$b \to s$ Transitions: A New Frontier for Indirect SUSY Searches

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Abstract

The present unitarity triangle fit, whose essential input is represented by the $s \to d$ and $b \to d$ transition processes, fully agrees with the SM. However, most of the phenomena involving $b \to s$ transitions are still largely unexplored and hence $b \to s$ phenomenology still constitutes a place for new physics manifestations, in spite of the tremendous experimental and theoretical progress on $B \to X_s\gamma$. We perform a systematic study of the CP conserving and violating SUSY contributions to $b \to s$ processes in a generic MSSM. We consider gluino exchange contributions including NLO QCD corrections and lattice hadronic matrix elements for $\Delta B = 2$ and $\Delta B = 1$ processes. We take into account all available experimental information on processes involving $b \to s$ transitions ($B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$ and the lower bound on the $B_s - \bar{B}_s$ mass difference $\Delta M_s$). We study the correlations among the relevant observables under scrutiny at present or in a not too far future: $\Delta M_s$ and the amount of CP violation in $B \to \phi K_s$, $B_s \to J/\psi\phi$, $B \to X_s\gamma$. In particular we discuss the recent data by BaBar and BELLE on the time-dependent CP asymmetry in the decay $B \to \phi K_s$ which suggest a deviation from the SM expectation. Our results show that the processes involving $b \to s$ transitions represent a splendid opportunity to constrain different MSSM realizations, and, even more important, that they offer concrete prospects to exhibit SUSY signals at $B$ factories and hadron colliders in spite of all the past frustration in FCNC searches of new physics hints.
1 Introduction

The Standard Model (SM) of electroweak and strong interactions is extremely successful in describing all available data on particle physics up to the highest energies reached presently at colliders. However, its least understood aspects concern electroweak and flavour symmetry breaking, i.e. the Higgs sector and fermion masses and mixings. Supersymmetry (SUSY) is the only known low-energy extension of the SM which, in addition to stabilizing the Higgs sector against radiative corrections, allows for gauge coupling unification at high energies, without spoiling the agreement with precision electroweak data. However, on its own it does not add any understanding of flavour symmetry breaking. Indeed, flavour physics is a very stringent test of SUSY extensions of the SM: in its general form, the Minimal Supersymmetric Standard Model (MSSM) contains more than 100 new parameters in the flavour sector, which can cause Flavour Changing Neutral Current (FCNC) and CP violating processes to arise at a rate much higher than what is experimentally observed [1]–[3].

Within the SM, the only sources of flavour and CP violation in the hadronic sector arise from the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. Recent progresses in experimental results and in theoretical methods allow for a very successful determination of the CKM parameters via the so-called Unitarity Triangle (UT) fit, which combines all presently available informations on flavour and CP violation. The success of the SM UT fit is a clear signal that present experimental data do not favour new generic sources of FCNC and CP violation. However, we think that it is premature to draw the conclusion that the room available for New Physics (NP) in FCNC and CP violating processes has shrunk to the point that no significant departure from SM expectations is foreseeable within such phenomena.

A closer look at the UT fit reveals that NP contributions to $s \to d$ and $b \to d$ transitions are strongly constrained, while new contributions to $b \to s$ transitions do not affect the fit at all, unless they interfere destructively with the SM amplitude for $B_s - \bar{B}_s$ mixing, bringing it below the present lower bound of $\sim 14$ ps$^{-1}$. It is certainly true that other processes not directly involved in the UT fit, in particular $B \to X_s \gamma$ and, to a lesser extent, $B \to K\pi$, $B \to \phi K_s$, $B \to X_s \ell^+\ell^-$ and $B_s \to \ell^+\ell^-$ decays represent a powerful constraint on any NP in $b \to s$ transitions. However, the celebrated $B \to X_s \gamma$ decay mostly constrains the helicity flipping contributions to the $b \to s$ transition and, as we shall see in the following, in the case of SUSY the effect of these constraints is not as dramatic as it is for $s \to d$ and $b \to d$ transitions, and plenty of room is left for SUSY contributions to interesting observables in this sector.

In this work we intend to make a systematic study of the SUSY contributions to the (CP conserving and violating) $b\to s$ transitions in the context of a generic MSSM model with R parity. We see three main motivations to pursue yet another analysis on the thoroughly explored issue of FCNC and MSSM.

i) Thanks to the advent of the new B factories, our experimental knowledge concerning the above processes has greatly improved in this last period and, in addition, we expect new results on the $B_s - \bar{B}_s$ mixing soon at Run II of the Tevatron from CDF and later on BTeV and LHCB. Hence, a more thorough investigation of the $b \to s$
transition both in $\Delta B = 2$ and $\Delta B = 1$ processes is now mandatory.

ii) While for $\Delta B = 2$ processes a refined treatment of the gluino exchange contributions including the NLO QCD evolution for the four-quark operators and a lattice computation of the hadronic matrix elements is now available [4], the same does not apply to the $\Delta B = 1$ case. Moreover correlations among different observables in $b \to s$ physics have still to be largely explored in the MSSM context.

iii) Finally, it was recently pointed out [5, 6] that the large mixing(s) in the neutrino sector may imply the presence of large mixing angles in the right-handed down-type quarks in GUT’s where the latter are unified with the lepton doublets. Although we cannot witness the presence of such large mixings in our experiments given that they are present in the right-handed charged hadronic currents, we can still have a visible implication in low-energy physics because of the possible large mixing between right-handed bottom and strange squarks through radiative corrections induced by the large top Yukawa coupling.

