FLAVOURED SUSY*

C.A. Savoy

Service de Physique Théorique, C.E. de Saclay
91191 Gif-s/Yvette, France

(Received November 14, 1996)

I briefly review some recent work on the flavour dependence of supersymmetrice theories. Attempts to solve the flavour puzzle based on horizontal — or vertical — symmetries predict flavour structures in the supersymmetric sector that could serve to constrain and even to test such theories in present and future experiments.

PACS numbers: 12.60. Jv

1. Lecture 1

1.1. Introduction

Now that the Standard Model has been well established and all known phenomena are consistent within the experimental accuracy with its predictions, the particle physicists are challenged to go beyond this mostly fundamental achievement. As a matter of fact, they have been speculating since quite a long time on more unified theories of several kinds to try to explain the structure and the measured values of the many parameters in the Standard Model. The flavour mystery, the fact that quarks and leptons replicate themselves in three families, with masses and mixings that are so different, is an excellent starting point for this quest. It goes without saying that the new theory must not disturb the agreement between experiments and the Standard Model phenomenology. Flavour changing neutral current processes (FCNC), which gave the clue to the GIM mechanism and the matter pattern in the Standard Model, provide a set of very selective constraints to physics beyond the present energies. Fortunately, theories of flavours often predict relatively large contributions to interactions that are strongly suppressed in the Standard Model. The observation of these

* Presented at the XXXVI Cracow School of Theoretical Physics, Zakopane, Poland, June 1–11, 1996.

phenomena would then test the new theories. Of course, this experimental validation is mandatory for any theoretically consistent solution of the problem of fermion masses and mixings.

The quark and lepton masses are given by the Yukawa couplings of the fermions to the Higgs scalars, $\sum_{ij}\left[Y^U_{ij}q^i u^j H_2 + Y^D_{ij}q^i d^j H_1 + Y^E_{ij}l^i e^j H_1\right]$, where we have allowed for two Higgs doublets to anticipate the use of supersymmetry herebelow as in most of the recent work on this subject. The physical content of the three Yukawa coupling 3×3 matrices is given by their eigenvalues $Y_i(i = u,c,t;d,s,b;e,\mu,\tau)$ as well as the Cabibbo–Kobayashi–Maskawa matrix V. The observed quark masses and mixings and lepton masses reveal a strong hierarchy conveniently displayed in terms of a small parameter which we choose to be the Cabibbo angle, $\lambda = .22$: $Y_t : Y_c : Y_u = \lambda^8 : \lambda^4 : 1, Y_b : Y_s : Y_d = \lambda^4 : \lambda^2 : 1, Y_\tau : Y_\mu : Y_e = \lambda^4 : \lambda^2 : 1, V_{us} = \lambda, V_{cb} \sim \lambda^2, V_{ub} \sim \lambda^3$. In particular, the FCNC effects in the Standard Model which are circumvented by the GIM mechanism, are increased by the large mass differences and reduced by the small mixing angles.

The smallness of these mass ratios and mixing angles faces us with a problem of naturalness. A parameter is naturally small when the symmetry of the system increases as the parameter vanishes. Then one should postulate new symmetries and their spontaneous breaking. Therefore new, higher scales are needed where these symmetries would become relevant. It is well known that multiple scales are usually associated with the so-called hierarchy problem and that supersymmetry is the only known issue. But it would remain the physical problem of understanding the new scales. It seems very attractive to assume them to coincide with the basic physical scale which is the Planck mass. This possibility of solving the flavour puzzle within a fundamental theory that includes gravity is certainly an ambitious aim, still we are pulled in this direction by the results obtained in string theory, for instance.

1.2. SFCNC

Generically, the supersymmetrization of the Standard Model does not evade the FCNC problem and, as expected in theories beyond the Standard Model, new contributions to these rare processes tend to be too large. A rich literature is available about FCNC restrictions on supersymmetric extensions of the Standard Model. Nevertheless, both the LEP (and Tevatron) constraints on supersymmetric theories and some fresh insight on the question of flavour in effective supergravity theories from superstrings have encouraged a recent revival of this subject. The basic supersymmetry induced FCNC (SFCNC) effects are produced by the analogues of the Standard Model loop diagrams for neutral current processes, with quarks and vector bosons replaced by squarks and gauginos. If quark (lepton) and squark (slepton) mass matrices are not diagonal in the same basis, then the supersymmetry charge will relate each physical quark (lepton) to an admixture of physical squarks (sleptons). In this sense supersymmetry becomes *flavoured*. Therefore, even if the neutral gauge bosons couple to fermions of the same flavour, the corresponding couplings of the neutral gauginos to fermions and sfermions will not be flavour diagonal and will induce FCNC effects. There are several sources of flavour mixing in gaugino couplings that we now turn to discuss. However, I want to keep in mind that supersymmetry must be a local symmetry, namely, a supergravity theory, at the fundamental level. This has implications on the structure of the low energy effective theory (and vice-versa, which is even more important!)

