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B decays and Supersymmetry *

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Abstract

I discuss how supersymmetry affects various observables in B decays, and point out the interesting channels in the context of B factories.

1 Introduction

Supersymmetry (SUSY) does not need any motivation any more. It is, however, interesting to ask whether one can have indirect SUSY signals from low-energy observables before LHC starts. The answer is *yes*, and in this talk we point out some of the SUSY signals that one may observe at the leptonic and hadronic B-factories. These factories have already started taking data, and in the near future, some of the observables from the factories will attain a precision which should be able not only to test the Standard Model (SM) but also to probe for physics beyond the Standard Model (BSM). In fact with a little bit of luck the B factories may be the first place where one will see the BSM signals much before the LHC starts. Such signals could then be enhanced and studied in detail in hadronic B-factories or in very high luminosity e^+e^- experiments like SuperBaBar [1]. Before going into such signals, let us first see why we need this 'luck'.

The present generation e^+e^- B factories will in no way verify the CKM ansatz of CP violation. They will measure quantities like V_{cb}, V_{ub}, $(\Delta M/\Gamma)_{B_d}$, $\sin 2\beta$ and $\sin 2\alpha$ to various degrees of precision. What one can at most say is that all measurements are consistent with the CKM picture, but existence of BSM cannot be ruled out, except that its parameter space will become more and more constrained with increasing amount of data. In other words, these indirect measurements will not be able to see the signatures of any arbitrary SUSY model; the model must have the parameters lying in the right ballpark. This statement will be quantified later.

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All SUSY models available in the market can be divided into two broad categories: R-parity conserving (RPC) and R-parity violating (RPV), where $R = (-1)^{3B+L+2S}$. The RPC models are further divided according to how SUSY breaks: the supergravity (SUGRA) type, the gauge-mediated (GMSB) type, the anomaly-mediated (AMSB) type, and so on [2]. In these models the SUSY effects always appear in loops and are therefore harder to detect unless the corresponding SM process is either absent or loop-mediated itself. Thus, one does not expect to see a SUSY signal in tree-level $b \to c, u$ decays, but B-$\bar{B}$ mixing, $b \to s\gamma$ or $b \to K(^*)\ell^+\ell^-$ are good places to look for such signals.

RPV SUSY is different in the sense that one can have tree-level slepton or squark mediated B decays and thus the new physics amplitude can very well compete with, or even overwhelm, the SM amplitude. The expected CP asymmetry in a particular decay may be completely different from the SM expectation; the branching ratio (BR) can be substantially high or low from the SM value; even the SM forbidden modes may appear. For lack of space we will just discuss some of the most important effects coming from RPV SUSY in B decays.

2 FCNC in SUSY

In R-parity conserving SUSY models, there can be two more independent phases ϕ_A and ϕ_B apart from the CKM phase, but the electric dipole moment of neutron constrains both of them to be $\sim \mathcal{O}(10^{-2}$- $10^{-3})$ unless the squarks are extremely heavy or there is a fine-tuning between ϕ_A and ϕ_B [3]. We take both of them to be zero, a choice which can be theoretically motivated, since ϕ_A (ϕ_B) is the relative phase between A (B) and the common gaugino mass M [4]. Even then one can have new contribution to CP-violation coming from SUSY FCNC effects [5]. The origin of SUSY FCNC can be easily understood: quark and squark mass matrices are not simultaneously diagonalizable. At $q^2 \sim m_W^2$, radiative corrections induced by up-type (s)quark loops are important. These corrections are typically of the order of $\log(\Lambda_S/m_W)$ and hence can be large for SUGRA type models. This generates FCNC which occurs even in the quark-squark-neutral gaugino vertices, but the flavour structure is controlled by the CKM matrix (this need not be true in any arbitrary SUSY model).

One generally works in the basis where the quark fields are eigenstates of the hamiltonian. SUSY FCNC can be incorporated in two ways: (i) *vertex mixing*, an approach where the squark propagators are flavour and 'chirality' conserving, and the vertices violate them; (ii) *propagator mixing*, where flavour and 'chirality' are conserved in vertices but changed in propagators. The second approach is more preferred for phenomenological analysis, since the higher order QCD corrections are known there.

Thus, at the weak scale one can write the 6×6 squark mass matrix (say the down-type) as

$$\tilde{\mathcal{M}_D}^2 = \begin{pmatrix} \mathcal{M}^2_{DLL}|^{tree} + \Delta^2_{LL} & \Delta^2_{LR} \\ \Delta^2_{RL} & \mathcal{M}^2_{DRR}|^{tree} + \Delta^2_{RR} \end{pmatrix} \quad (1)$$

where the Δ terms incorporate the FCNC effects. In fact, only Δ^{ij}_{LL} changes flavour, but the other Δ^{ij}s are not [6]. Different FCNC effects are parametrized in terms of $\delta \equiv \Delta/\tilde{m}^2$, where $\tilde{m} = \sqrt{\tilde{m}_1\tilde{m}_2}$. Of course they are completely calculable in MSSM; all such δs are $\leq \mathcal{O}(10^{-2})$. This is not true in general SUSY models; and such models can be constrained by the values of δ they produce. Theoretically, for the success of perturbative analysis, one expects $|\delta| < 1$.

