We present a systematic study of the CP conserving and violating SUSY contributions to $b \to s$ processes in a generic MSSM, considering gluino exchange contributions. Experimental information on $B \to X_s \gamma$, $B \to X_s \ell^+\ell^-$ and the $B_s - \bar{B}_s$ mass difference $\Delta M_s$ have been taken into account. We study the induced correlations among several observables: $\Delta M_s$ and the amount of CP violation in $B \to \phi K_s$, $B_s \to J/\psi \phi$, $B \to X_s \gamma$. Our results show that $b \to s$ transitions represent a splendid opportunity to constrain different MSSM realizations and offer concrete prospects to exhibit SUSY signals at $B$ factories and hadron colliders.

1 Introduction

Flavour physics is a very stringent test of SUSY extensions of the Standard Model: in its general form, the Minimal Supersymmetric Standard Model (MSSM) can cause Flavour Changing Neutral Current and CP violating processes to arise at a rate much higher than what is experimentally observed.\[6]

A closer look at the Unitarity Triangle fit reveals that new physics (NP) contributions to $s \to d$ and $b \to d$ transitions are strongly constrained, while new contributions to $b \to s$ transitions affect the fit only if they interfere destructively with the SM amplitude for $B_s - \bar{B}_s$ mixing, bringing the mass difference below the present lower bound. Other processes not involved in the UT fit, for example the celebrated $B \to X_s \gamma$, can provide constraints on any NP in $b \to s$ transitions. However, $B \to X_s \gamma$ mostly constrains the helicity flipping contributions to the

\[6\] Talk given by M.C.
b \to s transition. As we shall see in the following, plenty of room is left for SUSY contributions to interesting observables in this sector.

In these proceedings, we summarise the results of the analysis presented in ref.\cite{2}. We refer the interested reader to the original paper for all the details omitted here. This analysis aims at studying systematically SUSY contributions to the (CP conserving and violating) b \to s transitions in the context of a generic MSSM model with R parity at a level of accuracy comparable to the SM UT fit (i.e. using NLO QCD corrections and Lattice QCD hadronic matrix elements wherever possible).

We keep our analysis in the MSSM as general as possible. 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.\cite{3} In the Super-CKM basis, SUSY FCNC and CP violation arise from off-diagonal terms in squark mass matrices only. These are conveniently expressed as (δij)AB ≡ (∆ij)AB/mq2, where (∆ij)AB is the mass term connecting squarks of flavour i and j and “helicities” A and B, and mq is the average squark mass. In the absence of any horizontal symmetry and for a generic SUSY breaking mechanism, one expects (δij)LL ≤ O(1), (δij)RR ≤ O(1), (δij)LR ≤ O(mq/mk) and (δij)RL ≤ O(mq/mk), with k = 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.\cite{4}

Detailed analyses carried out in SUSY have shown that one must have (δi2)AB and (δi3)AB much smaller than what naively expected.\cite{5,6} It is therefore reasonable to assume that (δi2)AB ∼ (δi3)AB ∼ 0. Under this assumption, we present constraints on (δi3)AB from available data and possible effects in present and future measurements.

2 Phenomenological Analysis

Our analysis aims 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 the parameter space come from:

1. The BR(B \to Xs\gamma) = (3.29 ± 0.34) \times 10^{-4} (experimental results as reported in\cite{8}, rescaled according to ref.\cite{9}).
2. The CP asymmetry ACP(B \to Xs\gamma) = −0.02 ± 0.04\cite{8}.
3. The BR(B \to Xs\ell^+\ell^-) = (6.1 ± 1.4 ± 1.3) \times 10^{-6}\cite{8}.
4. The lower bound on the Bs − \bar{B}s mass difference ΔMBs > 14.4 ps^{-1}\cite{8}.

We have also considered BR’s and CP asymmetries for B \to K\pi and found that, given the large theoretical uncertainties, they give no significant constraints on the δ's.

For B \to φKs, we have studied the BR and the coefficients CφK and SφK of cosine and sine terms in the time-dependent CP asymmetry.

