We briefly discuss the phenomenology of $B \rightarrow \pi\pi$, $B \rightarrow K\pi$ and $B \rightarrow \phi K$ decays in the Standard Model and in Supersymmetry.

1 Introduction

After a few years of very successful running of $B$-factories, and with the bright prospects of experiments at the Tevatron, at the LHC and, hopefully, at a super $B$-factory, $B$ physics is playing a central role in testing the Standard Model (SM) and looking for new physics. In addition to the leptonic and semileptonic modes, it is certainly useful to use nonleptonic decays for this purpose, given the large amount of experimental data available on a huge variety of channels. Nonleptonic decays however pose serious theoretical challenges, since one must get rid of all the hadronic uncertainties due to the presence of exclusive hadronic final states in order to extract information on short-distance dynamics. Indeed, apart for a handful of golden channels in which hadronic uncertainties drop in CP asymmetries, such as the celebrated $B \rightarrow J/\psi K_s$ and, within the SM, $B \rightarrow \phi K_s$, we have to face the difficulty of estimating hadronic matrix elements including final state interactions, which in particular may play a crucial role in CP asymmetries.

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These considerations have stimulated an intense theoretical activity in the last few years, leading to various approaches to the computation of two-body nonleptonic $B$ decays: QCD factorization, pQCD, Soft-Collinear Effective Theory (SCET). Based on different assumptions on the relevant degrees of freedom and on the calculability of certain matrix elements, all these approaches have lead to factorization theorems for $B$ decays to two light mesons in the limit of infinite $B$-quark mass. These beautiful theoretical results can be safely and successfully applied to compute from first principles decay amplitudes in which power-suppressed terms are not accidentally enhanced and thus remain at the level of $10^{-20}$. On the other hand, most of the phenomenologically interesting channels contain penguin amplitudes, and in particular penguin contractions of current-current operators containing charm quarks (charming penguins). While no rigorous treatment of these contributions has been given in pQCD until now, in the QCD factorization approach these penguins are considered to be perturbatively calculable up to power suppressed terms, while it has been recently pointed out that charming penguins arise as leading-order nonfactorizable contributions in SCET. Adding this to the fact that charming penguins are doubly Cabibbo enhanced in $b \to s$ decays, it is clear that, as it was pointed out long ago, these processes are most probably dominated by non-calculable charming penguins, and even $b \to d$ transitions, where this Cabibbo enhancement is absent, might be affected by large theoretical uncertainties.

These observations can be tested with the help of experimental data: one can implement, for example, QCD factorization formulae for $B$ decays to two light mesons, add to these a parameterization of dominant nonfactorizable amplitudes, and check if this gives a satisfactory description of experimental data. If this is the case, it is also possible to quantify the size of nonfactorizable terms and to test the consistency of the factorization theory. One can also, varying these nonperturbative terms in a reasonable range, compute $B$ decays in models beyond the SM, for example in Supersymmetry (SUSY), and quantify the deviations from the SM prediction in particularly sensitive quantities, as for example the CP asymmetry in $B \to \phi K_s$.

In this talk, we will illustrate these points with some significant examples: $B \to \pi\pi$ decays, $B \to K\pi$ decays and $A_{CP}(B \to \phi K_s)$. A more general and comprehensive analysis can be found in ref. 8.

2 $B \to \pi\pi$ decays

$B \to \pi\pi$ decays are particularly interesting since the CP asymmetry in the $\pi^+\pi^-$ channel would be proportional to $\sin 2\alpha$ in the absence of penguins. In the presence of penguins, one can still use all the available experimental data, which now also include a measurement of the $BR(B \to \pi^0\pi^0)$, to identify the penguin contribution and extract $\alpha$ with some quantifiable uncertainty. Now, while early QCD factorization studies estimated $BR(B \to \pi^0\pi^0)$ to lie in the $10^{-8} - 10^{-7}$ range, it had also been pointed out that nonperturbative effects could easily bring it up to the level of $10^{-6}$. In this sense, there is actually no “$\pi\pi$ puzzle”: adding to the QCD factorization amplitude the effect of charming and GIM (up minus charm) penguins at the subleading level, one can perfectly reproduce the observed BR’s and asymmetries, although the present value of $BR(B \to \pi^0\pi^0)$ is at the upper end of the expected range. In Table 1 we report the (input) experimental data and the results of our fit, which corresponds to charming penguins $P_1 = (0.11 \pm 0.05)e^{i(-0.2 \pm 0.9)}$ and GIM penguins $P_{1}^{GIM} = (0.43 \pm 0.14)e^{i(-0.2 \pm 0.7)}$ in units of the factorized amplitude, using as input the best values of CKM parameters from the Unitarity Triangle fit (UTfit).

