck scale corrections, i.e., if one expands the potential in terms of higher dimensional operators in powers of the field that develops a heavy VEV over the Planck mass\cite{52,55}. After spontaneous breaking of the GUT symmetry one will generate entries in the quark-lepton textures which are suppressed by powers of $(M_{GUT}/M_{Pl})$.

In the picture discussed above where the textures are generated via Planck scale corrections one can get the correct mass ratios with $\lambda_{yuk} \sim 1$. Of course, once one fixes the textures in the Higgs doublet sector, the textures in the Higgs triplet sector can be computed. Now it turns out that if one does the most general analysis with the Planck scale interactions, one can generate a large number of different sets of textures in the Higgs triplet sector for a given set of textures in the Higgs doublet sector\cite{54}. Thus one needs a dynamical principle to constrain the Planck scale corrections. One suggestion is to extend supergravity unification to include an exotic sector\cite{53}.
The fields in the exotic sector couple to fields in
the hidden sector and to the would be heavy fields
of the visible sector. After spontaneous symmetry
breaking the exotic fields become superheavy
and can be integrated out generating the Planck
scale corrections. However, the Planck scale cor-
rections are now more constrained. If the fields in
the exotic sector are chosen to be in the minimal
vector like representations, then the textures in
the Higgs triplet sector are unique. Defining the
textures in the Higgs triplet sector by

\[ W_t = H_t B^E q + H_2 u^c B^D e^c \]
\[ + \epsilon_{abc}(H_4 d_b B^D u_c + H_2 u^c C^U d_c) \]  

one gets \[55\]

\[ B^E = \begin{pmatrix} 0 & a F & 0 \\ 0 & \frac{a}{4} E & 0 \\ 0 & 0 & -\frac{3}{4} D \end{pmatrix} \]  

\[ B^D = \begin{pmatrix} 0 & -\frac{a}{2} F & 0 \\ \frac{a}{2} F & \frac{1}{3} E & 0 \\ 0 & 0 & -\frac{2}{3} D \end{pmatrix} \]  

\[ B^U = \begin{pmatrix} 0 & 3 C & 0 \\ \frac{3}{4} C & 0 & -\frac{2}{3} B \\ 0 & -\frac{2}{3} B & A \end{pmatrix} \]  

where \( a = (-\frac{10}{9} + e^{i \phi}) \) and \( C^U = B^U \). An estimate
shows that inclusion of textures gives a moderate
modification of the decay branching ratios. Fur-
ther, the textures affect in a differential way the
various decay modes which in turn can be used

\[ \langle m_\chi \rangle_{\alpha \beta} = \frac{1}{4} \kappa^{-1} (G^a (K^{-1})^a_b) f_{\alpha \beta}^i m^{3/2} \]  

(Radiative corrections to this formula are dis-
cussed in refs. \[55\]). However, for the general \( f_{a \beta} \)
case there would be important corrections. Here
the corrections to the gaugino masses at the GUT
scale involve not only the derivatives of the func-
tion \( f_{a \beta} \) but also the the derivatives of the Kahler
metric \( K^a_b \). For the case when \( f_{a \beta} \sim \delta_{a \beta} \) one has
universal gaugino masses at the GUT scale, i.e.,

\[ M_i = (\alpha_i(Q)/\alpha_G) m_{1/2} ; \quad i = 1, 2, 3 \]  

where \( \alpha_i \) are the subgroup gauge coupling con-
stants, \( \alpha_G \) is the GUT coupling constant, \( c' \)
(which depends on \( c \) ) parametrizes the Planck
scale correction, and \( n_i = (2, -3, -1) \) character-
ize the subgroups in the product \( SU(3) \times SU(2) \times
U(1) \).