Within the general framework of supergravity, a theory is defined by the gauge and matter superfields, and by their couplings encoded in the Kähler potential' defining the geometry of the scalar fiel manifold, and the superpotential, an analytic function of these scalar fields. The low-energy theory is then fixed by the values of the auxiliary fields that provide supersymmetry breaking and their couplings to the light fields. The supersymmetric part of this effective theory contains the supersymmetrized gauge couplings and the supersymmetrized Yukawa couplings, encoded in an effective superpotential $W = \sum[Y_{ij}^U Q^i U^j H_2 + Y_{ij}^D Q^i D^j H_1 + Y_{ij}^E L^i E^j H_1]$, where H_1 and H_2 are the two Higgs superfields, and the matter superfields are as follows: Q, L, contain the $SU(2)_{weak}$ doublets of quarks and leptons, and U, D, E contain the right-handed quarks and leptons. While the B and L quantum numbers are automatic (or accidental) symmetries in the Standard Model, it is well-known that to avoid B and L violating terms in the superpotential, one has to postulate a R-parity symmetry whose origin should then be explained together with the solution of the flavour problem. Or one can allow for a pattern of those interactions that give small effects consistent with the experimental limits. Of course the observation of these processes would be a check for supersymmetry itself, but would also require a natural explanation of the new small parameters.

At the level of the effective theory, below the Planck scale, the supersymmetry breaking effects reduce to gaugino masses and the soft interactions in the scalar potential. The scalar $(\text{mass})^2$ matrix depend on the curvature tensor of Kähler manifold of the scalar fields in the theory and on the supersymmetry breaking auxiliary fields (More precisely, this applies to the breaking of the F-type, while the D-type breaking gives contributions to the scalar masses proportional to their charges.). In this sense, they are geometrical, in contrast with the masses of their fermionic partners given by the Yukawa couplings and gauge symmetry breaking. The soft triscalar couplings have an intermediate status. The mass matrices (in family space) of fermions and sfermions, have quite different origins and are not expected to commute, leading to a situation of flavoured supersymmetry and potentially dangerous FCNC effects.

1.3. Universality

The universality or flavour independence hypothesis assumes equal masses for all squarks at the unification. A perfect degeneracy would frustate FCNC processes by the GIM mechanism. At lower energies, radiative corrections from Yukawa interactions split this degeneracy with flavour dependent shifts. The triscalar couplings are basically proportional to the couplings in the superpotential. Again, if universality is assumed for the proportionality factors, referred to as A-parameters, their equality is spoilt at lower energies by the calculable radiative corrections. Universality of soft terms is sometimes assumed in SFCNC studies. Then, the most striking effects of radiative corrections are of two kinds. Gauge corrections are almost universal and attenuate loop effects by an overall rise in the squark masses if gluinos are relatively heavy. Yukawa corrections dominated by the top coupling, Y_t, tend to align the down squark mass eigenstates to the up quarks (if $\tan\beta$ is not too large). This reverses the pattern of gaugino couplings in comparison with the gauge boson ones. Chargino couplings to down squarks and up quarks are approximately flavour diagonal while gluino and neutralino couplings become proportional to the CKM matrix. However, the expected physical effects are either consistent with the present overall bounds on supersymmetric particles or they depend on unknown mixings and phases, with the possible exception of the $b \to s\gamma$ transition that provides some interesting information.