Although this latter motivation iii) would push us towards the choice of particular patterns of squark mass matrices with only the $\tilde{b}_R - \tilde{s}_R$ entry largely enhanced (see ref. [7]), in view also of the previous two motivations we think it more interesting not to commit ourselves to any specific choice of the squark masses, but rather to keep our analysis in the MSSM as general as possible. Obviously, then the enhanced $\tilde{b}_R - \tilde{s}_R$ case turns out to be just a particular case and we are able to appreciate even more its characterizing features when we embed it in a generic low-energy SUSY extension of the SM. Needless to say, there is a price to pay to allow ourselves to be so general: the complete ignorance of the squark mass textures prevents us from using the basis of the squark physical (mass) eigenstates, but rather we have to make use of an efficient parametrization of the generic squark mass matrix diagonalization. Such a tool has been available for a long time [8]: we parametrize the new sources of flavour and CP violation in the hadronic sector present in a generic MSSM choosing the so-called Super-CKM basis. In this basis, all gauge couplings involving SUSY partners of quarks have the same flavour structure as the corresponding quark couplings. FCNC and CP violation arise then from off-diagonal terms in squark mass matrices. These are conveniently expressed as $(\delta_{ij})_{AB} \equiv (\Delta_{ij})_{AB}/m_{\tilde{q}}^2$, where $(\Delta_{ij})_{AB}$ is the mass term connecting squarks of flavour $i$ and $j$ and “helicities” $A$ and $B$, and $m_{\tilde{q}}$ is the average squark mass. In the absence of any horizontal symmetry and for a generic SUSY breaking mechanism, one expects $(\delta_{ij})_{LL} \leq O(1)$, $(\delta_{ij})_{RR} \leq O(1)$, $(\delta_{ij})_{LR} \leq O(m_{d_k}/m_{\tilde{q}})$ and $(\delta_{ij})_{RL} \leq O(m_{d_k}/m_{\tilde{q}})$, with $k = \text{max}(i, j)$. The last two inequalities are also imposed by the requirement of avoiding charge and colour breaking minima as well as unbounded from below directions in scalar potentials [9]. We argued above that the UT fit poses stringent constraints on NP contributions to $s \to d$ and $b \to d$ transitions, which in the MSSM are governed by $(\delta_{12})_{AB}$ and $(\delta_{13})_{AB}$ respectively. Indeed, detailed analyses carried out in SUSY at a level of accuracy comparable to the SM UT fit (NLO QCD corrections, Lattice QCD hadronic matrix elements) have shown that one must have $(\delta_{12})_{AB}$ and $(\delta_{13})_{AB}$ much smaller than what naively expected [4, 10]. It is therefore reasonable to assume that, either due to the effect of some horizontal symmetry or to the explicit form of SUSY breaking, $(\delta_{12})_{AB} \sim (\delta_{13})_{AB} \sim 0$. The pur-
pose of this paper is to thoroughly analyze, once again at the same level of accuracy of SM investigations, constraints on \((\delta_{23}^d)_{AB}\) from available data and possible effects in present and future measurements. As we shall see, in this case \((\delta_{23}^d)_{AB}\) at the level of what naively expected are certainly allowed by present data. Moreover, if some recent experimental results, such as the CP asymmetry in \(B \to \phi K_s\) decays [11, 12] will be confirmed with better accuracy, values of \((\delta_{23}^d)_{AB}\) close to the naive expectations could be even favoured by experiments, giving an indirect hint of SUSY in \(B\) physics.

2 Analysis

We now describe in detail the analysis we carried out. Preliminary results had been already presented at ICHEP02 [13]. We aim at determining the allowed regions in the SUSY parameter space governing \(b \to s\) transitions, studying the correlations among different observables and pointing out possible signals of SUSY. The constraints on parameter space come from:

1. The BR\((B \to X_s\gamma) = (3.29 \pm 0.34) \times 10^{-4}\) (experimental results as reported in [12], rescaled according to ref. [14]).
2. The CP asymmetry \(A_{CP}(B \to X_s\gamma) = -0.02 \pm 0.04\) [12].
3. The BR\((B \to X_s\ell^+\ell^-) = (6.1 \pm 1.4 \pm 1.3) \times 10^{-6}\) [12].
4. The lower bound on the \(B_s - \bar{B}_s\) mass difference \(\Delta M_{B_s} > 14.4\) ps\(^{-1}\) [12].

