The Beauty of SUSY*

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Abstract

$B$ physics represents a privileged place to look for supersymmetry (SUSY) through its virtual effects. Here we discuss rare $B$ decays ($b \to s\gamma$, $b \to sq$, $b \to s\ell^+\ell^-$) and $B-\bar{B}$ oscillations in the context of low-energy SUSY. We outline the variety of predictions that arise according to the choice of the SUSY extension ranging from what we call the “minimal” version of the MSSM to models without flavour universality or with broken R-parity. In particular, we provide a model-independent parameterization of the SUSY FCNC effects which is useful in tackling the problem in generic low-energy SUSY. We show how rare $B$ physics may be complementary to direct SUSY searches at colliders, in particular for what concerns extensions of the most restrictive version of the MSSM.

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1 Introduction

Flavour Changing Neutral Current (FCNC) phenomena represent a major test for any extension of the Standard Model (SM) which is characterized by an energy scale $\Lambda$ close to the electroweak scale. Low-energy supersymmetry (SUSY) is no exception in this way: its prediction of new particles carrying flavour numbers with masses not exceeding a few TeV’s (i.e., $\Lambda < \text{few TeV’s}$ in this case) makes the indirect search of SUSY manifestations through virtual effects in FCNC processes of utmost interest.

The potentiality of probing SUSY in FCNC phenomena was readily realized when the era of SUSY phenomenology started in the early 80’s [1]. In particular, the major implication that the scalar partners of quarks of the same electric charge but belonging to different generations had to share a remarkable high mass degeneracy was emphasized.

Throughout the large amount of work in this last decade it became clearer and clearer that generically talking of the implications of low-energy SUSY on FCNC may be rather misleading. We have a minimal SUSY extension of the SM, the so-called Minimal Supersymmetric Standard Model (MSSM) [2], where the FCNC contributions can be computed in terms of a very limited set of unknown new SUSY parameters. Remarkably enough, this minimal model succeeds to pass all the set of FCNC tests unscathed. To be sure, it is possible to severely constrain the SUSY parameter space, for instance using $b \to s\gamma$ in a way which is complementary to what is achieved by direct SUSY searches at colliders.

However, the MSSM is by no means equivalent to low-energy SUSY. First, there exists an interesting large class of SUSY realizations where the customary discrete R-parity (which is invoked to suppress proton decay) is replaced by other discrete symmetries which allow either baryon or lepton violating terms in the superpotential. But, even sticking to the more orthodox view of imposing R-parity, we are still left with a large variety of extensions of the MSSM at low energy. The point is that low-energy SUSY “feels” the new physics at the superlarge scale at which supergravity (i.e., local supersymmetry) broke down. In this last couple of years we have witnessed an increasing interest in supergravity realizations without the so-called flavour universality of the terms which break SUSY explicitly. Another class of low-energy SUSY realizations which differ from the MSSM in the FCNC sector is obtained from SUSY-GUT’s. The interactions involving superheavy particles in the energy
range between the GUT and the Planck scale bear important implications for the amount and kind of FCNC that we expect at low energy.

After an initial effort on the study of FCNC SUSY effects in kaon physics it became clear that $B$ physics represents the new (and, for many aspects, more promising) frontier for probing SUSY through FCNC effects in the hadronic sector. There has already been an intense research activity in the realm of rare FCNC $B$ decays and SUSY. The simultaneous progress on the experimental side and, even more, the prospects that new $B$ facilities open up in these coming years make these studies of enormous interest in our effort to detail the structure (and the existence!) of low-energy SUSY.

In this talk I will review some of the most recent work along these lines, in particular distinguishing the situation concerning the MSSM and other low-energy SUSY realizations.

2 FCNC in SUSY without R-Parity

It is well known that in the SM case the imposition of gauge symmetry and the usual gauge assignment of the 15 elementary fermions of each family lead to the automatic conservation of baryon ($B$) and lepton ($L$) numbers (this is true at any order in perturbation theory).