Thus, universality naturally suppresses SFCNC effects as it amounts to postulate the largest possible horizontal symmetry, $\mathrm{U}(3)^5$, for each of the 5 irreps of the Standard Model in the 3 fermion families, as an accidental symmetry, *i.e.*, a symmetry of the scalar potential in the limit where all Yukawa couplings vanish. This is justified if the couplings of the supersymmetry breaking auxiliary fields (or equivalently, the couplings of the gravitino) to quarks and leptons are flavour independent. Of course, in the framework of a supersymmetric fundamental theory that incorporates a solution of the flavour problem, this is not a generic situation. But it has been assumed in the earlier studies of broken supergravity, by postulating a flavour blind gravitino, and, even previously, in models with global supersymmetry, recently called "gauge mediated supersymmetry breaking" and reanalyzed on more modern grounds by many authors, where the gravitino couples indirectly through the family independent (*i.e.* , vertical) gauge couplings. As we now turn to discuss, it is not necessarily so, specially when the flavour question is addressed.

1.4. SFCNC from GUT's

Recently, the question of FCNC effects arising from SUSY GUTs has been analysed in detail in a series of papers [2] . This possibility was pointed out already some time ago, but the fact that the top Yukawa coupling is so large considerably enhances the effects. The idea is to estimate the renormalization correction from the running of the soft parameters in the theory from the supergravityscale ($M_{\rm Planck}$) down to the GUT scale ($M_{\rm GUT}$) in presence of very large Yukawa couplings, which is certainly the case for Y_t. In a GUT, above $M_{\rm GUT}$, the following part of the superpotential give also rise to loop diagrams $\sum[Y^U_{ij}E^iU^jH_3 + Y^D_{ij}Q^iL^jH'_3 + Y^D_{ij}D^iE^jH'_3]$ involving the Higgs triplet partners. The coupling Y_t is always large, while $Y_b = Y_\tau$ is large in O(10) unification or even for SU(5) with large $\tan\beta$. The effects of the loops containing these heavy leptoquark states into the running of the Yukawa couplings from $M_{\rm Planck}$ to $M_{\rm GUT}$, where they decouple, can be very important: the $\tilde{\tau}_R$ (mass)^2 is roughly reduced by a factor $(1 - Y_t^2/2Y^2_{\rm max})$, defined at $M_{\rm GUT}$, where $Y^2_{\rm max}$ is the value of Y_t for a Landau pole at $M_{\rm Planck}$. The mass splitting with respect to $\tilde{e}_R$ and $\tilde{\mu}_R$ will remain at low energies and produce lepton flavour violating processes. However, the results also depend on the unknown angles defined by the diagonalization of the lepton and slepton masses. Assuming naive GUT relations for the lepton mixings — *cum grano salis* in view of the bad naive GUT predictions for the two light families — one gets sizeable FCNC effects in large regions of the parameter space. For large Y_b the effects are even bigger. The results can be illustrated by assuming universal boundary conditions at $M_{\rm Planck}$, so that the slepton splitting is only due to the Higgs triplet. In this case, it is possible to present detailed predictions for the various lepton flavour violating processes (for quark FCNC, those are rather masked by the analogous contributions from the MSSM superpotential).

This analysis shows that grandunification might affect the tree-level relations for the parameters in a non-negligible way . Of course if one attempts a real theory of fermion masses based on GUTs, and O(10) has been preferred in this respect [3], for instance, by the introduction of non-renormalizable interactions and discrete symmetries, there will be corresponding constraints on the soft scalar masses and couplings, not necessarily consistent with the universality assumption. Instead, the framework will be similar to what is discussed herebelow in the case of abelian horizontal symmetries.

1.5. The pseudo-Goldstone approach

Dimopoulos and Giudice [4] invoke the pseudo-Goldstone phenomenon to enforce FCNC suppression. They assume a large $\Pi_{A=Q,U,D,L,E}{\rm U}(3)$