We have also considered BR’s and CP asymmetries for \(B \to K\pi\). For \(B \to \phi K_s\), we have studied the BR and the coefficients \(C_{\phi K}\) and \(S_{\phi K}\) of cosine and sine terms in the time-dependent CP asymmetry. Due to theoretical and experimental uncertainties, these processes are less effective as a constraint on SUSY, as we discuss in the following.

Concerning \(B_s - \bar{B}_s\) mixing, we closely follow the treatment of \(B_d - \bar{B}_d\) mixing in ref. [4], where all the relevant formulae for matching conditions [2], NLO QCD evolution [15, 16] and hadronic matrix elements [17] can be found (with the obvious replacement \(d \to s\)), as well as a detailed discussion of the uncertainties of this kind of analysis. We include SM and gluino-mediated SUSY contributions, which are expected to be dominant for large mass insertions. However, in particular cases, such as large \(\mu\) tan\(\beta\) scenarios, chargino exchange can also be important. See ref. [18] for a discussion of the impact of chargino-mediated contributions in \(\Delta B = 2\) processes.

For \(\Delta B = 1\) transitions, the matching conditions for four-quark operators are given in ref. [19], and the NLO QCD evolution can be obtained from the anomalous dimensions given in ref. [20]. The NLO anomalous dimensions for magnetic and chromomagnetic operators can be found in ref. [21]. The matching conditions including semileptonic operators are given in ref. [22] and the anomalous dimensions were given in ref. [23]. NLO QCD matrix elements and matching conditions to the Standard Model for \(B \to X_s\gamma\) can be found in ref. [24].

Concerning \(B \to K\pi\) and \(B \to \phi K_s\) decays, we adopt BBNS factorization [25], with the caveats on \(\Lambda/M_b\) corrections raised in ref. [26]. The importance of power-suppressed contributions in \(B \to K\pi\) decays is widely recognized. However, it is a matter of debate
whether these corrections come mainly from the matrix elements of penguin operators or from penguin contractions of current-current operators containing charm quarks (the charming penguins of ref. [27]). These contributions, having the same quantum numbers, cannot be disentangled using experimental data. Indeed, present data can be reproduced using either mechanism. SUSY only affects the coefficients of penguin operators, leaving current-current operators unmodified. Therefore, the sensitivity to SUSY effects is expected to be much lower in the presence of charming penguins. For this reason, in order to maximize the sensitivity to SUSY contributions, we use the BBNS treatment of power-suppressed terms in this paper. However, in the spirit of the criticism of ref. [26], we let the annihilation parameter $\rho_A$ of the BBNS model vary between 0 and 8.

Another source of potentially large SUSY effects in $B \to K\pi$ and $B \to \phi K_s$ decays is the contribution of the chromomagnetic operator. As pointed out in ref. [28], this operator can be substantially enhanced by SUSY without spoiling the experimental constraints from $B \to X_s\gamma$. Also here the hadronic uncertainties can be large. In fact, this term is generated as an $O(\alpha_s)$ correction to the leading power amplitude. For this reason, the one-loop proof of factorization does not apply to this term. In any case, power-suppressed contributions may be numerically of the same size.

We have checked explicitly that, given the large hadronic uncertainties, $B \to K\pi$ modes give no significant constraints on the $\delta$’s. The time-dependent asymmetry in $B \to \phi K_s$, instead, is sensitive to the SUSY parameters. This sensitivity is more pronounced in the case of $LR$ insertions. However, this comes from the contribution of the chromomagnetic operator, via the matrix element that, as already mentioned, has large uncertainties.

We performed a MonteCarlo analysis, generating weighted random configurations of input parameters (see ref. [29] for details of this procedure) and computing for each configuration the processes listed above. We study the clustering induced by the constraints on various observables and parameters, assuming that each unconstrained $\delta_{23}^d$ fills uniformly a square ($-1 \ldots 1, -1 \ldots 1$) in the complex plane. The ranges of CKM parameters have been taken from the UT fit [30] ($\bar{\rho} = 0.178 \pm 0.046, \bar{\eta} = 0.341 \pm 0.028$), and hadronic parameter ranges are as given in refs. [12, 14, 17, 26]. Concerning SUSY parameters, we fix $m_{\tilde{q}} = m_{\tilde{g}} = 350$ GeV and consider different possibilities for the mass insertions. In addition to studying single insertions, we also examine the effects of the left-right symmetric case $(\delta_{23}^d)_{LL} = (\delta_{23}^d)_{RR}$ and of $(\delta_{23}^d)_{RR} = (\delta_{23}^d)_{LR}$ inspired by large $RR$ mixing at large $\tan\beta$ [7].