All the details concerning the treatment of the different amplitudes entering the analysis can be found in ref.\cite{2}. In summary, we use:

i) ∆B = 2 amplitudes. Full NLO SM and LO gluino-mediated matching condition, NLO QCD evolution and hadronic matrix elements from lattice calculations.

ii) ∆B = 1 amplitudes. Full NLO SM and LO gluino-mediated matching condition and NLO QCD evolution. The matrix elements of semileptonic and radiative decays include αs terms, Sudakov resummation, and the first corrections suppressed by powers of the heavy quark masses. For non-leptonic decays, such as B \to K\pi and B \to φKs, we adopt BBNS factorization,\cite{10,11} with an enlarged range for the annihilation parameter ρA, in the spirit of the criticism of ref.\cite{11}. This
choice maximizes the sensitivity of the factorized amplitudes to SUSY contributions, which is expected to be much lower if the power corrections are dominated by the “charming penguin” contributions.\textsuperscript{12}

Another source of potentially large SUSY effects in $B \to \phi K_s$ is the contribution of the chromomagnetic operator which can be substantially enhanced by SUSY without spoiling the experimental constraints from $B \to X_s \gamma$.\textsuperscript{13} Indeed, the time-dependent asymmetry in $B \to \phi K_s$ is more sensitive to the SUSY parameters in the case of chirality-flipping insertions which enter the amplitude in the coefficient of the chromomagnetic operator. One should keep in mind, however, that the corresponding matrix element, being of order $\alpha_s$, has large uncertainties in QCD factorization.

We performed a MonteCarlo analysis, generating weighted random configurations of input parameters (see ref.\textsuperscript{14} 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 $\delta_{23}$ 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 ($\rho = 0.178 \pm 0.046, \eta = 0.341 \pm 0.028$), and hadronic parameter ranges are those used in ref.\textsuperscript{2}.

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 $(\delta_{23})_{LL} = (\delta_{23})_{RR}$.

In fig.\textsuperscript{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 applied, 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 $10^{-2}$. For these values of the parameters, $\Delta M_s$ is unaffected. 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.

In figs.\textsuperscript{2,3} we study the correlations of $S_{\phi K}$ with $\text{Im}(\delta_{23}^{d})_{AB}$ and $A_{CP}(B \to X_s \gamma)$ for the various SUSY insertions considered in the present analysis. The reader should keep in mind that, in all the results reported in figs.\textsuperscript{2,3} 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.\textsuperscript{2,3}), generating, for those channels in which the SUSY amplitude can interfere with the SM one, a $A_{CP}(B \to X_s \gamma)$ 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.\textsuperscript{2}).

Finally, fig.\textsuperscript{4} contains the same plots as fig.\textsuperscript{1,2} in the case of the double mass insertion $(\delta_{23}^{d})_{LL} = (\delta_{23}^{d})_{RR}$. In this case, 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 $\Delta M_s < 20 \text{ ps}^{-1}$.

3 Where to look for SUSY

A crucial question naturally arises at this point: what are the more promising processes to reveal some signal of low energy SUSY among the FCNCs involving $b \to s$ transitions? For this purpose, it is useful to classify different “classes of MSSM” according to the “helicities” $LL$, $RR$, etc, of the different $\delta_{23}^{d}$'s.
The BaBar and BELLE Collaborations have recently reported the time-dependent CP asymmetry in $B_d(B_d) \rightarrow \phi K_s$. 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), the combined result from both collaborations for the corresponding $S_{\phi K}$ of $B_d \rightarrow \phi K_s$ is $-0.39 \pm 0.41$ with a $2.7\sigma$ discrepancy between the two results. In the SM, they should be the same up to doubly Cabibbo suppressed terms. Obviously, one should be very cautious before accepting such result as a genuine indication of NP. Nonetheless, the negative value of $S_{\phi K}$ could be 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 could be detected.

3.1 RR and LL cases

We start discussing the RR case. As shown in Fig. (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 $S_{\phi K}$ in agreement with the results of BaBar and BELLE quoted above. 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 200 ps$^{-1}$ for our choice of the range of $\delta_{RR}$. In addition, we find that the expected correlation requiring large $\Delta M_s$ for negative $S_{\phi K}$ is totally wiped out by the large uncertainties (see fig. lower right). Hence, in the RR case it is possible to have a strong
Figure 2: Correlations between $S_{\phi K}$ and $\text{Im}(\delta_{23})_{AB}$ for $AB = (LL, RR, LR, RL)$.

