

# Supersymmetry and CP Violating Asymmetries in $B_{d,s}$ Decays

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## Abstract

We study possible effects of supersymmetry (SUSY) in CP asymmetries in non-leptonic  $B_{d,s}$  decays in a variety of SUSY flavour models considered in literature. We use both mass insertion and vertex mixing methods to calculate squark-gluino box diagrams contribution to  $B_{d,s}$ - $\bar{B}_{d,s}$  mixings. With the squark mixing parameter  $\eta = 0.22$ , and with large new CP phases, it turns out that the CP asymmetries to be measured in upcoming B-factories, HERA-B and LHC-B, can be completely dominated by the SUSY contribution in almost every considered model. Discrimination between the different models can be done by comparing experimental results in different decay modes. In some models squark masses up to  $\sim 5$  TeV can be probed through these experiments provided the SUSY contribution to  $B$ - $\bar{B}$  mixing is at 10% level,  $|M_{12}^{SUSY}/M_{12}^{SM}| \sim 0.1$ . This implies that models with heavy squarks have a fair chance to be tested in the future CP experiments before LHC.

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## 1 Introduction

There are two major questions to be answered in particle physics. One is the possible origin of CP violation, to be tested in forthcoming B-factories and the dedicated experiments LHC-B and HERA-B. The other one is the possible existence of supersymmetry (SUSY) as evidenced by the continuing efforts of both experimentalists and theorists in searching for new physics beyond the Standard Model (SM). The SM has specific predictions [1] on the size as well as on the patterns of CP violation in  $B_{d,s}$  meson decays which, if disproved in future experiments, would signal doubtless the existence of new physics [2].

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SUSY theories have been subject of an extensive study from the flavour physics point of view since they naturally offer new sources of flavour changing neutral currents (FCNC) and CP violation, arising from the Yukawa and SUSY breaking sectors of these models. These extra contributions are already constrained in a rather stringent way by the experimental bounds on  $\epsilon_K$ ,  $K$ ,  $B$ ,  $D$  mixings, electric dipole moments of electron  $d_e$  and neutron  $d_n$  as well as on the branching ratio of  $b \rightarrow s\gamma$ . Many works on radiatively induced FCNC processes in SUSY [3] have concentrated on the minimal supersymmetric extension of the SM (MSSM), and assumed often the minimal supergravity (mSUGRA) framework for the SUSY breaking sector. Updated analyses of mSUGRA imply [4] that  $\Delta M_{B_d}$ ,  $\epsilon_K$  as well as the branching ratio of the processes  $b \rightarrow sll$  may be enhanced at most by a few tens of percent while the branching ratios of  $b \rightarrow s\nu\bar{\nu}$  and  $K \rightarrow \pi\nu\bar{\nu}$  may be reduced by only a few percent. The new SUSY CP phases have negligible effects on the decays  $B \rightarrow X_s\gamma$  and  $B \rightarrow X_sll$  in mSUGRA. In particular, there is no new large phase shift in the  $B$ - $\bar{B}$  mixing [5] implying no major deviations in any CP asymmetry as compared with the SM predictions.

This conclusion changes dramatically as soon as one considers SUSY GUTs or other SUSY models without universality in the soft breaking sector. As the squark mass matrices are in general independent of the quark mass matrices, they introduce a major source of FCNC which, together with new CP phases, can substantially modify the SM predictions for CP violating observables to be measured in B-factories and LHC-B. There is a plethora of SUSY models, to be considered below, which satisfy all the present phenomenological constraints and allow large signals of new physics in these experiments<sup>3</sup>.

Many of the recent works on SUSY signatures in CP violating decays of  $B_{d,s}$  mesons have concentrated on studying new physics contributions to decay amplitudes. These analyses cover the full spectrum of SUSY models. Large deviations from the SM in CP asymmetries in  $b \rightarrow s\gamma$  are predicted in Ref. [7] and in penguin dominated non-leptonic  $b$  decays in Ref. [8]. As the new physics contributions to decay amplitudes are non-universal, comparison of CP asymmetries in different decay modes allows to find new physics in a model independent way. Surprisingly, while the effects of new physics contribution to  $B$ - $\bar{B}$  mixing in CP violating *lepton* asymmetries have been analyzed in almost all possible SUSY flavour models in both  $B_d$ ,  $B_s$  decays [9], the well known mixing effects in CP asymmetries in *non-leptonic*  $B_d$ ,  $B_s$  decays have been considered in detail only in a few particular models of supersymmetry [10,11]. The mass insertion method has been used to describe the internal squark effects in these works. These recent analyses have shown [12] that LEP2 experiments pose a serious naturalness problem to all conventional mSUGRA models, motivating the search for different SUSY models. In addition, motivated by the recent claim [13] that the CP violating observable  $\epsilon_K$  may have a fully supersymmetric origin in general SUSY models, we feel encouraged to study the predictions of the full range of SUSY flavour models considered in literature on the CP asymmetries to be measured in the upcoming experiments.

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<sup>3</sup> For a review of SUSY CP violating signals at future colliders see Ref. [6].