'accidental' symmetry of the scalar potential, including the scalar masses, in the limit of vanishing Yukawa couplings. They introduce on-purpose multiplets, say in the $Adj(\mathrm{U}(3)^5)$, whose vev's break $\mathrm{U}(3)^5 \to \mathrm{U}(1)^{15}$ or $\to [\mathrm{U}(2) \times \mathrm{U}(1)]^5$. The remaining symmetries entail the following form for each one of the sfermion mass matrices: $\tilde{m}_A^2 = e^{-i\theta_A} diag(\tilde{m}_{A1}^2,\ \tilde{m}_{A2}^2\ \tilde{m}_{A3}^2) e^{i\theta_A}$, where θ_A are matrices, each one containing five Goldstone fields living in the coset $\mathrm{U}(3)/\mathrm{U}(1)^3$ (the extension to $[\mathrm{U}(2) \times \mathrm{U}(1)]$ is obvious). These are massless states as the potential is flat along the θ_A directions. Actually, they are 'pseudo-Goldstone' states since the flavour symmetries are explicitly broken by the Yukawa couplings. The latter are taken *a priori* as given by the quark masses and CKM mixings. Then, at the quantum level, the hidden flavour symmetry is broken by loops with quarks that spoil the flatness along the θ_A directions. By minimization one obtains the θ_A vev's (and masses) in terms of the Yukawa couplings Y_A, such that the $\tilde{m}_A^2$ matrices are all "aligned" to the Yukawa couplings Y_A matrices (*i.e.*,$[Y_A, \tilde{m}_A^2] = 0$), but $\tilde{m}_Q^2$ aligns to the matrix $Y_U^2 + K^+ Y_D^2 K$. The quark squark alignment is as good as possible, still the $\tilde{m}_Q^2$ disalignment could induce too much $K\bar{K}$ mixing. This is avoided if the remaining accidental symmetry is $\mathrm{U}(2) \times \mathrm{U}(1)$ so that $\tilde{m}_{Q1}^2 = \tilde{m}_{Q2}^2$. This can be implemented [4] by enlarging the accidental $\mathrm{U}(3)^5$ symmetry to $O(8)$, spontaneously broken into $O(7)$.

In spite of its formal elegance, this approach does not address the flavour problem as far as the expected dependence of the Yukawa couplings on new fields is not envisaged while it might provide a prediction for quark masses as well. The hierarchical Yukawa couplings are given *a priori*. Also, the necessarily large number of *ad hoc* Goldstone fields could mitigate one's enthusiasm.

2. Lecture 2

2.1. Flavour theories and supersymmetry

The fermion unit in the Standard Model is a family of 15 fermions that provide a non-trivial anomalous-free representation of the gauge group. GUTs are attempts to understand the fermion pattern by (vertical)unification of the elements of the family within a representation of a larger gauge theory at very high energies. The triplication of families is a real enigma. But these fermion replicas do not look as clones since they quite differ by the strong hierarchy in their Yukawa couplings. The natural explanation of this situation is to hypothetize that quarks/leptons of the same charge have different quantum numbers of some new symmetries at high energies (symmetries that commute with the Standard Model symmetries have been called horizontal).

As in many particle physics issues, hints come from superstrings models, where one finds examples of compactifications with fermion families and neither vertical nor horizontal unification. Instead, there are in general additional abelian U(1) symmetries that differentiate between fermions. Moreover, the superstring theory particle masses and couplings are field dependent dynamically determined quantities.

A conspicuous result of superstring studies is that the three families of quark superfields may couple to supergravity according to different terms in the Kähler potential. The relevant low energy limit of superstring models are described by $N = 1$ supergravities. The zero-mass string spectrum contain an universal dilaton S, moduli fields, related to the compactification of six superfluous dimensions, denoted by $T_\alpha(\alpha = 1..m)$, and matter chiral fields A^i. A crucial role is played by the target-space modular symmetries SL(2, Z) , transformations on the T_α that are invariances of the effective supergravity theory. In string models of the orbifold type, the matter fields A^i transform under SL(2, Z) according to a set of numbers, $n_i^{(\alpha)}$, called the modular weights of the fields A^i with respect to the modulus T^α.

The dilaton superfield in these theories does have universal supergravity couplings to matter superfields. But the moduli couplings are fixed by modular invariances. Thus, the Kähler potential and the superpotential can have different dependencies on the moduli for each flavour. On the other hand, these moduli correspond to flat directions of the scalar potential so that their vev's are fixed by quantum corrections. Assuming that the relevant ones come from the light sector, namely by the coupling of moduli to quarks and leptons in the low energy theory, it has been suggested that modular invariances can also provide a theory of flavour, by predicting the hierarchies in the moduli dependent Yukawa couplings. Indeed, this interesting idea has been recently developed in the literature [8].

Motivated by superstrings, as well as symmetries proposed to explain the structure of Yukawa couplings, new analyses [1, 9] have been performed on FCNC transitions produced by non-universality in supergravitycouplings. Of course, the results are model dependent, one variable being the amount of the flavour independent supersymmetry breaking (say, in the dilaton direction) responsible for gaugino masses, that attenuates SFCNC. With this proviso the more important constraints in the quark sector are coming from K-physics. The lepton sector is less sensitive to gaugino masses, and lepton flavour violations put severe constraints on the parameters, but only as functions of unknown lepton mixing angles.