On the contrary, imposing in addition to the usual $SU(3) \otimes SU(2) \otimes U(1)$ gauge symmetry an N=1 global SUSY does not prevent the appearance of terms which explicitly break $B$ or $L$ [3]. Indeed, the superpotential reads:

$$W = h^U Q H_U u^c + h^D Q H_D d^c + h^L L H_D e^c + \mu H_U H_D$$
$$+ \mu' H_U L + \lambda''_{ijk} u^c_i d^c_j d^c_k + \lambda'_{ijk} Q_i L_j d^c_k + \lambda_{ijk} L_i L_j e^c_k ,$$

where the chiral matter superfields $Q$, $u^c$, $d^c$, $L$, $e^c$, $H_U$ and $H_D$ transform under the above gauge symmetry as:

$$Q \equiv (3, 2, 1/6); \quad u^c \equiv (\bar{3}, 1, -2/3); \quad d^c \equiv (\bar{3}, 1, 1/3);$$
$$L \equiv (1, 2, -1/2); \quad e^c \equiv (1, 1, 1); \quad H_U \equiv (1, 2, 1/2); \quad H_D \equiv (1, 2, -1/2).$$

The couplings $h^U$, $h^D$, $h^L$ are $3 \times 3$ matrices in the generation space; $i$, $j$ and $k$ are generation indices. Using the product of $\lambda'$ and $\lambda''$ couplings it is immediate to construct four-fermion operators leading to proton decay through the exchange of a squark. Even if one allows for the existence of
\( \lambda' \) and \( \lambda'' \) couplings only involving the heaviest generation, one can show that the bound on the product \( \lambda' \times \lambda'' \) of these couplings is very severe (of \( O(10^{-7}) \)) \[4\].

A solution is that there exists a discrete symmetry, B-parity \[5\], which forbids the B violating terms in eq. (1) which are proportional to \( \lambda'' \). In that case it is still possible to produce sizeable effects in FC B decays. For instance using the product of \( \lambda'_{ijk} \lambda_{ijc} \) one can obtain \( b \to s (d) + ll^c \) taking \( k = 2 \) (1) and through the mediation of the sneutrino of the \( j \)-th generation.

Two general features of these R-parity violating contributions are:

1. we completely lose any correlation to the CKM elements. For instance, in the above example, the couplings \( \lambda' \) and \( \lambda \) have nothing to do with the usual angles \( V_{tb} \) and \( V_{ts} \) which appear in \( b \to sl^+l^- \) in the SM;

2. we also lose correlation among different FCNC processes which are tightly correlated in the SM. For instance, in our example \( b \to dl^+l^- \) would depend on \( \lambda' \) and \( \lambda \) parameters which are different from those appearing in \( B_d - \bar{B}_d \) mixing.

In this context it is difficult to make predictions given the arbitrariness of the large number of \( \lambda \) and \( \lambda' \) parameters. There exist bounds on each individual coupling (i.e. assuming all the other L violating couplings are zero) \[6\]. With some exception, they are not very stringent for the third generation (generally of \( O(10^{-1}) \)), hence allowing for conspicuous effects. Indeed, one may think of using the experimental bounds on rare B decays to put severe bounds on products of L violating couplings.

Obviously, the most practical way of avoiding any threat of B and L violating operators is to forbid all such terms in eq. (1). This is achieved by imposing the usual R matter parity. This quantum number reads +1 over every ordinary particle and −1 over SUSY partners. We now turn to rare B decays in the framework of low energy SUSY with R-parity.

### 3 Model-independent analysis of FCNC processes in SUSY

Given a specific SUSY model it is in principle possible to make a full computation of all the FCNC phenomena in that context. However, given the
variety of options for low-energy SUSY which was mentioned in the Introduction (even confining ourselves here to models with R matter parity), it is important to have a way to extract from the whole host of FCNC processes a set of upper limits on quantities which can be readily computed in any chosen SUSY frame.

The best model-independent parameterization of FCNC effects is the so-called mass insertion approximation \[7\]. It concerns the most peculiar source of FCNC SUSY contributions that do not arise from the mere supersymmetrization of the FCNC in the SM. They originate from the FC couplings of gluinos and neutralinos to fermions and sfermions \[8\]. One chooses a basis for the fermion and sfermion states where all the couplings of these particles to neutral gauginos are flavour diagonal, while the FC is exhibited by the non-diagonality of the sfermion propagators. Denoting by $\Delta$ the off-diagonal terms in the sfermion mass matrices (i.e. the mass terms relating sfermion of the same electric charge, but different flavour), the sfermion propagators can be expanded as a series in terms of $\delta = \Delta / \bar{m}^2$ where $\bar{m}$ is the average sfermion mass. As long as $\Delta$ is significantly smaller than $\bar{m}^2$, we can just take the first term of this expansion and, then, the experimental information concerning FCNC and CP violating phenomena translates into upper bounds on these $\delta$’s \[9\].