For the universal case SUSY particles obey
the scaling relations over most of the SUGRA para-
meter space under the constraint of electro-weak
symmetry breaking. The scaling phenomenon
arises because under the constraint of electro-
weak symmetry breaking one finds that over most
of the parameter space one has \( \mu^2/M_Z^2 \gg 1 \)
which leads to the scaling laws \[28\]
the corrections to the parameter tor and the third generation sector we exhibit ∆ universali-

ty

\[ \delta \]

where a reasonable range of

\[ m \]

the non-universalities in the Higgs sector and in
coupling[60,61]. It is convenient to parametrize
highly coupled because of the large top Yukawa
also in the third generation sector as they are
non-universalities in the Higgs sector then you must allow for non-universalities
in the third generation sector must be included along
with those in the Higgs sector for an appropriate
treatment of these sectors. Non-universalities can
affect low energy phenomena such as analyses of
dark matter and \( R_b \). We shall discuss the effect
of non-universalities on \( R_b \) in Sec. 8.

7. Constraints of FCNC

Suppression of FCNC processes impose serious
constraints on model building. First one has the
well known constraint of the suppression of
\( K_s \rightarrow \mu^+\mu^- \) where the branching ratio is < 3.2 × 10^{-7}.
In the SM this suppression is
gotten via the GIM mechanism where the loop
diagram allowing for this process is suppressed by
\( (m^2_{\tau} - m^2_{\mu})/M_W^2 \approx 10^{-4} \). In supersymmetric
models there are additional diagrams where one has
exchange of the chargino and squarks. Here the
loop diagram contains a factor \( (m^2_{\tau} - m^2_{\mu})/M_W^2 \).
Now in the minimal supergravity model with uni-
versal boundary conditions one has \( (m^2_{\tau} - m^2_{\mu}) \approx (m^2_{\tau} - m^2_{\mu}) \). Thus the minimal supergravity
unification automatically generates the super GIM
mechanism which again leads to a natural sup-
pression of the \( K_s \rightarrow \mu^+\mu^- \). Of course any inclu-
sion of non-universalities in the SUGRA bound-
ary conditions must respect this constraint and
that is what was done in the analysis of non-
universalities above.

There are of course also other FCNC processes
which put constraints on models. One of the
more important of these is the process \( b \rightarrow s + \gamma \).
Recently the CLEO Collaboration has deter-
mined this branching ratio to be

\[ BR(b \rightarrow s + \gamma)_{exp} = (2.32 \pm 0.67) \times 10^{-4} \]
a significant QCD enhancement factor. Including the leading order and most of the next to leading order QCD corrections one finds that in the SM the \( b \to s + \gamma \) branching ratio is given by
\[
BR(b \to s + \gamma)_{SM} = (3.48 \pm 0.31) \times 10^{-4}
\]
for \( m_t = 176 \) GeV. In supersymmetric models there are additional diagrams arising from the exchange of the charged Higgs, the charginos, the neutralinos and the gluino which contribute to this process\(^{[66]}\). While the contribution from the charged Higgs exchange is always positive\(^{[66]}\), the sum of the remaining SUSY particle exchange contributions can be either positive or negative\(^{[67]}\). In the minimal SUGRA model over most of the parameter space the charged Higgs turns out to be heavy, i.e., it has a mass much larger than \( M_2 \), and thus its contributions to \( b \to s + \gamma \) is generally small. Among the remaining SUSY particle exchanges it is the chargino exchange which is normally the largest contribution. Thus a large deviation of the experimental value of \( BR(b \to s + \gamma) \) from the SM value will point to the presence of a light chargino mass and a light stop mass. The constraint on the chargino and the light stop mass depends of course on the level of deviation from the SM value. However, as a guideline one can expect that the light chargino mass and the light stop mass should be in the vicinity of 100 GeV or below to make any significant contribution. The \( b \to s + \gamma \) experiment puts a strong constraint on dark matter analyses\(^{[68]}\) and on other SUSY phenomenology.

Finally we mention the FCNC process \( \mu \to e + \gamma \) which can arise in a variety of different ways in SUSY/SUGRA/string models\(^{[69]}\). In most such schemes the process involves Yukawa couplings in the lepton sector and thus carries information on physics at the GUT scale and/or on physics at the string/Planck scales where one believes such interactions originate.