Nevertheless, in this lecture I would like to focus on the SFCNC problem from the stand-point of different attempts to explain the origin of flavour, hence of fermion masses and mixings.

2.2. The Froggatt–Nielsen paradigm

The smallness of the mass ratios and mixing angles faces us with a problem of naturalness. The direction initiated by Froggatt and Nielsen [5] to understand such a hierarchical pattern goes as follows: (*i*) The key assumption is a gauged horizontal $\mathrm{U}(1)_X$ symmetry violated by the small quark masses so that small Yukawa couplings are protected (forbidden) by this symmetry. Gauging the symmetry avoids massless Goldstone bosons when the symmetry is broken. The effective $\mathrm{U}(1)_X$ symmetric theory below some scale M is supposed to be natural to the extent that all parameters are of $O(1)$. The scale M is the limit of validity of the effective theory, of $O(M_{\mathrm{Planck}})$ if one adopts a superstring point of view. The X-charges of quarks, leptons and Higgses are free parameters to be fixed *a posteriori* and simply denoted q_i,u_i, d_i,l_i,e_i,h_1,h_2, for the different flavours, where $i = 1, 2, 3$ is the family index. (*ii*) One (or more) Froggatt–Nielsen field Φ, a Standard Model gauge singlet is introduced, and we normalize the $\mathrm{U}(1)_X$ so that its charge is $X_\Phi = -1$. The effective (non-renormalizable) $\mathrm{U}(1)_X$ allowed couplings are then of the form $g^U_{ij}(\Phi/M)^{q_i+u_j+h_2}Q^iU^jH_2$, with analogous expressions for the H_1 couplings to down quarks and leptons. The coefficients g^U_{ij}, etc, are taken to be natural, *i.e.*, of $O(1)$, unless they are required to vanish by the $\mathrm{U}(1)_X$ symmetry. (*iii*) The small parameter λ is identified with the ratio $(\frac{<\Phi>}{M})$ as the $\mathrm{U}(1)_X$ symmetry is broken by the Φ v.e.v. Below the scale $<\Phi>= \lambda M$, one recovers the Standard Model with the effective Yukawa coupling matrices given by $Y^U_{ij} = \lambda^{|q_i+u_j+h_2|}$, $Y^D_{ij} = \lambda^{|q_i+d_j+h_1|}$, $Y^E_{ij} = \lambda^{|l_i+e_j+h_1|}$. The Yukawa matrix entries corresponding to negative total charge should vanish but these zeroes are filled by the diagonalization of the λ -dependent metrics.

The X-charges are now chosen to fit the hierarchy in the mass eigenvalues and mixing angles. The experimental masses (at $O(M_{\mathrm{Planck}})$) of the third families give: $h_2+q_3+u_3 = 0$ and $x = h_1+q_3+d_3 = h_1+l_3+e_3$, where the parameter x depends on the assumed value for $\tan\beta$. With this restriction the Yukawa couplings depend only on the charge differences $q_i - q_3$, $u_i - u_3$,..., $e_i - e_3$ and x.

Recently, there has been an intensive investigation of this model [6, 7], including a classification of the possible charge assignments [7]. But the question I would like to discuss here was first investigated by Leurer, Nir and Seiberg [9] in the Froggatt–Nielsen framework. Just like the Yukawa couplings, the soft supersymmetry breaking terms contain powers of the Φ -field to implement the $\mathrm{U}(1)_X$ symmetry. The scalar mass matrices have a corresponding hierarchy among their elements, so that $(\widetilde{m}^2_A)_{ij} \propto \lambda^{|q_i-q_j|}$, $A = Q, U, D, L, E$. Even in the flavour basis that diagonalizes quark mass matrices, the squark mass matrices will still be of the same non-diagonal form. Therefore large FCNC effects might be induced from loop diagrams with the exchange of neutral sfermions (gluino, photino,...) in possible disagreement with experiments. Indeed, with only one Φ -field , the acceptable $U(1)_X$ charge assignments yield $(\tilde{m}^2_D)_{12}(\tilde{m}^2_Q)_{12} \propto \frac{m_d}{m_s}$, which yields much too large FCNC effects in K-physics. One solution [9] is to double the Froggatt–Nielsen, with another abelian symmetry and a smaller scale. In this case it is possible to strongly suppress $(\tilde{m}^2_D)_{12}$. Interestingly enough, the model predicts large $(\tilde{m}^2_U)_{12}$ leading to sizeable $D\bar{D}$ mixing that could be experimentally tested.

