FCNC IN SUSY THEORIES

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Recent work on flavour changing neutral current effects in supersymmetric models is reviewed. The emphasis is put on new issues related to solutions to the flavour problem through new symmetries: GUTs, horizontal symmetries, modular invariances.

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1 Introduction

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 spontaneously broken supergravities 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, even the the couplings to neutral gauginos to fermions and sfermions will not be 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 and the supersymmetry breaking auxiliary potentials. The universality or flavour independence hypothesis assumes equal masses for all squarks at the unification.

At lower energies, radiative corrections from Yukawa interactions split this degeneracy with flavour dependent shifts. The triscalar couplings are basically proportional to couplings in the superpotential. 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 (mass)$^2$ matrix depend on the Kähler potential and on the supersymmetry breaking auxiliary fields. The universality or flavour independence hypothesis assumes equal masses for all squarks at the unification.

Universality of soft terms is often 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 corrections dominated by the top coupling, $\lambda$. This reverses the pattern of flavour independent Yukawa couplings.

At lower energies, radiative corrections from Yukawa interactions split this degeneracy with flavour dependent shifts. The triscalar couplings are basically proportional to couplings in the superpotential. 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 often 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 corrections dominated by the top coupling, $\lambda$. This reverses the pattern of flavour independent Yukawa couplings. However, the expected physical effects are either consistent with the present overall bounds on supersymmetric particles or they depend on unknown mixings and phases, but the $b \to s\gamma$ transition provides interesting information.

Thus, universality naturally suppresses SFCNC effects as it amounts to postulate the largest possible horizontal symmetry, $U(3)^5$, 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 supergravity Yukawa couplings to the supersymme-
try breaking are flavour independent. As we now turn to
discuss, they are not necessarily so.

2 Flavour theories and supersymmetry

The fermion unit in the Standard Model is a family of 15
fermions that provide a non-trivial anomalous-free rep-
resentation 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 tripli-
cation of families is a puzzle. But these fermion repli-
cas do not look as clones since they quite differ by the
strong hierarchy in their Yukawa couplings. The natu-
ral explanation of this situation is to hypothetize that
quarks/leptons of the same charge have different quan-
tum 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 com-
 pactifications with fermion families and neither vertical
nor horizontal unification. Instead, there are in general
superstrings models, where one finds examples of com-
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(1) symmetries that differentiate be-
tween fermions. Moreover, the superstring theory parti-
cle masses and couplings are field dependent dynamically
determined quantities.

A conspicuous result of superstring studies is that the
two families of quark superfields may couple to super-
gravity according to different terms in the Kähler poten-
tial. The relevant low energy limit of superstring models
are described by a $N = 1$ supergravities. The zero-mass
string spectrum contain an universal dilaton $S$, moduli
fields, related to the compactification of six superfluos
dimensions, denoted by $T_a(\alpha = 1..m)$, and matter chil-
ral fields $A^i$. A crucial role is played by the target-space
modular symmetries $SL(2, Z)$, transformations on the
$T_a$ that are invariances of the effective supergravity the-
ory. 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 $T^\alpha$.

The dilaton superfield in these theories does have
universal supergravity couplings to matter superfields.
But the moduli couplings are fixed by modular invar-
iances. Thus, the Kähler potential and the superpoten-
tial can have different dependences on the moduli for
each flavour. On the other hand, these moduli corre-
spond 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 pre-
dicting the hierarchies in the moduli dependent Yukawa
couplings. This interesting idea is discussed in more de-
tail in the contributions of E. Dudas and F. Zwirner.
For this reason, it is not developed here.

Motivated by superstrings, as well as symmetries
proposed to explain the structure of Yukawa couplings,
new analyses have been performed on FCNC transition-
transitions produced by non-universality in supergravitycouplings. Of course, the results are model dependent, one
variable being the amount of the flavour independent su-
persymmetry breaking (in the dilaton direction) respon-
sible 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 viola-
tions put severe constraints on the parameters, but only
as functions of unknown lepton mixing angles.

Nevertheless, in this talk 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.