8. \( R_b \) Status

In the SM \( R_b \) has the value\(^{[70]}\)
\[
R_b^{SM} = 0.2159, \quad m_t = 175 \text{GeV}
\]

The experimental value of \( R_b \) has been been shifting over the last 2-3 years. In 1995 values of \( R_b \) as large as 3.5 std above the SM value was reported. Since then the value of \( R_b \) has moved down and in 1996 the LEP group reported
\[
R_b^{\text{EXP}} = 0.2178 \pm 0.0011
\]

The result of Eq.(30) is only 1.8 \( \sigma \) above the SM result. Further, a more recent evaluation by the ALEPH group indicates no deviation from the SM value while the other three LEP groups still report an \( R_b \) anomaly. It is instructive to review briefly the status of \( R_b \) in SUSY models. In MSSM there are additional contributions to \( R_b \) which involve the exchange of the charginos, the neutralinos, the gluino, and the stops\(^{[71-74]}\). Of these the chargino-stop exchange diagrams are the most important and here the dominant contributions arise when the light stop is mostly right handed. In MSSM by fine tuning of parameters one can get an \( R_b \) correction as large as \( 0.0022 - 0.0028 \). However, in minimal SUGRA one finds that this correction is much smaller, i.e., it lies in the range \( \Delta R_b^{\text{max}} = 0.0002 - 0.0003 \). For the case of supergravity analyses with non-universalities one finds a maximal correction of 0.0011 for \( \mu < 0 \) and a maximal correction of 0.0008 for \( \mu > 0 \). The \( \Delta R_b \) corrections would also partially help bridge the gap between the low DIS value of \( \alpha_s \) of \( 0.116 \pm 0.005 \) and the high LEP value of \( \alpha_s \) of \( 0.123 \pm 0.006 \). \( \Delta R_b \) gives a correction to the LEP value of \( \alpha_s \) of \( \Delta \alpha_s = -4 \Delta R_b \) which would result in a maximal correction to \( \alpha_s \) of \( \Delta \alpha_s = -0.0044 \) for \( \mu < 0 \) and of \(-0.0032 \) for \( \mu > 0 \). Thus the maximal \( R_b \) correction can bridge the gap only half way between the DIS value and the LEP value\(^{[75,76]}\).

For the non-universal SUGRA case the maximal \( \Delta R_b \) correction puts a stringent constraint on the sparticle spectrum. For instance, if one requires that the \( \Delta R_b \) correction be greater than \( \sim 0.0006 \) which at the current level of accuracy is \( \sim \frac{1}{2} \sigma \) then the supergravity constraints require that the light chargino and the light stop should have masses below 100 GeV, and the gluino mass must lie below 450 GeV(525 GeV) for \( \mu < 0 \) (\( \mu > 0 \)).
Figure 2. $R_{\text{max}}^{m}$ as a function of the light chargino mass for the Standard Model, for SUGRA model with universal boundary conditions and for the SUGRA model with non-universal boundary conditions for $\mu > 0$ and $\mu < 0$ from ref.\[76\].

| Quantity | Numerical Values |
|----------|------------------|
| $R_{\text{max}}^{\text{exp}} - R_{\text{max}}^{\text{SM}}$ | 0.0019$\pm$0.0011 |
| $\Delta R_{b}^{\text{SUSY}(\text{max})}$ (MSSM) | 0.0022$^{[74]}$ |
| $\Delta R_{b}^{\text{SUSY}(\text{max})}$ (MSSM) | 0.0028$^{[76]}$ |
| $\Delta R_{b}^{\text{SUSY}(\text{max})}$ (mSUGRA) | 0.0008$^{[76]}$ |
| $\Delta R_{b}^{\text{SUSY}(\text{max})}$ (nSUGRA) | 0.0011($\mu < 0$)$^{[76]}$ |
| $\Delta R_{b}^{\text{SUSY}(\text{max})}$ (nSUGRA) | 0.0008($\mu > 0$)$^{[76]}$ |

Table 1: The current experimental value of $\Delta R_{b}$ vs the maximal $\Delta R_{b}^{\text{SUSY}}$ in MSSM and in SUGRA models with universal boundary conditions at the GUT scale (mSUGRA) and with non-universal boundary conditions (nSUGRA) from ref.\[76\].