Obviously the above mass insertion method presents the major advantage that one does not need the full diagonalization of the sfermion mass matrices to perform a test of the SUSY model under consideration in the FCNC sector. It is enough to compute ratios of the off-diagonal over the diagonal entries of the sfermion mass matrices and compare the results with the general bounds on the $\delta$’s that we provide here from all available experimental information.

There exist four different $\Delta$ mass insertions connecting flavours $i$ and $j$ along a sfermion propagator: $(\Delta_{ij})_{LL}$, $(\Delta_{ij})_{RR}$, $(\Delta_{ij})_{LR}$ and $(\Delta_{ij})_{RL}$. The indices $L$ and $R$ refer to the helicity of the fermion partners. The size of these $\Delta$’s can be quite different. For instance, it is well known that in the MSSM case, only the $LL$ mass insertion can change flavour, while all the other three above mass insertions are flavour conserving, i.e. they have $i = j$. In this case to realize a $LR$ or $RL$ flavour change one needs a double mass insertion with the flavour changed solely in a $LL$ mass insertion and a subsequent flavour-conserving $LR$ mass insertion. Even worse is the case of a FC $RR$ transition: in the MSSM this can be accomplished only through a laborious set of three mass insertions, two flavour-conserving $LR$ transitions and an
LL FC insertion. Instead of the dimensional quantities ∆ it is more useful to provide bounds making use of dimensionless quantities, δ, that are obtained dividing the mass insertions by an average sfermion mass.

The FCNC processes in B physics which provide the best bounds on the δ_{23} and δ_{13} FC insertions are b → sγ and B_d − ̄B_d, respectively.

The process b → sγ requires a helicity flip. In the presence of a (δ_{23}^d)_{LR} mass insertion we can realize this flip in the gluino running in the loop. On the contrary, the (δ_{23}^d)_{LL} insertion requires the helicity flip to occur in the external b-quark line. Hence we expect a stronger bound on the (δ_{23}^d)_{LR} quantity. Indeed, this is what happens: (δ_{23}^d)_{LL} is essentially not bounded, while (δ_{23}^d)_{LR} is limited to be < 10^{-3} – 10^{-2} according to the average squark and gluino masses (see fig. 1). Given the upper bound on (δ_{23}^d)_{LR} from b → sγ, it turns out that the quantity x_s of the B_s – ̄B_s mixing receives contributions from this kind of mass insertions which are very tiny. The only chance to obtain large values of x_s is if (δ_{23}^d)_{LL} is large, say of O(1). In that case x_s can easily jump up to values of O(10^2) or even larger.

As for the mixing B_d − ̄B_d, we obtain

\[
\sqrt{|\text{Re}(δ_{13}^d)_{LL}|} < 4.6 \cdot 10^{-2}; \\
\sqrt{|\text{Re}(δ_{13}^d)_{LR}|} < 5.6 \cdot 10^{-2}; \\
\sqrt{|\text{Re}(δ_{13}^d)_{LL}(δ_{13}^d)_{RR}|} < 1.6 \cdot 10^{-2};
\]

for x ≡ m_\tilde{g}^2/m_\tilde{q}^2 = 0.3 with m_\tilde{q} = 500 GeV. The above bounds scale with m_\tilde{q}(GeV)/500 for different values of m_\tilde{q} (at fixed x).

Then, imposing the bounds (3), we can obtain the largest possible value for BR(b → dγ) through gluino exchange. As expected, the (δ_{13}^d)_{LL} insertion leads to very small values of this BR of O(10^{-7}) or so, whilst the (δ_{13}^d)_{LR} insertion allows for BR(b → dγ) ranging from few times 10^{-4} up to few times 10^{-3} for decreasing values of x = m_\tilde{g}^2/m_\tilde{q}^2. As reminded by Ali at this meeting, in the SM we expect BR(b → dγ) to be typically 10 – 20 times smaller than BR(b → sγ), i.e. BR(b → dγ) = (1.7 ± 0.85) × 10^{-5}. Hence a large enhancement in the SUSY case is conceivable if (δ_{13}^d)_{LR} is in the 10^{-2}
range. Notice that in the MSSM we expect $(\delta^d_{13})_{LR} < m_b^2/m_t^2 \times V_{td} < 10^{-6}$, hence with no hope at all of a sizeable contribution to $b \to d\gamma$.

However, as we shall see in Sect. 4, sizeable deviations from the expected values of the $\delta$ quantities in the MSSM are possible in SUSY schemes which are obtained as the low-energy limit of $N = 1$ supergravities with a GUT structure and/or non-universal soft breaking terms.