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).

To conclude the discussion of the $RR$ case, we expect the CP asymmetry in $B \rightarrow X_s\gamma$ to be as small as in the SM, while, differently from the SM, the time-dependent CP asymmetry in the decay channel $B_s \rightarrow J/\psi\phi$ is expected to be large.

We now move on to discuss the $LL$ insertion. A major difference with the previous case concerns the SUSY contributions to $B \rightarrow X_s\gamma$. The $LL$ insertion contributes to the same operator which is responsible for $B \rightarrow X_s\gamma$ in the SM and hence the SM and SUSY amplitudes 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. 2 left). However, given the uncertainties, the correlation of $A_{CP}(B \rightarrow X_s\gamma)$ 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 $A_{CP}(B \rightarrow X_s\gamma)$, 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. 5 which is quite similar to the $RR$ case. Finally, one expects also in this case to observe CP violation in $B_s \rightarrow J/\psi\phi$ at hadron colliders.
3.2 LR and RL cases

In these cases negative values of $S_{\phi K}$ can be easily obtained (although a positive $S_{\phi K}$ is slightly favoured, cfr. Fig. 2 bottom row). The severe bound on the LR mass insertion imposed by 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. 3 upper right), offering a potentially interesting hint for NP.

Notice that the LR mass insertion contributes to $b_R \to s_L \gamma$, much like the SM. The interference with the SM amplitude produces 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 interfere. Consequently, the CP asymmetry is as small as in the SM and the RL mass insertion is less constrained than the LR one by $B \to X_s \gamma$, allowing for negative values of $S_{\phi K}$ to be produced more easily.

3.3 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. 4 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.

Finally, we remark that in the $LR$ and $RL$ cases, since for $m_{\tilde{g}} = m_{\tilde{q}} = 350$ GeV the constraints on the $\delta_{23}^{d}$'s are of order $10^{-2}$, the same phenomenology in $\Delta B = 1$ processes can be obtained at larger values of mass insertions and of squark and gluino masses, while contributions to $\Delta B = 2$ processes become more important for larger masses. 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

Our results confirm that FCNC and CP violation in physics involving $b \to s$ transitions still offer opportunities to disentangle effects genuinely due 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 $BR(B \to X_s \gamma)$. The relevant question is then which processes offer the best chances to
provide other hints of the presence of low-energy SUSY.

First, it is mandatory to further assess the time-dependent CP asymmetry in the decay channel $B \to \phi K_s$. If the measurement will be 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 are more or less tightly constrained according to the kind of $\delta_{23}^d$ mass insertion which dominates.

In order of importance, it then comes the measurement of the $B_s - \bar{B}_s$ mixing. Finding $\Delta M_s$ larger than 20 $\text{ps}^{-1}$ would hint at NP. $RR$ or $LL$ could account for a $\Delta M_s$ up to 200 $\text{ps}^{-1}$. 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 $BR(B \to X_s \gamma)$. An interesting alternative would arise if $\Delta M_s$ 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 $LR$ possibility, even though all other cases but $LL = RR$ do not necessarily lead to large $\Delta M_s$.

Keeping to $B_d$ physics, we point out that the CP asymmetry in $B \to X_s \gamma$ remains of utmost interest. This asymmetry is so small in the SM that it should not be possible to detect it. We have seen that in particular with $LR$ 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 $B_s$, it will be of great interest to study processes which are mostly CP conserving in the SM, while possibly receiving large contributions from SUSY. In the SM the amplitude for $B_s - \bar{B}_s$ mixing does not have an imaginary part up to doubly Cabibbo suppressed terms and decays like $B_s \to J/\psi \phi$ also 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 $b \to s$ amplitudes and the $B_s$ mixing would receive non negligible contributions from Im $\delta_{23}^d$, while, if the $LR$ insertions is dominant, we do not expect any sizable contribution to $B_s$ mixing. Still, the SUSY contribution to CP violation in the $B_s \to J/\psi \phi$ decay amplitude could be fairly large.

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