Further, in this situation the light Higgs must have a mass which lies below 93 GeV. Now at the Tevatron in the Main Injector Era one will be able to probe the light chargino via the trilepton signal$^{[75]}$ and the light stops in the ranges indicated above. At TEV33 one will be able to explore gluino masses up to 450 GeV with an integrated luminosity of 100$fb^{-1}$\[82]\]. Further, Higgs mass in the range indicated will be accessible at LEP II if one can achieve center of mass energies of $\sqrt{s} = 192$ GeV. A Higgs mass in the range above will also be accessible at TEV33 with an integrated luminosity of 5-10$fb^{-1}$. This means that the non-universal SUGRA model with $\Delta R_{b} > 0.0006$ can be completely tested in the chargino, stop, and Higgs sector at LEP II and at TEV33 and also fully (partially) tested in the gluino sector for the case $\mu < 0$ ($\mu > 0$) at TEV33. Thus the results of non-universal SUGRA analysis are very strong. One is predicting that if there is any sizable $\Delta R_{b}$ correction which we construe here to imply that $\Delta R_{b} > 0.0006$, or $\Delta R_{b} > \frac{1}{2}\sigma$, then one must see either a chargino, or a stop and a Higgs at LEP II and at TEV33. The gluino must also be seen if $\mu < 0$ while for $\mu > 0$ it could escape detection at TEV33 if it lies in the region between 450-525 GeV.

9. The Brookhaven $g_\mu - 2$ Experiment as a Probe of SUGRA/String Unification

$g_\mu - 2$ is a powerful probe of SUGRA/string unified theories. We discuss briefly now as to the implications of the improved results on $g_\mu - 2$ expected from Brookhaven in the near future$^{[82]}$. The theoretical value of $a_\mu \equiv (g_\mu/2 - 1)$ within the SM is given by

$$a_{\mu}^{\text{theory}}(\text{SM}) = 11659172(15.4) \times 10^{-10}$$ \hspace{1cm} (32)

Here the theoretical value is computed to the $\alpha^5$ Q.E.D. order, and to $\alpha^2$ order in the hadronic corrections, and includes two loop corrections from the electro-weak sector. The hadronic correction is given by$^{[82]}$

$$a_{\mu}^{\text{hadron}}(\text{SM}) = 687.0(15.4) \times 10^{-10}$$ \hspace{1cm} (33)

while the electro-weak correction is given by$^{[82]}$

$$a_{\mu}^{\text{EW}}(\text{SM}) = 15.1(0.4) \times 10^{-10}.$$ \hspace{1cm} (34)

Recently Alemany et.al.$^{[82]}$ have used the new $\tau$ data at LEP to achieve a significant reduction in the hadronic error, i.e., they get

$$a_{\mu}^{\text{hadron}}(\text{SM}) = 701.4(9.4) \times 10^{-10}$$ \hspace{1cm} (35)

One expects that the error in the hadronic correction will reduce further in the near future from experiments at VEPP-2M, DAΦNE, and BEPC$^{[82]-[88]}$. A reduction in the error by another factor of 2 is not out of reach. The current experimental value of $a_{\mu} \equiv (g_\mu/2 - 1)$ is $a_{\mu}^{\text{exp}} =$
11659230(84) × 10^{−10} and the new Brookhaven experiment is expected to reduce the uncertainty by a factor of 20 [89]. The expected reduction in the experimental error at Brookhaven and a corresponding reduction in the hadronic error as discussed above will allow one to test the Standard Model electro-weak contribution. However, it was pointed out early on that any experiment that can test the SM electro-weak contribution will also test the supersymmetric contribution as often the supersymmetric contribution tends to be as large or larger than the SM contribution [90]. The more recent precision analyses of g_\mu - 2 within SUGRA [91,92] and in MSSM [93] support these observations.