### 4 Rare $B$ decays in the MSSM and beyond

Although the name seems to indicate a well-defined particle model, actually MSSM denotes at least two quite different classes of low-energy SUSY models. In its most restrictive meaning it denotes the minimal SUSY extension of the SM (i.e. with the smallest needed number of superfields) with R-parity, radiative breaking of electroweak symmetry, universality of the soft breaking terms and simplifying relations at the GUT scale among SUSY parameters. In this “minimal” version the MSSM exhibits only four free parameters in addition to those of the SM. Moreover, some authors impose specific relations between the two parameters $A$ and $B$ that appear in the trilinear and bilinear scalar terms of the soft breaking sector further reducing the number of SUSY free parameters to three. Then, all SUSY masses are just function of these few independent parameters and, hence, many relations among them exist. Obviously this very minimal version of the MSSM can be very predictive. The most powerful constraint on this minimal model in the FCNC context comes from $b \to s\gamma$.

In SUSY there are five classes of one-loop diagrams which contribute to FCNC $B$ processes. They are distinguished according to the virtual particles running in the loop: $W$ and up-quarks, charged Higgs and up-quarks, charginos and up-squarks, neutralinos and down-squarks, gluinos and down-squarks. It turns out that, at least in this “minimal” version of the MSSM, the charged Higgs and chargino exchanges yield the dominant SUSY contributions. As for $b \to s\gamma$ the situation can be summarized as follows. The CLEO measurement yields $\text{BR}(B \to X_s\gamma) = (2.32 \pm 0.67) \times 10^{-4}$ [10]. On the theoretical side we are going to witness a major breakthrough with the computation of the next-to-leading logarithmic result for the BR. This is achieved thanks to the calculation of the $O(\alpha_s)$ matrix elements [11] and of the next-to-leading order Wilson coefficients at $\mu \simeq m_t$ [12]. The result
quoted by Greub and Hurth [13] is $\text{BR}(B \to X_s \gamma) = (3.25 \pm 0.50) \times 10^{-4}$ in the SM with $m_t = (170 \pm 15)$ GeV and $m_b/2 \leq \mu \leq 2m_b$. A substantial improvement also on the experimental error is foreseen for the near future. Hence $b \to s\gamma$ is going to constitute the most relevant place in FCNC $B$ physics to constrain SUSY at least before the advent of $B$ factories. So far this process has helped in ruling out regions of the SUSY parameter space which are even larger than those excluded by LEP I and it is certainly going to be complementary to what LEP II is expected to do in probing the SUSY parameter space. After the detailed analysis in 1991 [14] for small values of $\tan \beta$, there have been recent analyses [15] covering the entire range of $\tan \beta$ and including also other technical improvements (for instance radiative corrections in the Higgs potential). It has been shown [16] that the exclusion plots are very sensitive also to the relation one chooses between $A$ and $B$. It should be kept in mind that the “traditional” relation $B = A - 1$ holds true only in some simplified version of the MSSM. A full discussion is beyond the scope of this talk and so we refer the interested readers to the vast literature which exists on the subject.

The constraint on the SUSY parameter space of the “minimal” version of the MSSM greatly affects also the potential departures of this model from the SM expectation for $b \to s l^+ l^-$. The present limits on the exclusive channels $\text{BR}(B^0 \to K^{*0} e^+ e^-)_{\text{CLEO}} < 1.6 \times 10^{-5}$ [17] and $\text{BR}(B^0 \to K^{*0} \mu^+ \mu^-)_{\text{CDF}} < 2.1 \times 10^{-5}$ [18] are within an order of magnitude of the SM predictions. On the theoretical side, it has been estimated that the evaluation of $\Gamma(B \to X_s l^+ l^-)$ in the SM is going to be affected by an error which cannot be reduced to less than $10 - 20\%$ due to uncertainties in quark masses and interference effects from excited charmonium states [19]. It turns out that, keeping into account the bound on $b \to s\gamma$, in the MSSM with universal soft breaking terms a $20\%$ departure from the SM expected BR is kind of largest possible value one can obtain [20]. Hence the chances to observe a meaningful deviation in this case are quite slim. However, it has been stressed that in view of the fact that three Wilson coefficients play a relevant role in the effective low-energy Hamiltonian involved in $b \to s\gamma$ and $b \to s l^+ l^-$, a third observable in addition to $\text{BR}(b \to s\gamma)$ and $\text{BR}(b \to s l^+ l^-)$ is needed. This has been identified in some asymmetry of the emitted leptons (see refs. [20, 21] for two different choices of such asymmetry). This quantity, even in the “minimal” MSSM, may undergo a conspicuous deviation from its SM expectation and, hence, hopes of some manifestation of SUSY, even in this minimal realization, in
$b \to s l^+ l^-$ are still present.