The gluino-mediated $b \to s$ transitions in the MSSM had already been investigated by several authors [31]–[42] before the announcement of $S_{\phi K}$ negative and have been vigorously reassessed [7, 43]–[47] after such results were announced last Summer. In particular in the works of refs. [46, 47] the correlation between $B \to \phi K_s$ and $B_s - \bar{B}_s$ mixing has been investigated making use of the mass insertion approximation. In our present work we largely improve at the level of accuracy with the inclusion of NLO QCD corrections and lattice QCD hadronic matrix elements and also in the correlation of $b \to s$ related processes with the selection of the $\Delta B = 1$ and $\Delta B = 2$ phenomena outlined above. Indeed, for instance the inclusion of the process $B \to X_s\ell^+\ell^-$ leads
to further constraints which were not included in such previous analyses. As for the evaluation of \( B \to K\pi \) and \( B \to \phi K_s \), ref. [46] adopts the BBNS factorization, but without discussing the possibly large \( \Lambda/M_b \) corrections. This may be the source of some relevant quantitative difference on the \( RR \) contributions to \( BR(B \to \phi K_s) \) with respect to refs. [46, 47], as we will detail in next Section. As for the analysis of ref. [7], this is performed in the mass eigenstate basis taking a specific down squark mass matrix (as suggested in SUSY GUT’s where the large neutrino mixing is linked to a large \( \tilde{b}_R \to \tilde{s}_R \) mixing). Comparing the results of our cases of \( RR \) dominance and \( RR = RL \) dominance with their results we find some discrepancy in particular in the case of large \( (\delta_{23}^{d})_{RR} \) (see below). Once again a potential source of discrepancy in constraining the \( \delta_{23}^{s} \)'s from \( A_{CP}(B \to \phi K_2) \) is represented by the delicate evaluation of the matrix elements of the chromo-dipole operators.

In fig. 1 we display the clustering of events in the \( \text{Re}(\delta_{23}^{d})_{AB} - \text{Im}(\delta_{23}^{d})_{AB} \) plane in the single insertion case. Here and in the following plots, larger boxes correspond to larger numbers of weighted events. Constraints from \( BR(B \to X_s\gamma) \), \( A_{CP}(B \to X_s\gamma) \), \( BR(B \to X_s\ell^+\ell^-) \) and the lower bound on \( \Delta M_s \) have been used, as discussed above. The darker regions are selected imposing the further constraint \( \Delta M_s < 20 \text{ ps}^{-1} \) for \( LL \) and \( RR \) insertions and \( S_{\phi K} < 0 \) for \( LR \) and \( RL \) insertions. For helicity conserving insertions, the constraints are of order 1. A significant reduction of the allowed region appears if the cut on \( \Delta M_s \) is imposed. The asymmetry of the \( LL \) plot is due to the interference with the SM contribution. In the helicity flipping cases, constraints are of order \( 1 \times 10^{-2} \). For this values of the parameters, \( \Delta M_s \) is unaffectted. We show the effect of requiring \( S_{\phi K} < 0 \): it is apparent that a nonvanishing \( \text{Im}(\delta_{23}^{d}) \) is needed to meet this condition.

Fig. 2 contains the same plots as fig. 1 in the two cases of double mass insertion that we consider in this analysis, namely \( (\delta_{23}^{d})_{LL} = (\delta_{23}^{d})_{RR} \) and \( (\delta_{23}^{d})_{RL} = (\delta_{23}^{d})_{RR} \) (see next Section for a justification of this choice of the double mass insertion cases). For \( (\delta_{23}^{d})_{LL} = (\delta_{23}^{d})_{RR} \), the constraints are still of order 1, but the contribution to \( \Delta M_s \) is huge, due to the presence of operators with mixed chiralities. This can be seen from the smallness of the dark region selected by imposing \( \Delta M_s < 20 \text{ ps}^{-1} \). As for the double mass insertion with \( (\delta_{23}^{d})_{RL} = (\delta_{23}^{d})_{RR} \), by comparison of RHS of fig. 2 with the \( RL \) case in the lower right side of fig. 1, we argue that both the allowed regions and the portions of them for which \( S_{\phi K} < 0 \) are very similar in these two cases. In other words, a double mass insertion with \( (\delta_{23}^{d})_{RL} = (\delta_{23}^{d})_{RR} \) does not exhibit remarkably different features from the case of a single mass insertion \( (\delta_{23}^{d})_{RL} \), at least at this value of squark and gluino masses.