10. Test of GUT, Post GUT and String Physics via Precision Measurement of Sfermion Masses

One of the interesting aspects of SUGRA unified models and string models is that sensitive measurement of sparticle masses can be used as a probe of physics at post GUT and string scales. It is already known that sfermion masses carry information on gauge symmetry breaking at the GUT scale [24]. For example, the breaking of SO(10) via various sequences leads to distinguishable patterns in the sparticle spectrum. It was recently suggested that sparticle spectrum can also act as a probe of physics in the post GUT region all the way up to the string scales [24,25]. For example, it is easy to demonstrate that post GUT scenarios such as SU(5), SO(10), SU(3)^3, G_{SM} etc., produce distinct signatures in the sfermion spectrum.

We discuss now briefly how the various post GUT scenarios can be tested. Consider for instance a scenario where the group in the post GUT region is SU(5). In this case one finds that mass differences \( m_{\tilde{e}_L}^2 - m_{\tilde{\mu}_L}^2 \), \( m_{\tilde{e}_R}^2 - m_{\tilde{\mu}_R}^2 \), \( m_{\tilde{u}_L}^2 - m_{\tilde{d}_L}^2 \), \( m_{\tilde{u}_R}^2 - m_{\tilde{d}_R}^2 \) are independent of the specific assumption of universality and thus would vanish when extrapolated to the GUT scale. One can also determine the string scale experimentally from data on sfermion masses. In the above scenario and under the assumption of universality of the soft SUSY parameters at the string scale, we can determine the string scale using renormalization group from the intersection, for example, of the lines of \( \tilde{e}_L \) and \( \tilde{\mu}_L \) as a function of running scale Q. Thus \( M_{str} \), which is one of the most fundamental parameters of string theory can be determined from accurate data on the sfermion masses. A similar analysis can be carried out for other post GUT possibilities. For example, consider the case of SO(10) in the post GUT region with fermions in the three generations of 16-plets of SO(10) where a 16 plet decomposes to 10+\( \bar{5} \) of SU(5), and the usual 5+\( \bar{5} \) of SU(5) Higgs lie in the 10 of SO(10). Now assume that at \( M_G \) one has breaking of SO(10) into the SM gauge group. In this case because of rank reduction one has D term contributions in the matching conditions below \( M_G [74,75] \). Absorbing \( \delta_5 \) in the definition of \( \tilde{m}_5 \) and defining \( \tilde{m}_2 = \tilde{m}_2(1 + \delta_5) \), \( m_{H_1}^2 = \tilde{m}_G^2(1 + \delta_1) \) and \( m_{H_2}^2 = \tilde{m}_G^2(1 + \delta_2) \) one has \( \delta_5 = \delta_1 - \delta_2 \) (36)

Thus SO(10) models of the type described above have an extra constraint which again can be tested by extrapolation of the sfermion data from the low energy scales to the GUT scale. Similar considerations can be extended to other post GUT scenarios such as SU(3)^3 and SU(3)\times SU(2) \times U(1), and one finds that in each case accurate data on sfermion masses allows one to distinguish that particular scenario from others.

One can extend the same general procedure to testing string models. The origin of supersymmetry breaking in string theory is not fully understood and thus one must rely on certain parametrizations [88,94]. One useful approach in this direction is parametrizing soft SUSY breaking by the VEVs of the dilaton (S), and the moduli fields \((T_i, U_i)\). As an illustration we consider (2,2) Calabi-Yau compatifications with the gauge groups \( E_6 \times E_8 \). Although the models investigated thus far in this type of compactification have not resulted in any realistic model, the framework does provide a testing ground for some of the ideas discussed here. Thus we consider the case of a compactification with a single modulus \( T_{[10]} \) where the soft SUSY breaking parameters are universal at the string scale [95]. In this case one may parametrize soft SUSY breaking by
\[m_{\tilde{t}} = \sqrt{3}\sin \theta e^{-i\gamma_S} m_{\tilde{t}}
\]
\[A_0 = -(1 + \omega e^{-i(\gamma_T - \gamma_S)} \cot^2 \theta) m_{\tilde{t}}^2
\]
\[m_0^2 = \frac{\gamma}{3}(1 + \Delta e^{-i\gamma_S} \cot^2 \theta) m_{\tilde{t}}^2
\] (37)