Finally, also for the $B_d - \bar{B}_d$ mixing, in the above-mentioned analysis of rare $B$ physics in the MSSM with universal soft breaking terms [14] it was emphasized that, at least in the low tan $\beta$ regime, one cannot expect an enhancement larger than $20\%-30\%$ over the SM prediction (see also ref. [22]). Moreover it was shown that $x_s/x_d$ is expected to be the same as in the SM.

It should be kept in mind that the above stringent results strictly depend not only on the minimality of the model in terms of the superfields that are introduced, but also on the “boundary” conditions that are chosen. All the low-energy SUSY masses are computed in terms of the $M_{Pl}$ four SUSY parameters through the RGE evolution. If one relaxes this tight constraint on the relation of the low-energy quantities and treats the masses of the SUSY particles as independent parameters, then much more freedom is gained. This holds true even if flavour universality is enforced. For instance, BR($b \to s \gamma$) and $\Delta m_{B_d}$ may vary a lot from the SM expectation, in particular in regions of moderate SUSY masses [23].

Moreover, flavour universality is by no means a prediction of low-energy SUSY. The absence of flavour universality of soft-breaking terms may result from radiative effects at the GUT scale or from effective supergravities derived from string theory. For instance, FCNC contributions in a minimal SUSY SO(10) model might be comparable to some of the upper bounds on the FCNC $\delta$ quantities given above [24]. In the non-universal case, BR($b \to s l^+ l^-$) is strongly affected by this larger freedom in the parameter space. There are points of this parameter space where the nonresonant BR($B \to X_s e^+ e^-$) and BR($B \to X_{\mu} \mu^+ \mu^-$) are enhanced by up to $90\%$ and $110\%$ while still respecting the constraint coming from $b \to s \gamma$ [20].

Finally, let us add a short comment on another rare $B$ decay, $b \to s g$, which has attracted some attention in these last years for its potentiality to increase the $b$ hadronic width, hence lowering the $b$ semileptonic branching ratio. It was recently noticed in refs. [25, 26] that a BR($b \to s g$) close to $10\%$ could simultaneously solve the two famous problems in $B$ physics of the semileptonic branching ratio and of the number of charms per $B$ decay (charm counting). At first sight, one could object that it is unlikely to have such a large BR($b \to s g$) given that its close “friend” BR($b \to s \gamma$) is at the $10^{-4}$ level. However it was shown in ref. [26] that there exists an admittedly small region of the SUSY parameter space where, indeed, BR($b \to s g$) is as high as
10% without conflicting with the measured value of $\text{BR}(b \rightarrow s\gamma)$. However, at this meeting S. Stone and some of his collaborators have emphasized that a $\text{BR}(b \rightarrow sg)$ at the 10% level is in difficulty with the results of searches for the $\Phi$ from $B \rightarrow X_s\Phi$.

5 Conclusions

We summarize the results reported in this talk in the following three points.

1. First, a warning: under the commonly used expression of low-energy SUSY there exists actually a large choice of models (with or without R parity, with or without flavour universality of the soft breaking terms, with or without GUT assumptions,...) which lead to quite different implications for rare $B$ decays.

2. What we called here the “minimal” version of the MSSM, i.e. its most restrictive version with only four independent parameters, is mainly constrained by $b \rightarrow s\gamma$, with little hope of significant departures from SM in other FCNC $b$ physics (however, some exception is possible, like, for instance, lepton asymmetries in $b \rightarrow s l^+ l^-$).

3. Extensions of the above “minimal” version of the MSSM with non-universality, or with SUSY-GUT’s, have room for conspicuous departures from the SM in $b \rightarrow s l^+ l^-$ and $b \rightarrow sg$.

The hope is that the advent of $B$ factories may promote $B$ physics to a ground for “precision tests” of new physics analogously to what has been done for the LEP Z factory.

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Figure 1: The $|\delta_{23}^d|_{LR}$ as a function of $x = m_{\tilde{q}}^2/m_{\tilde{q}}^2$, for an average squark mass $m_{\tilde{q}} = 100$GeV. For different values of $m_{\tilde{q}}$, the limits scale as $m_{\tilde{q}}$(GeV)/100.