In figs. 3–7, we study the correlations between \( S_{\phi K} \) and \( C_{\phi K} \), \( \text{Im}(\delta_{23}^{d})_{AB} \) and \( A_{CP}(B \to X_s\gamma) \) for the various SUSY insertions considered in the present analysis. In view of the discussion in the previous Section on the hadronic matrix elements for \( B \to \phi K_s \), the reader should keep in mind that, in all the results reported in figs. 3–7, the hadronic uncertainties affecting the estimate of \( S_{\phi K} \) are not completely under control. Low values of \( S_{\phi K} \) can be more easily obtained with helicity flipping insertions. A deviation from the SM value for \( S_{\phi K} \) requires a nonvanishing value of \( \text{Im}(\delta_{23}^{d})_{AB} \) (see figs. 5 and 6), generating, for those channels in which the SUSY amplitude can
Figure 1: Allowed regions in the $\text{Re}(\delta_{23}^d)_{AB} - \text{Im}(\delta_{23}^d)_{AB}$ space for $m_{\tilde{q}} = m_{\tilde{g}} = 350$ GeV and $AB = (LL, RR, LR, RL)$. Constraints from $\text{BR}(B \to X_s\gamma)$, $\text{ACP}(B \to X_s\gamma)$, $\text{BR}(B \to X_s l^+ l^-)$ and the lower bound on $\Delta M_s$ have been used. The darker regions are selected imposing the further constraint $\Delta m_s < 20$ ps$^{-1}$ for $LL$ and $RR$ insertions and $S_{\phi K} < 0$ for $LR$ and $RL$ insertions.
interfere with the SM one, a $A_{CP}(B \rightarrow X_s\gamma)$ at the level of a few percents in the LL and LL=RR cases, and up to the experimental upper bound in the LR case (see fig. 7).

3 $b \rightarrow s$ transitions: where to look for SUSY?

We now wish to address the crucial question which naturally arises after accomplishing the analysis of the constraints on the $\delta_{d23}$ quantities of the previous section: what are the more promising processes to reveal some indirect signal of low energy SUSY, among the FCNC ones involving $b \rightarrow s$ transitions? As it stands, this question cannot have a clear-cut answer: indeed, low-energy SUSY is an ill-defined notion. Rather, sticking as we do here to the MSSM, one can speak of different MSSM realizations characterized by different sets of soft breaking terms. For the purpose of the present discussion, the best way to classify such different “classes of MSSM” is according to the role played by the different $\delta_{d23}$'s according to their “helicities” $LL$, $RR$, etc. First we will focus on the case where only one $\delta_{d23}$ dominates (single mass insertion), while in the final part we will contemplate the possible coexistence of two sizeable $\delta_{d23}$'s (double mass insertion).
Figure 3: Correlations between the sine ($S_{\phi K}$) and cosine ($C_{\phi K}$) coefficients of the time-dependent CP asymmetry of $B \to \phi K_s$ for $m_{q} = m_{\tilde{g}} = 350$ GeV and various SUSY mass insertions $(\delta^{d}_{23})_{AB}$ with $AB = (LL, RR, LR, RL)$. Constraints from $BR(B \to X_s \gamma)$, $A_{CP}(B \to X_s \gamma)$, $BR(B \to X_s l^+ l^-)$ and the lower bound on $\Delta M_s$ have been used.
Before starting our analysis, a relevant remark is in order. The BaBar and BELLE Collaborations have recently reported the time-dependent CP asymmetry in $B_d(\bar{B}_d) \rightarrow \phi K_s$. The SM predicts such asymmetry to be the same as that measured in the $J/\psi K_s$ decay channel. On the contrary, while $\sin 2\beta$ as measured in the $B \rightarrow J/\psi K_s$ channel is $0.734 \pm 0.054$ (in agreement with the SM prediction [12]), the combined result from both collaborations for the corresponding $S_{\phi K}$ of $B_d \rightarrow \phi K_s$ is $-0.39 \pm 0.41$ [11, 48] with a $2.7\sigma$ discrepancy between the two results. Obviously, in particular after similar experiences in these last years, we should be very cautious before accepting such result as a genuine indication of NP. Nonetheless, it is certainly legitimate to entertain the possibility that the negative value of $S_{\phi K}$ is due to large SUSY CP violating contributions. Then one can wonder which $\delta$'s are relevant to produce such enhancement and, even more important, which other significant deviations from the SM expectations in $b \rightarrow s$ physics could be detected at $B$ factories or hadron accelerators, if really $S_{\phi K}$ has a SUSY origin.

We remind the reader that our analysis is performed for squark and gluino masses of 350 GeV. We will comment at the end on what happens if we increase such masses up to the TeV region.

3.1 **RR case**

As shown in Fig. 3 (upper right), although values of $S_{\phi K}$ in the range predicted by the SM are largely favoured, still pure $\delta_{RR}$ insertions are able to give rise to a negative $S_{\phi K}$. 

Figure 4: Same as in fig. 3 for double insertions $LL = RR$ and $RL = RR$. 