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Table 1: Fit of $B \to \pi \pi$ observables: BR’s, direct CP asymmetries ($A_{CP}$) and coefficients of the $\sin \Delta M t$ term in time-dependent CP asymmetries ($S$)

| Channel | $BR^{th} \times 10^6$ | $BR^{exp} \times 10^6$ | $A_{CP}^{th}$ | $A_{CP}^{exp}$ | $S^{th}$ | $S^{exp}$ |
|---------|------------------------|------------------------|--------------|--------------|--------|--------|
| $\pi^+\pi^-$ | 4.6 ± 0.4 | 4.6 ± 0.4 | 0.45 ± 0.13 | 0.46 ± 0.13 | -0.7 ± 0.2 | -0.7 ± 0.3 |
| $\pi^+\pi^0$ | 5.2 ± 0.7 | 5.3 ± 0.8 | - | -0.07 ± 0.14 | - | - |
| $\pi^0\pi^0$ | 1.8 ± 0.5 | 1.9 ± 0.5 | -0.27 ± 0.46 | - | - | - |

Figure 1: Probability density function for $\gamma$ and $\alpha$ as extracted from $B \to \pi \pi$ decays, assuming a flat a priori distribution for $\gamma$.

and corrections to emission topologies).

It is interesting to notice that if one leaves $\gamma$ as a free parameter in the fit, the a posteriori distribution for $\gamma$, or equivalently for $\alpha$, contains some nontrivial information. In fig. we report the p.d.f. for the angles $\gamma$ and $\alpha$. The shape is similar to the one obtained in a completely model-independent SU(2) analysis.

3 $B \to K \pi$ decays

$B \to K \pi$ decays are particularly interesting as they are penguin-dominated $b \to s$ transitions in which SM penguin operators are doubly Cabibbo enhanced with respect to current-current operators. On one hand, this means that these channels are particularly sensitive to NP contributions; on the other, as we stressed in the Introduction, this also implies that nonfactorizable contributions, and in particular charming penguins, are expected to dominate the amplitude. This unfortunately introduces large theoretical uncertainties and possibly spoils the sensitivity to NP.

Let us now quantify these statements. First of all, we report in Table 2 the theoretical predictions and the experimental values for $B \to K \pi$ BR’s and CP asymmetries. These correspond to a fitted value of $P_1 = (0.08 \pm 0.02) e^{i(-0.6 \pm 0.5)}$, while $P_1^{GIM}$ is irrelevant in these channels and therefore not determined by the fit.

From Table 2 we see a $\sim 2\sigma$ deviation in the $K^0\pi^0$ channel, which cannot be fixed by any
isospin invariant physics. Indeed, to reproduce the experimental value, an $O(1)$ isospin breaking in $P_1$ would be needed. If confirmed with increased experimental accuracy, this discrepancy would call for NP contributions in EW penguins.\[15\]

4 $B \to \phi K$ decays

$B \to \phi K$ decays are pure penguin $b \to s$ transitions. In the absence of GIM penguins, and neglecting doubly Cabibbo suppressed terms in $V_{tb} V_{ts}^*$, the decay amplitude in the SM has a vanishing weak phase and therefore one expects no direct CP violation and the same time-dependent CP asymmetry as in $B \to J/\psi K$ decays. In our framework, we can quantify this statement: we add charming and GIM penguins to the QCD factorization amplitude, fit them to the BR’s and obtain a p.d.f. for the CP asymmetries in $B \to \phi K_s$ decays. Taking as input the UTfit values for CKM angles,\[10\] in particular $\sin 2\beta = 0.710 \pm 0.037$, we obtain the SM prediction:

$$S_{\phi K_s} = 0.73 \pm 0.07, \quad C_{\phi K_s} = 0.00 \pm 0.07$$

(1)

which is fully compatible with the BaBar result $S_{\phi K_s} = 0.47 \pm 0.08 \pm 0.09$, but $\sim 3\sigma$ away from the Belle measurement $S_{\phi K_s} = -0.96 \pm 0.50 \pm 0.09$.