The standard way to look for SUSY models whose signatures can be found in low-energy machines can thus be divided in two steps: (i) Compute the constraints on Re and $Im\ \delta$ from low-energy observables like $K-\bar{K}$, $B-\bar{B}$ and $B_s-\bar{B}_s$ mixing, ϵ_K, ϵ'/ϵ, $b\to s\gamma$ etc. Unconstrained δs can have $|\delta|\leq 1$ and arbitrary phases. (ii)Find CP-conserving and CP-violating effects compatible with such constraints.

Before proceeding further, let us note a few points. Since there is no a priori reason why the FCNC should be small, there must be some inherent mechanism, from a theoretical point, that suppresses FCNC. This can be *alignment*, where quark and squark mass matrices are aligned even at the electroweak scale; *heavy squarks*, where the squarks — particularly those in the first two generations — are at the TeV scale; or some *family symmetry* which suppresses such FCNC. Since SUSY particles always appear in loops, the leading contribution is a constant (the so-called superGIM mechanism), and effects are observable only if the corresponding SM amplitude is zero or loop-induced. Furthermore, SUSY does not induce any new operators from that in the SM, so all one has to do is to compute the SUSY Wilson coefficients.

Recently, it has been shown [7] that even if the SUSY phases are large, there cannot be any significant CP-violating effect if the flavour structure is governed by the CKM matrix alone (the universal unitarity triangle scenario). This means that B-factories will probe the flavour structure of SUSY much before LHC! However, this is not true for general SUSY flavour models, and we will concentrate on those models where this constraint can be bypassed.

3 B_d-$\bar{B}_d$ mixing, Unitarity Triangle and SUSY

In the SM, the phase coming from B_d-$\bar{B}_d$ is 2β. It can be shown that all four new boxes (t-H^+, $\tilde{t}$-$\tilde{\chi}^+$, $\tilde{b}$-$\tilde{g}$ and $\tilde{b}$-$\tilde{\chi}^0$) coming in MSSM with alignment have same phases and hence the CP asymmetry does not change.

In general SUSY models the off-diagonal SUSY hamiltonian M_{12}^{SUSY} depends on $(\delta^d_{13})_{LL,LR,RR}$ and their phases may change the prediction of $\sin 2\beta$ by 10-15% [8]. Thus, the measured values of β and α change, but by a compensating amount if the former is extracted from $B_d\to J/\psi K_S$ (or ϕK_S) and the latter from $B_d\to\pi^+\pi^-$ (since one actually measures $\beta+\gamma=\pi-\alpha$):

$$\beta'=\beta+\phi_{SUSY},\quad \alpha'=\alpha-\phi_{SUSY} \tag{2}$$

so that their sum remains unchanged. γ measured from B_s decays will also be changed by a different amount, and hence the unitarity triangle (UT) will not close: this is the signal. However, γ determination needs hadronic machines and is not easy, and even α determination is substantially contaminated with penguins as is evident from the recent CLEO, BaBar and BELLE data [9].

4 $b\to s\gamma$: the most 'promising' place to find SUSY?

The radiative penguin decay $b\to s\gamma$, and $b\to s\ell^+\ell^-$, which is closely related to it, has been discussed in the literature in great detail [10]. The CP asymmetry in $b\to s\gamma$ is negligible in the SM. The SUSY contribution, on the otherhand, is zero if SUSY is unbroken [11]. This decay is controlled by the magnetic penguin operator $O_7\sim\bar{s}\sigma_{\mu\nu}(m_bP_R+m_sP_L)bF^{\mu\nu}$.

In MSSM only the electroweak t-H^+ and $\tilde{t}$-$\tilde{\chi}^+$ penguins are important (gluino and neutralino penguins are subdominant, and vanish if squark mass matrices are flavour-diagonal). The t-H^+

penguin always adds constructively with the SM penguin; the stop-chargino penguin can be either constructive or destructive depending on the mass and composition of stop and chargino. Of course, the effect is significant only for relatively light stop and chargino: the BR can even be doubled if they are ~ 100 GeV. For this particular parameter space, enhancement of BR is a good signal, more so if one remembers that the theoretical prediction for SM and the experimental numbers are in the same ballpark.