3 SFCNC effects from SUSY unification

Recently, the question of FCNC effects arising from
SUSY GUTs has been analysed in detail in a series of paper.
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 supergrav-
ityscale ($M_{Planck}$) down to the GUT scale ($M_{GUT}$) in
presence of very large Yukawa couplings, which is cer-
tainly the case for $Y_t$. In a GUT, above $M_{GUT}$, the
following part of the superpotential give also rise to loop


diagrams $\sum Y_{ij}^{U} \bar E^{U} H_{3} + Y_{ij}^{Q} \bar D^{L} H_{3} + Y_{ij}^{D} \bar E^{L} H_{3}$

involving the Higgs triplet partners. The coupling $Y_l$ is al-
ways large, while $Y_l > Y_t$ is large in O(10) unification or
even for SU(5) with large tan $\beta$. The effect of the running
from $M_{Planck}$ to $M_{GUT}$ can be very important: the $\tilde{\tau}_R$

is roughly reduced by a factor $(1 - Y_t^2/2Y_{max}^2)$, defined
at $M_{GUT}$, where $Y_{max}^2$ is the value of $Y_t$ for a Landau
pole at $M_{Planck}$. The mass splitting with respect to $\tilde{\tau}_R$

and $\tilde{\mu}_R$ will remain at low energies and produce lepton
flavour violating processes. Of course the results also de-
pend on the angles defined by the diagonalization of the
lepton and slepton masses. Assuming naive GUT rela-
tions 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 $Y_t$ the effects are even bigger.

The results can be illustrated by assuming universal
boundary conditions at $M_{Planck}$, so that the slepton
splitting is only due to the Higgs triplet. In this case, it
is possible to present detailed predictions for the vari-
ous lepton flavour violating processes (for quark FCNC,
those are concealed by the analogous contributions from the MSSM superpotential).

Of course if one attempts a real theory of fermion masses based on GUTs, and O(10) has been preferred in this respect for instance, by the introduction of non-renormalizable interactions and discrete symmetries, there will be corresponding constraints on the soft scalar masses and couplings. The framework will be similar to what is discussed here below in the case of abelian horizontal symmetries.

4 The pseudo-Goldstone approach

Dimopoulos and Giudicci invoke the pseudo-Goldstone phenomenon to enforce FCNC suppression. They assume a large $\Pi_{A=Q,U,D,L,E}U(3)$ ‘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 $Adj(U(3)^3)$, whose vev’s break $U(3)^5 \rightarrow U(1)^{15}$ or $[U(2) \times U(1)]^5$.

The remaining symmetries entail the following form for each one of the fermion mass matrices: $\tilde{m}_A^2 = e^{-i \theta_A} \text{diag}(\tilde{m}_{A1}^2, \tilde{m}_{A2}^2, \tilde{m}_{A3}^2) e^{i \theta_A}$, where $\theta_A$ are matrices, each one containing five Goldstone fields living in the coset $U(3)/U(1)^3$ (the extension to $[U(2) \times U(1)]$ is obvious). These are massless states as the potential is flat along the $\theta_A$ 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 $\theta_A$ directions. By minimization one obtains the $\theta_A$ vev’s (and masses) in terms of the Yukawa couplings $Y_A$, such that the $\tilde{m}_A^2$’s are all aligned to the Yukawa couplings $Y_A$ but $\tilde{m}_A^2$ to the matrix $Y_D^2 + K^+ Y_D^3 K$. The quark squark alignment is as good as possible, still the $\tilde{m}_A^2$ disalignment could induce too much $K \bar{K}$ mixing. This is avoided if the remaining accidental symmetry is $U(2) \times U(1)$ so that $\tilde{m}_Q^2 = \tilde{m}_D^2$. This can be implemented by enlarging the accidental $U(3)^5$ 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. Also, the necessarily large number of ad hoc Goldstone fields could mitigate one’s enthusiasm.

5 The supersymmetric Foggatt-Nielsen approach

The smallness of the mass ratios and mixing angles faces us with a problem of naturalness. The direction initiated by Foggatt and Nielsen to understand such a hierarchical pattern goes as follows: (i) The key assumption is a gauged horizontal $U(1)_X$ symmetry violated by the small quark masses so that small Yukawa couplings are protected by this symmetry. The effective $U(1)_X$ 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 $O(M_{Planck})$ 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) Foggatt-Nielsen field $\Phi$, a Standard Model gauge singlet, is introduced, and we normalize the $U(1)_X$ so that its charge is $X_\Phi = -1$. The effective (non-renormalizable) $U(1)_X$ allowed couplings are then of the form $g_{ij}^U \Phi/M_n (\bar{h}_1 + h_2) \Phi U D H_2$, with analogous expressions for the $H_1$ couplings to down quarks and leptons. The coefficients $g_{ij}^U$, etc, are taken to be fixed, i.e., of $O(1)$, unless they are required to vanish by the $U(1)_X$ symmetry. (iii) The small parameter $\lambda$ is identified with the ratio $(\frac{\bar{h}_1}{h_2})$ as the $U(1)_X$ symmetry is broken by the $\Phi$ v.e.v... Below the scale $< \Phi > = \lambda M_n$, one recovers the Standard Model with the effective Yukawa coupling matrix given by $Y_Q^{ij} = \lambda |r_i + s_j|$, $Y_D^{ij} = \lambda |q_i + d_j + h_1|$, $Y_L^{ij} = \lambda \tilde{r}_i + e_j + h_1|$. The Yukawa matrix entries corresponding to negative total charge should vanish but these zeroes are filled by the diagonalization of the $\lambda$-dependent metrics.