where \(\theta\) is the angle between the dilaton and the Goldstino directions, \(\omega\) and \(\Delta\) include the sigma model and instanton contributions, and \(\gamma_S\) and \(\gamma_T\) are CP violating phases. On the CP preserving manifolds one has \(\gamma_S = 0 = \gamma_T\) and eliminating \(\theta\) one gets a constraint between the SUSY breaking parameters \(m_0, m_{\tilde{t}}, A_0\), and \(\Delta\) and \(\omega\). One has
\[\omega^2/\Delta = (A_0/m_0 + m_{\tilde{t}}/m_0)^2
\] (38)

Now the soft SUSY parameters \(m_0, m_{\tilde{t}}, A_0\) can be gotten from the particle mass measurements. These determinations then allow us to test a given string model. Thus, it is shown in ref.[96] that the SUSY parameters \(M_2 = 120\) GeV, \(m_0 = 187\) GeV, \(A_u = -285\) GeV, and \(\tan \beta = 5\) rule out the model with \(\Delta = 1.62\) and \(|\omega| = 0.64\).[99]

The discussion above shows that one can extract SUSY parameters from the particle masses and use them to test specific string models. Of course the extraction of the SUSY parameters from the collider data depends on the accuracy with which mass measurements can be made. Several recent papers have addressed this issue. Hadron colliders may be able to provide us with the mass measurements of sparticle masses with accuracies of few percent\[101\]-\[102\]. At linear colliders one may be able to achieve accuracies of up to 1-2\% level\[103\]-\[105\]. Such data can then be used to explore physics beyond the GUT scale.

11. Conclusion

Supersymmetric models currently provide an attractive framework for the solution to the hierarchy problem. Supergravity grand unification with spontaneous breaking of supersymmetry via a hidden sector provides a concrete model where supersymmetric particle spectrum can be computed and their interactions analysed. The minimal SUGRA model is consistent with the LEP data with a possible 2 std discrepancy in \(\alpha_s\), which may point to the existence of Planck scale corrections. Thus in addition to SUGRA unification we may already be witnessing Planck scale corrections in the LEP data. The minimal SUGRA also predicts that supersymmetric corrections to \(R_h\) are small and that \(R_h\) is close to the SM value. The recent experimental data on \(R_h\) appears to be moving towards eliminating the previously large (~ 3\sigma) \(R_h\) anomaly. This is precisely what is predicted by the minimal SUGRA model. There are many other predictions of SUGRA models which are testable in accelerator and non-accelerator experiments. These include SUGRA corrections to \(b \rightarrow s + \gamma\), \(g_{\mu} - 2\), predictions on proton decay, and the existence of a low energy supersymmetric particles spectrum which should be visible at colliders.

An interesting interface of GUTs and strings would occur if SUGRA GUT can indeed arise from strings. Recent progress in string GUTS with Kac-Moody levels \(k > 1\) appears encouraging from this view point and the models that arise here have many appealing features. However, the detailed phenomenology of all models of this type needs to be fully worked out to determine if a model satisfying all the phenomenological constraints will survive. Another development which will shape phenomenology in the future is the development of string dualities and M theory. This development has opened new directions and perhaps set new ground rules for model building. Perhaps enhanced symmetry groups and stringy effects at scales far below the string scale may play a role in a new generation of model building. However, prudence requires that in view of the enormity of the problems at hand, i.e., the existence of many string vacua, difficulty regarding the breaking of supersymmetry in strings, the problem of getting zero vacuum energy after SUSY breaks etc., that it is desirable to work from both ends, i.e., from the top down as in string theory and from the bottom up as in SUSY/SUGRA phenomenology. In either case a hint from experiment regarding the existence of SUSY in nature will be helpful. One hopes such a hint will come in the near future from the various experiments underway, such as the Brookhaven
$g_{\mu}^{-2}$ experiment, and CLEO's analysis of the process $b \rightarrow s + \gamma$, from the detection of an LSP in dark matter detectors, or in the direct observation of supersymmetric particles at the Tevatron, at LEP or at the LHC.

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