For destructive interference, there can be another interesting observable [12]: the CP asymmetry $A_{CP}^{b\to s\gamma}$, defined as

$$A_{CP}^{b\to s\gamma} = \frac{BR(\bar{B}_d \to X_s\gamma) - BR(B_d \to X_s\gamma)}{BR(\bar{B}_d \to X_s\gamma) + BR(B_d \to X_s\gamma)}. \tag{3}$$

This can go upto 5% for destructive $\tilde{t}$-$\tilde{\chi}^+$ loop where the BR is about the lowest possible experimental value: 2×10^{-4}. For constructive loops, this asymmetry quickly falls to zero. This signal can just be observable in current e^+e^- factories and will certainly be observable in future high-lumonisty machines.

In general SUSY models, the data on $b \to s\gamma$ constrains $|(\delta_{23}^d)_{LR}| \leq 1.6\times 10^{-2}$ for $m_{\tilde{g}} = m_{\tilde{q}}$. Corresponding LL term is not at all constrained since the chirality flip occurs on the b quark line and not on the $\tilde{g}$ line.

5 Leptonic and Semileptonic B decays

Recently Belle has observed $B \to K\mu^+\mu^-$; all three e^+e^- machines have put constraints on other $B \to K(^*)\ell^+\ell^-$ modes [13]. Unfortunately the SM prediction for these exclusive modes is not very pecise [14]. The exclusive mode $B \to X_s e^+e^-$ ($B \to X_s\mu^+\mu^-$) can be changed by a factor of 40-500% (25-550%) in general SUSY models. The forward-backward asymmetry $A_{FB}(e/\mu)$ can range between -0.18 to 0.33 in contrast to a SM prediction of 0.23. These signals should be measurable in current and upcoming factories.

The dilepton and single lepton asymmetries may also be useful tools for distinguishing SUSY flavour models. However, this definitely requires hadronic or high-luminosity e^+e^- machines [15].

6 Nonleptonic B decays

These processes are plagued mainly with hadronic uncertainties. As stated already, if the flavour structure is governed by the CKM matrix, the CP violation is bound to be small. In general SUSY models, decays proceeding through $b \to s$ have a competing chance since the SM process is penguin and the corresponding δ, $(\delta_{23}^d)_{LL}$ is unconstrained both in its magnitude and phase. For example, the exclusive mode $B_d \to \phi K_S$ may have a SUSY amplitude which can be 70% (20%) for $m_{\tilde{q}} = 250$ (500) GeV. Thus, A_{CP} from this mode may deviate significantly from $\sin 2\beta$. The MSSM effect may be just perceptible in $B_d \to J/\psi K_S$. There is almost no hope for detecting RPC SUSY signals from other nonleptonic decays.

7 R-parity violating SUSY and B decays

This is, in some sense, a goldmine for phenomenologists. From the superpotential

$$W = \frac{1}{2}\lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \frac{1}{2}\lambda''_{ijk}U^c_iD^c_jD^c_k, \tag{4}$$

one constructs a four-fermi effective theory by integrating out the slepton or squark fields to find that (i) with slepton exchange, $\lambda\lambda'$ type products contribute to leptonic and semileptonic decays; (ii) $\lambda'\lambda'$ products contribute to nonleptonic decays; (iii) with squark exchange, $\lambda''\lambda''$ products contribute to nonleptonic decays.

There are two different approaches in the literature. First, one takes a particular product coupling — allowed with the phenomenological constraints — and finds the implication for different decay modes. People have shown that with suitable values of RPV couplings, (i) A_{CP} in $B_d \to J/\psi K_S$ and in $B_d \to \phi K_S$ may be significantly modified [16]; (ii) BR for the mode $B \to \eta' K$ can be enhanced to explain the discrepancy between data and prediction assuming no charm content in η' [17]; (iii) modes forbidden in SM (like $\Delta B = 1, \Delta S = 2$) may be seen even in present-day colliders [18]; (iv) prediction for $b \to s\gamma$ can be modified [19]; (v) there can be couplings which contribute to both neutral B mixing and tree-level decays, and thus the signal can be more complex [20].

The second approach constrains various products from data on mixing and decay to rare channels. Significant bounds on various $\lambda\lambda'$ and $\lambda'\lambda'$ products have been obtained from B_d-$\bar{B}_d$ mixing [21], $B_{d,s} \to \ell^+_i\ell^-_j$ [22, 23], $B \to K\ell^+_i\ell^-_j$ [23]. These bounds generally are orders of magnitude better than the bounds obtained from other processes.

8 Conclusion

The best possible searching grounds for RPC SUSY signals are $b \to s\gamma$ and, to a certain extent, $b \to s\ell^+\ell^-$. One should look for a change in BR and CP and/or FB asymmetries.

RPV models have a rich phenomenology, not all of which have been explored so far. Both BR and A_{CP} can change significantly. To be more precise, A_{CP} coming from modes which are expected to yield same result for SM may give completely different results. SM forbidden processes like $B \to e\mu$ may be observed.

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