Another solution [7] is to assume only one more singlet Φ' and an appropriate charge assignment so that $(\tilde{m}^2_D)_{12}(\tilde{m}^2_Q)_{12} \propto \frac{m^2_d}{m^2_s}$, which is just enough. Remarkably, in this model all anomalies related to $U(1)_X$ can be cancelled, while in the other models one has to rely upon the Green–Schwarz mechanism [6, 7](see later). It should be clear at this point that a supersymmetric theory imposes additional phenomenological constraints on flavour models as it increases their predictions.

2.3. Horizontal symmetries in supergravity

The attractive idea of Froggatt and Nielsen raises some relevant questions, and I want to argue that they all find satisfactory answers in the supergravity framework.

1)What fixes the scale M of the effective theory possessing the horizontal symmetry? Well, the obvious solution is to identify M to the highest physical scale, the Planck mass, M_{Planck}. A supergravity theory is nonrenormalizable as it contains powers of the Newton constant, the inverse of M_{Planck}. Then it is natural to take $M = M_{\text{Planck}}$.

2)What gives rise to the "small number" λ? A recent suggestion is to relate it to the coefficient that appears in the Green–Schwarz mechanism, as follows. In general the horizontal $U(1)_X$ potentially has (triangle) anomalies with the other gauge symmetries, including the Standard Model gauge group. Models exist where all these anomalies vanish, as already mentioned. However, the more promising models [6, 7] rely upon the Green–Schwarz mechanism: the shift of a scalar, an axion, under the $U(1)_X$ gauge transformations can cancel all the anomalies if and only if their coefficients obey an appropriate proportionality factor. Now, it can be shown that this requires a Fayet–Iliopoulos term, with a coefficient $M^2_{\text{Planck}} trX/192\pi^2$. the minimization of the scalar potential then fixes $\Phi^2 = M^2_{\text{Planck}} trX/192\pi^2$. With $M = M_{\text{Planck}}$, this defines the number $\lambda = \sqrt{3trX}/24\pi$, which can be small enough for reasonable values of trX.

3)How can such flavour theories be experimentally tested? Indeed, the charges are "fitted" to reproduce the masses and mixings (with some predicted relations) up to some coefficients of $O(1)$, and one needs some predictions that can be experimentally measured. Let me outline how this could happen in a superstring inspired supergravity theory.

On one hand, horizontal symmetries are a natural way to solve the family puzzle and the fermion mass hierarchy, and give some restrictions on squark masses as well. On the other hand, in string inspired supergravity, the sfermion masses depend on the modular properties of the matter fields and their modular dependence might well be related to the origin of flavour. What if one imposes both symmetries on a broken supergravity model? This has been recently investigated [10]. For definiteness, let us define the modular properties by some set of modular weights $n_i^{(\alpha)}$ associated to each of the matter fields, and their transformation under an abelian $\mathrm{U}(1)_X$ symmetry implementing the Froggatt–Nielsen mechanism, by their charges X_i. Analogously, $n_\Phi^{(\alpha)}$ and X_Φ are introduced for the singlet field Φ. Now, let us require the supergravity theory to be invariant under these $\mathrm{SL}(2,\mathrm{Z})$ and $\mathrm{U}(1)_X$ transformations. Then, one derives the very interesting relation: $(q_i - q_j)n_\Phi^{(\alpha)} = X_\Phi(n_{q_i}^{(\alpha)} - n_{q_j}^{(\alpha)})$ between charge and modular weight differences. Though the results are easily generalized [10], let us keep only one modulus, say, the overall one, T. Through some mechanism that we do not quite understand yet, the dilaton S and the moduli T get their vev's that fix in turn the gauge couplings and the compactified dimensions in string theory. Let us assume that supersymmetry is broken by the auxiliary components of the S and T supermultiplets, F_S and F_T, and define the so-called gravitino angle [1], $\tan\theta = F_S/F_T$. The Φ vev, in this one-singlet case, is fixed by the Fayet–Iliopoulos term to be $\lambda M_{\mathrm{Planck}}$, and there is additional (induced) supersymmetry breaking, with F_Φ and D_X components precisely fixed in terms of n_Φ and X_Φ. We further assume that the fermion mass hierarchy is solely due to the Froggatt–Nielsen mechanism. Then the squark and slepton mass matrices can be calculated, with surprisingly simple expressions, resulting of the coalescence of all sources of supersymmetry breaking. For instance, for diagonal entries one gets the relations: $\tilde{m}_{i\bar{i}}^2 - \tilde{m}_{j\bar{j}}^2 = (X_i - X_j)m_{3/2}^2$, where X_Φ is normalized to -1. Notice that the unit in this mass differences is exactly $m_{3/2}^2$. By comparing the dependencies on the $\mathrm{U}(1)_X$ charge differences of the Yukawa coupling matrices and the squark and slepton mass differences, one finds the nice relation, $\frac{1}{2}\sum_{L,R}(\tilde{m}_i^2 - \tilde{m}_j^2) = \frac{1}{3}m_{3/2}^2 \ln(m_i/m_j)$. This corresponds to an inverse "hierarchy" of masses for sfermions with respect to fermions, since for the latter the larger charges are associated to the lightest states. This predictions provide simple tests of these models.