![Figure 4](image-url)
Figure 5: Correlations between $S_{\phi K}$ and $\text{Im}(\delta_{23}^{AB})$ for $m_{\tilde{q}} = m_{\tilde{g}} = 350$ GeV and $AB = (LL, RR, LR, RL)$. Constraints from $BR(B \rightarrow X_s \gamma)$, $A_{CP}(B \rightarrow X_s \gamma)$, $BR(B \rightarrow X_s l^+ l^-)$ and the lower bound on $\Delta M_s$ have been used.
in agreement with the results of BaBar and BELLE quoted above. On this point we seem to agree with the conclusions of ref. [7], while being in disagreement with refs. [46] and [47]. Notice that in correspondence to negative values of $S_{\phi K}$, a vanishing $C_{\phi K}$, although not favoured, is however still possible. This is due to our choice of varying the hadronic parameter $\rho_A$, corresponding to power-suppressed annihilation contributions, over a large range. In this way there are always particular configurations in which the strong phase difference, and therefore the CP asymmetry, vanish. Had we assumed $|\rho_A| < 1$ as suggested in ref. [25], we would have found $C_{\phi K} \neq 0$ for $S_{\phi K} < 0$ [45]. As for the $B_s - \bar{B}_s$ mixing, the distribution of $\Delta M_s$ is peaked at the SM value, but it has a long tail at larger values, up to $\sim 120 \text{ ps}^{-1}$ for our choice of the range of $\delta_{RR}$. In addition, we find that the expected correlation requiring a large $\Delta M_s$ for negative $S_{\phi K}$ is totally wiped out by the large uncertainties (see fig. 8, lower right). In this respect, we are at variance with ref. [7], where it was emphasized that if the $RR$ squark mixing yields the large deviation from the SM for the value of $S_{\phi K}$, then a huge contribution to the $B_s$ mixing should necessarily follow making such oscillation unobservable at Tevatron. Hence, according to our analysis, in the $RR$ case it is compatible to have a strong discrepancy between $\sin 2\beta$ and $S_{\phi K}$ whilst $B_s - \bar{B}_s$ oscillations proceed as expected in the SM (thus, being observable in the Run II of Tevatron).

As for other CP violating asymmetries to be searched for, the CP asymmetry in $B \to X_s\gamma$ is expected to be as small as in the SM, while, differently from the SM, we expect here in general a large time-dependent CP asymmetry in the decay channel $B_s \to J/\psi\phi$. 

Figure 6: Same as in fig. 5 for double insertions $LL = RR$ and $RL = RR$. 

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Figure 7: Correlation between $S_{\phi K}$ and $A_{CP}(b \rightarrow s\gamma)$ for various SUSY mass insertions \((\delta^3_{23})_{AB}\) with $AB = (LL, LR, LLRR)$. Constraints from $BR(B \rightarrow X_s\gamma)$, $A_{CP}(B \rightarrow X_s\gamma)$, $BR(B \rightarrow X_s l^+ l^-)$ and the lower bound on $\Delta M_s$ have been used.
Figure 8: Distributions of $\Delta M_s$ for various SUSY mass insertions ($\delta_{23}^A$)$_{AB}$ with $AB = (LL, RR, LLRR)$. Different curves correspond to the inclusion of constraints from $B \to X_s \gamma$ only (magenta), $B \to X_s l^+ l^-$ only (cyan) and all together (blue). Lower right: correlation between $\Delta M_s$ and $S_{\phi K}$ in the $RR$ case.
3.2 LL case

A major difference between the LL and the RR cases concerns the SUSY contributions to $B \to X_s \gamma$. When $\delta_{LL}$ dominates, SUSY contributes to the same operator which is responsible for $B \to X_s \gamma$ in the SM and, hence, the SUSY and SM contributions interfere. As a consequence, the rate tends to be larger than the RR case, and, moreover, a CP asymmetry can be generated up to 5% (see fig. 7, upper left). However, given the uncertainties, the correlation of $A_{CP}(B \to X_s \gamma)$ with $S_{\phi K}$ is not very stringent.

As can be seen from the figure, negative values of $S_{\phi K}$ do not necessarily correspond to non-vanishing $A_{CP}(B \to X_s \gamma)$, although typical values are around 2%. Also, the constraint coming from the present measurement of the CP asymmetry is not very effective, as can be seen for instance from the distribution of $\Delta M_s$ in fig. 8 which is quite similar to the RR case. Finally, one expects also in this case to observe CP violation in $B_s \to J/\psi \phi$ at hadron colliders.