The X-charges are now chosen to fit the hierarchy in the mass eigenvalues and mixing angles. The experimental masses (at $O(M_{Planck})$) of the third families give: $h_2 + q_3 + u_3 = 0$ and $x = b_3 + q_3 + d_3 = b_3 + l_3 + e_3$, 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 including a classification of the possible charge assignment. But the question I would like to discuss here was first investigated by Leurer, Nir and Seiberg in the Foggatt-Nielsen framework. Just like the Yukawa couplings, the soft supersymmetry breaking terms contain powers of the $\Phi$ -field to implement the $U(1)_X$ symmetry. The scalar mass matrices have a corresponding hierarchy among their elements, so that $(\tilde{m}_Q^2)_{ij} = f_{ij} \lambda |u_i - q_j|, A_{Q,U,D,L,E}$, where, in the absence of any other symmetry principle, the coefficients $f_{ij}$ are all of the order of the supersymmetry breaking parameter $m_{3/2}$, where $m_{3/2}$ is the gravitino mass. 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 dis-
agreement with experiments. Indeed, with only one $\Phi$ field, the acceptable $U(1)_X$ charge assignements yield $(\tilde{m}_D^2)_{12}(\tilde{m}_Q^2)_{12} \propto m_\alpha^2/2$, which imply much too large FCNC effects in K-physics. One solution is to double the Froggatt-Nielsen, with another abelian symmetry and a smaller scale. In this case it is possible to strongly suppress $(\tilde{m}_D^2)_{12}$. Interestingly enough, the model predicts large $(\tilde{m}_D^2)_{12}$ leading to sizeable $D\bar{D}$ mixing that could be experimentally tested.

Another solution is to assume only one more singlet $\Phi'$ and an appropriate charge assignment so that $(\tilde{m}_D^2)_{12}(\tilde{m}_Q^2)_{12} \propto m_\alpha^2/2$, 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 Horizontal symmetries in supergravity

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 fermion 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. For definiteness, let us define the modular properties by some set of modular weights $n_1(\alpha)$ associated to each of the matter fields, and their transformation under an abelian $U(1)_X$ symmetry implementing the Froggatt-Nielsen mechanism, by their charges $X_1$. Analogously, $n_\Phi(\alpha)$ and $X_\Phi$ are introduced for the singlet field $\Phi$. Now, let us require the supergravity theory to be invariant under these $SL(2, Z)$ and $U(1)_X$ transformations. Then, one shows the following interesting relation: $(q_i - q_j)n_\Phi = X_\Phi(n_\Phi(\alpha) - n_\Phi(\beta))$ between charge and modular weight differences. Though the results are easily generalized, 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 the gauge couplings and the compactified dimensions in string theory. Then, assume 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 $\tan \theta = F_S/F_T$. The $F$ vev, in this one-singlet case, is fixed by the Fayet-Iliopoulos term to be of $O(M_{Planck})$, and the supersymmetry breaking is precisely fixed in terms of $n_\Phi$ and $X_\Phi$, with a $F_\Phi$ and a $D_X$ components. Then the squark and slepton masses can be calculated, with a surprisingly simple expression, resulting of the coalescence of all sources of supersymmetry breaking. For instance, for diagonal entries one gets the relations: $m_{1i}^2 - m_{1j}^2 = (X_i - X_j)m_\Phi^2/2$, where $X_\Phi$ is normalized to -1. For non-diagonal entries one has $m_{ij}^2 \sim 3(X_i - X_j)m_\Phi^2/2\cos^2 \theta/\lambda |X_i - X_j|$. 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 with charges $d_1 = d_2$, and the same trick is possible to avoid too much lepton flavour violation.

7 Conclusion

Supersymmetry is the highway connection between flavour physics at low energies and flavour theories at the Planck scale. SFCNC phenomenology provide very selective constraints in this adventure.

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