The same exercise can be done for $B \to K_s \pi^0$: fitting the relevant hadronic parameters to $B \to K \pi$ BR’s, we obtain the following SM prediction for the time-dependent asymmetry, always starting from the UTfit CKM angles:

$$S_{K_s \pi^0} = 0.79 \pm 0.08, \quad C_{K_s \pi^0} = -0.03 \pm 0.07,$$

(2)

to be compared to the BaBar result $S_{K_s \pi^0} = 0.48 \pm 0.38 \pm 0.11$. It should be stressed that, in the presence of NP, deviations from the SM could differ considerably in the $K \phi$, $K \pi$ and $K \eta'$ systems. Indeed, NP contributions can be very sensitive to poorly known hadronic matrix elements, and large direct CP violation could be generated in these channels.\[16\]

5 Beyond the Standard Model: A simple SUSY example

If the discrepancy between the experimental value of the time-dependent asymmetry in $B \to \phi K_s$ and the SM prediction is confirmed by future measurements at B factories, the question arises of what kind of NP could account for this deviation. After the pioneering pre-B factory studies,\[18\] this problem has been widely studied in the SUSY context in the recent literature.\[19\] Just for the purpose of illustration, we briefly report the results of a model-independent analysis in the Minimal Supersymmetric Standard Model (MSSM).\[20\] 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

| Channel | $BR^{th} \times 10^6$ | $BR^{exp} \times 10^6$ | $A_{CP}^{th}$ | $A_{CP}^{exp}$ |
|---------|----------------------|----------------------|--------------|--------------|
| $K^+\pi^-$ | 18.7 ± 0.7 | 18.2 ± 0.8 | -0.08 ± 0.03 | -0.095 ± 0.028 |
| $K^+\pi^0$ | 12.2 ± 0.6 | 12.8 ± 1.1 | -0.08 ± 0.03 | 0.00 ± 0.07 |
| $K^0\pi^+$ | 22.2 ± 0.9 | 21.8 ± 1.4 | 0.00 ± 0.05 | 0.02 ± 0.06 |
| $K^0\pi^0$ | 8.7 ± 0.6 | 11.9 ± 1.5 | 0.03 ± 0.07 | 0.03 ± 0.37 |
Figure 2: Allowed regions in the $\text{Re}(\delta^d_{23})_{AB}$–$\text{Im}(\delta^d_{23})_{AB}$ space for $AB = (LL, RR, LR, RL)$. The black line contains 68% of the weighted events. The darker regions are selected imposing $\Delta m_s < 20 \text{ ps}^{-1}$ for $LL$ and $RR$ insertions and $S_{\phi K} < 0$ for $LR$ and $RL$ insertions.

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. 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 $(\delta_{ij})_{AB} \equiv (\Delta_{ij})_{AB}/m_{\tilde{q}}$, 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.

We performed a MonteCarlo analysis, generating weighted random configurations of input parameters and computing for each configuration the weight corresponding to the experimental values of $\text{BR}(B \to X_s \gamma)$, $A_{CP}(B \to X_s \gamma)$, $\text{BR}(B \to X_s \ell^+\ell^-)$, and the $B_s - \bar{B}_s$ mass difference $\Delta M_{B_s}$. We study the clustering induced by the constraints on various observables and parameters, assuming that each unconstrained $\delta^d_{ij}$ fills uniformly a square $(-1\ldots1, -1\ldots1)$ in the complex plane. The ranges of CKM parameters have been taken from the UTfit, and hadronic parameter ranges are those used in ref. Concerning SUSY parameters, we fix $m_{\tilde{q}} = m_{\tilde{g}} = 350 \text{ GeV}$ and consider different possibilities for the mass insertions.

In fig. we display the clustering of events in the $\text{Re}(\delta^d_{23})_{AB}$–$\text{Im}(\delta^d_{23})_{AB}$ plane. Here and in the following plots, larger boxes correspond to larger numbers of weighted events. 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 $\text{Im} (\delta_{23}^{d})_{AB}$ is needed to meet this condition.

In fig. 3 we study the correlations of $S_{\phi K}$ with $\text{Im} (\delta_{23}^{d})_{AB}$ for the various SUSY insertions considered in the present analysis. The reader should keep in mind that, in all the results reported in fig. 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 $\text{Im} (\delta_{23}^{d})_{AB}$, 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 case, and up to the experimental upper bound in the LR case.

6 Conclusions

Two-body nonleptonic $B$ decays are not only a very interesting theoretical playground to test our understanding of hadronic dynamics, but also offer a precious window on NP. If any of the present discrepancies between experimental values and theoretical predictions will be confirmed in the future, it will be possible to test NP models against experimental data. As we have shown,
SUSY model can accommodate the Belle result for $\phi K_s$ and one can find interesting correlation with other observables in $B$ physics.

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