For non-diagonal entries one gets $\widetilde{m}^2_{i\bar{j}} \sim -\frac{1}{2}|X_i - X_j|/\lambda^{|X_i - X_j|} m^2_{3/2}$. Similar results also follow for triscalar couplings. The consequences for SFCNC are an improvement with respect to those in the previous section. For instance, the contribution to $K\bar{K}$ mixing can be reduced by choosing models [7] with charges $d_1 = d_2$, and the same trick is possible to avoid too much lepton flavour violation.

REFERENCES

[1] A. Brignole, L.E. Ibáñez, C. Muñoz, *Nucl. Phys.* **B422**, 235 (1994); D. Choudhury, F. Eberlein, A. König, J. Louis, S. Pokorski *Phys. Lett.* **B342**, 180 (1995); P. Brax, M. Chemtob, *Phys. Rev.* **D51**, 6550 (1995); J. Louis, Y. Nir, *Nucl. Phys.* **B447**, 18 (1995); P. Brax, C.A. Savoy, *Nucl. Phys.* **B447**, 227 (1995); A. Brignole, L.E. Ibáñez, C. Muñoz, C. Scheich, Madrid preprint FTUAM-95-26, hep-ph/9508258.

[2] R. Barbieri, L.J. Hall, *Phys. Lett.* **B338**, 212 (1994); R. Barbieri, L.J. Hall, A. Strumia, hep-ph/9501334.

[3] S. Dimopoulos, L. Hall, S. Raby, *Phys. Rev. Lett.* **68**, 1984 (1992); *Phys. Rev.* **D45**, 4192 (1992); M. Carena, S. Dimopoulos, C.E. Wagner, S. Raby, CERN preprint TH95-053, hep-ph/9503488.

[4] S. Dimopoulos, G.F. Giudice, CERN preprint TH95-90, hep-ph/9504296.

[5] C.D. Froggatt, H.B. Nielsen, *Nucl. Phys.* **B147**, 277 (1979); J. Bijnens, C. Wetterich, *Nucl. Phys.* **B283**, 237 (1987).

[6] L.E. Ibáñez, G.G. Ross, *Phys. Lett.* **B332**, 100 (1994); P. Binétruy, P. Ramond, *Phys. Lett.* **B350**, 49 (1995); V. Jain, R. Shrock, *Phys. Lett.* **B352** , 83 (1995); Y. Nir, *Phys. Lett.* **B354**, 107 (1995).

[7] E. Dudas, S. Pokorski, C.A. Savoy, *Phys. Lett.* **B356**, 45 (1995).

[8] P. Binétruy, E. Dudas, *Nucl. Phys.* **B451**, 31 (1995).

[9] M. Leurer, Y. Nir, N. Seiberg, *Nucl. Phys.* **B398**, 319 (1993); **B420**, 468 (1994); Y. Nir, N. Seiberg, *Phys. Lett.* **B309**, 337 (1993).

[10] E. Dudas, S. Pokorski, C.A. Savoy, *Phys. Lett.* **B369**, 255 (1996); hep-ph/9509410, to appear in *Nucl. Phys.* **B**.