3.3 LR and RL cases

In these cases, negative values of $S_{\phi K}$ can be easily obtained (although a positive $S_{\phi K}$ is favoured, cfr. Fig. 3, bottom row). The severe bound on the LR mass insertion imposed by $\text{BR}(B \to X_s \gamma)$ (and $A_{CP}(B \to X_s \gamma)$ in the LR case) prevents any enhancement of the $B_s - \bar{B}_s$ mixing as well as any sizeable contribution to $A_{CP}(B_s \to J/\psi \phi)$. On the other hand, $A_{CP}(B \to X_s \gamma)$ as large as $5 - 10\%$ is now attainable (Fig. 7, upper right), offering a potentially interesting hint for NP.

Notice that the LR case corresponds to a dominant $\bar{s}_L - \bar{b}_R$ mass insertion, hence yielding a contribution to $b_R \to s_L \gamma$ which interferes with the analogous leading contribution from the SM, producing the 'hole' in fig. 1, lower left. On the contrary, the RL mass insertion contributes to $b_L \to s_R \gamma$ and thus it does not add to the leading SM amplitude. Consequently, the CP asymmetry is as small as in the SM.

3.4 Double mass insertion: $(\delta_{23})_{LL} = (\delta_{23})_{RR}$ case

The main feature of this case is the huge enhancement of $\Delta M_s$ which is made possible by the contribution of the double insertion $LL$ and $RR$ in the box diagrams to operators with mixed chiralities (Fig. 8, lower left). Differently from all the previous cases, we are facing a situation here where $A_{CP}(B \to \phi K_s)$ at its present experimental value should be accounted for by the presence of SUSY, while $\Delta M_s$ could be so large that the $B_s - \bar{B}_s$ mixing could escape detection not only at Tevatron, but even at BTeV or LHCb. Hence, this would be a case for remarkable signatures of SUSY in $b \to s$ physics.

3.5 Double mass insertion: $(\delta_{23})_{RL} = (\delta_{23})_{RR}$ case

As we previously mentioned, in MSSM realizations obtained as low-energy limits of SUSY GUT’s where neutrinos and right-handed down quarks live in the same SU(5) fiveplets, the case for a large $(\delta_{23})_{RR}$ is strongly motivated by the observed large mixing
between neutrinos of the second and third generation. In addition, we can have also a large $\tilde{b}_R - \tilde{b}_L$ if the product $\mu \tan \beta$ happens to be enhanced (by large values of $\mu$ and/or $\tan \beta$)\(^1\). If this is the case, the subsequent $\tilde{b}_L - \tilde{b}_R$ and $\tilde{b}_R - \tilde{s}_R$ mass insertions lead to a large $\tilde{b}_L - \tilde{s}_R$ transition, i.e. a large $(\delta_{23}^d)_{LR}$. This makes of interest to consider the case where $(\delta_{23}^d)_{RR}$ and $(\delta_{23}^d)_{RL}$ are both simultaneously large. Phenomenologically, there is no big difference between this case and the $RL$ case, as can be seen from figs. 2–6.

We close this section by remarking that in the $LR$, $RL$ and $RL = RR$ cases, since for $m_{\tilde{g}} = m_{\tilde{q}} = 350$ GeV the constraints on the $\delta_{23}^d$’s are of order $1 \times 10^{-2}$, it is obvious that the same phenomenology in $\Delta B = 1$ processes can be obtained at larger values of mass insertions and of squark and gluino masses. In this case, contributions to $\Delta B = 2$ processes become more important for larger masses. One could naively think of going up to 3.5 TeV with $\delta_{23}^d \sim 1$, however so large values of $\delta_{23}^d$ and $m_{\tilde{q}}$ produce charge and color breaking minima [9]. In the remaining cases, where the limits on $\delta_{23}^d$ at $m_{\tilde{g}} = m_{\tilde{q}} = 350$ GeV are of order 1, the SUSY effects clearly weaken when going to higher values of sparticle masses.

4 Outlook

All the known FCNC and CP violation phenomenology in kaon, beauty, charm, lepton physics and the EDM’s confirm the simple CKM picture of flavor physics as provided by the SM.

This may be interpreted as an indication that the relevant new physics involved in the electroweak symmetry breaking is flavor blind or that the new particles associated with it are actually relatively heavy, say at least beyond the TeV threshold.

However, sticking more strictly and cautiously to what has been experimentally ascertained so far, one should actually conclude that although FCNC physics involving the first two generations (i.e. $s \rightarrow d$ transitions) can hardly offer any prospect of “visibility” for NP, the same cannot be said for FCNC and CP violation involving the third generation, in particular as far as $b \rightarrow s$ transitions are concerned. The first result on $A_{CP}(B \rightarrow \phi K_s)$ from BaBar and Belle is an example that some room for surprise is still available.

In this paper we analyzed the prospects for the $b \rightarrow s$ physics for the particularly interesting case where the low-energy new physics is represented by a generic MSSM. Minimality refers here only to the minimal amount of superfields needed to supersymmetrize the SM and to the presence of R parity. Otherwise the soft breaking terms are left completely free and constrained only by phenomenology. Technically the best way we have to account for the SUSY FCNC contributions in such a general framework is via the mass insertion method using the leading gluino exchange contributions.

Our results in a generic MSSM confirm that FCNC and CP violation in physics involving $b \rightarrow s$ transitions still offer opportunities to disentangle effects genuinely due

\(^1\)This is however the case in which chargino-mediated contributions are expected to be important and should be included choosing a specific model. Therefore, in this case the results of our model-independent analysis should be interpreted with care.
to NP. In particular the discrepancy between the amounts of CP violation in the two $B_d$ decay channels $J/\psi K_s$ and $\phi K_s$ can be accounted for in the MSSM while respecting all the existing constraints in $B$ physics, first of all the $BR(B \rightarrow X_s \gamma)$. The relevant question is then which processes offer the best chances to provide other hints of the presence of low-energy SUSY.

First, needless to say, it is mandatory to further assess the time-dependent CP asymmetry in the decay channel $B \rightarrow \phi K_s$. Should the abovementioned discrepancy signaling NP be firmly confirmed, then this process would become decisive in discriminating among different MSSM realizations. Although, as we have seen, it is possible to reproduce the negative $S_{\phi K}$ in a variety of different options for the SUSY soft breaking down squark masses, the allowed regions in the SUSY parameter space to obtain this result are more or less tightly constrained according to the kind of $\delta_{23}^d$ mass insertion which is dominant.

We think that in order of importance after the reassessment of $A_{CP}(B \rightarrow \phi K_s)$, comes the measurement of the $B_s - \bar{B}_s$ mixing. Finding $\Delta M_s$ larger than 20 ps$^{-1}$ would hint at NP and, in our context, would imply that the chirality-changing mass insertions or the $RL = RR$ double insertion should not be dominant in $b \rightarrow s$ transitions. $RR$ or $LL$ could account for a $\Delta M_s$ up to $\sim 120$ ps$^{-1}$. Larger values would call for the double insertion $LL = RR$ to ensure such a huge enhancement of $\Delta M_s$ while respecting the constraint on $BR(B \rightarrow X_s \gamma)$. An interesting, alternative prospect would arise in case $\Delta M_s$ is found as expected in the SM while, at the same time, $S_{\phi K}$ is confirmed to be negative. This scenario would favour the $RL$ or $LR$ possibility, even though all other cases but $LL = RR$ do not necessarily lead to large $\Delta M_s$.

Keeping to $B$ physics to be studied at $B$ factories, we point out that the CP asymmetry in $B \rightarrow X_s \gamma$ remains of utmost interest. As we know, this asymmetry is so small in the SM that it should not be possible to detect it. We have seen that in particular with $LR$ $b \rightarrow s$ insertions such asymmetry can be enhanced up to 10% making it possibly detectable in a not too distant future.

Finally, once we will have at disposal large amounts of $B_s$ at hadron colliders it will be of great interest to study processes which are expected to be mostly CP conserving in the SM, while they are expected to receive possibly large contributions from SUSY in the $b \rightarrow s$ transitions. Indeed, in the SM the amplitude for $B_s - \bar{B}_s$ mixing is dominated by the top quark exchange and, hence, it does not have an imaginary part up to doubly Cabibbo suppressed terms. Also the transition $b \rightarrow s$ through top and $W$ exchange does not exhibit the CKM phase and, hence, no leading CP contribution should arise in amplitudes for $b \rightarrow s$ processes. In conclusion decays like $B_s \rightarrow J/\psi \phi$ should have a negligible amount of CP violation. Quite on the contrary, if the measured negative $S_{\phi K}$ is due to a large, complex $\delta_{23}^d$ mass insertion, we expect some of the above processes to exhibit a significant amount of CP violation. In particular in the case of $RR$ insertions both the $b \rightarrow s$ amplitudes and the $B_s$ mixing would receive non negligible contributions from $\text{Im} \, \delta_{23}^d$, while in the case where $S_{\phi K}$ is dominated by $RL$ or $LR$ insertions we do not expect any sizable contribution to $B_s$ mixing. Still, we can expect a potentially interesting contribution to CP violation in the $B_s \rightarrow J/\psi \phi$ decay amplitude.
We hope that we made the case for $b \to s$ physics in the search for indirect SUSY signals quite clear. Still someone could object that at least some of the relevant probes of $b \to s$ transitions in $B_s$ physics are likely to have to wait for the advent of BTeV or LHC to become feasible. And at that point, one would be tempted to say, we will know whether low energy SUSY is there just by direct tests without invoking the indirect searches that we advocated in this work. We do not agree with this position: even if SUSY particles are detected, we are convinced that FCNC and CP violation, in $b \to s$ physics in particular, will constitute an ideal ground to have a further access to the SUSY structure and will be complementary to the other direct forms of SUSY studies.

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