Following the model independent analyses of Ref. [14] we study in this letter the CP violating asymmetries in  $B_{d,s}$  meson decays in the SUSY flavour models classified in Ref. [9]. This includes models where FCNC and CP problems are solved using alignment [15–18], non-abelian symmetries [18–26] and decoupling of squarks of the first two generations [23,27–32]. These cover a large variety of general SUSY flavour models considered in literature. We use both the mass insertion method [33,34] as well as the vertex mixing method [35] to describe the dominant gluino-squark box diagram’s contribution to the meson mixing. We consider both  $B_d$  and  $B_s$  decays, as they provide complementary information for distinguishing new physics from the SM as well as discriminating between different SUSY models. We show that despite the quite strong bounds on the squark masses in these models, given the predictions for squark mixings, the SUSY CP violating contribution in  $B_{d,s}$  systems might dominate over the SM one in almost all the models. In some models measurable effects can be achieved for squarks masses as high as several TeV. This implies the possibility of discovering SUSY in B-factories before LHC.

## 2 New physics in $B$ - $\bar{B}$ mixing

Possible ways of evidencing the existence of new physics in B-factory experiments have been studied in the literature in a model independent way. Signals of new physics arising from new contributions in the decay amplitudes have been studied in [8] and are beyond the scope of this paper. If new physics contributes to the  $B$ - $\bar{B}$  mixing, as it is the case with the general SUSY models, it has been shown, that the planned experiments will be able to distinguish the effects of new CP phases from the effects of the SM Cabibbo-Kobayashi-Maskawa (CKM) phase [36]. This can be done by comparing the CP asymmetries in the different decay modes of both  $B_d$  and  $B_s$  mesons. This important result implies that future experiments will allow us to discriminate between different SUSY models, as will be shown below.

In terms of the off-diagonal elements of the  $2 \times 2$   $B_q^0$ - $\bar{B}_q^0$ ,  $q = d, s$ , mixing Hamiltonian  $\mathbf{M} - i\Gamma/2$  the  $B_q^0$ - $\bar{B}_q^0$  mixing phase  $\phi_M^q$  is expressed as

$$e^{-2i\phi_M^q} = \sqrt{\frac{M_{12}^{q*} - \frac{i}{2}\Gamma_{12}^{q*}}{M_{12}^q - \frac{i}{2}\Gamma_{12}^q}}. \quad (1)$$

In the analysis that follows, we make use of the fact that  $M_{12}$  can be parametrized as [14]

$$M_{12} = M_{12}^{SM} + M_{12}^{SUSY} = M_{12}^{SM} \left(1 + h e^{i\theta}\right), \quad (2)$$

where  $M_{12}^{SUSY}$  denotes the new SUSY contribution and  $h = |M_{12}^{SUSY}/M_{12}^{SM}|$ . The relative phase  $\theta = \arg(M_{12}^{SUSY}/M_{12}^{SM})$  is in principle not restricted because it results from the

possibly large new phases arising in the squark sector. As  $|\Gamma_{12}| \ll |M_{12}|$  and  $\Gamma_{12} \approx \Gamma_{12}^{SM}$ , the  $B^0$ - $\bar{B}^0$  mixing gets modified by the phase  $\phi_M$

$$\phi_M = \arctan\left(\frac{h \sin \theta}{1 + h \cos \theta}\right). \quad (3)$$

In the  $B_d$  system the new physics contribution is constrained by the measured  $B_H^0$ - $B_L^0$  mass difference which may be expressed as  $\Delta M_{B_d} = 2|M_{12}^d|$ .

The phase (3) directly modifies the CP asymmetries as discussed in [36,14]. Its effects are universal in all decay modes. Because the SM predicts almost vanishing CP asymmetries in most of  $B_s$  decays, non-zero experimental results in these measurements unambiguously measure the new physics phase  $\phi_M$ . However, in  $B_d$  system (to be experimentally probed in B-factories) the CP asymmetries can be also large within the SM, therefore finding new physics contributions to  $B$ - $\bar{B}$  mixing requires an accurate knowledge of the SM predictions for these asymmetries. In the presence of new phases, the CP asymmetries which measure the SM CKM angle  $\beta$  (e.g. in  $B_d \rightarrow J/\psi K$ ) are modified as  $a_{CP} = -\sin 2(\beta + \phi_M)$  while the CP asymmetries which measure the SM CKM angle  $\alpha$  (e.g. in  $B_d \rightarrow \pi^+\pi^-$ ) receive a new contribution with the opposite sign,  $a_{CP} = -\sin 2(\alpha - \phi_M)$ . As the new phase,  $\phi_M$ , cancels out in  $\alpha + \beta$  measurements of the third CKM angle  $\gamma$  are crucial.

However, if the new physics contribution is large enough so that the measured CP asymmetries are outside the allowed SM regions then, the new physics can be traced off unambiguously also in B-factories. Fortunately, recent global analyses [37] show that the precision reached in constraining the CKM matrix is quite good even now, yielding the result  $\sin 2\beta = 0.73 \pm 0.21$  at 95% confidence level. Therefore it follows from Eq. (3) that a SUSY contribution of  $h = 0.1$ , together with large phase  $\theta$ , implies measurable deviations from the SM. In the following we assume that the minimal detectable value of  $h$  is 0.1. Note that this assumption is somehow conservative, with better experimental precision, in the future much smaller effects can be probed.

### 3 SUSY flavour models

There are two distinct sources of flavour violation in general SUSY models in addition to the usual CKM mixing in the quark sector: (i) flavour violating interactions of top quark with charged Higgs, and (ii) misalignment between the fermion and sfermion mass matrices. The former possibility has been studied in [3] and it is quite constrained to lead to significant deviations from the SM. In this work we concentrate on the latter possibility. In this case the new physics contribution to the  $B_{d,s}$  mixing is dominated by the box diagrams with gluinos,  $\tilde{g}$ , and squarks,  $\tilde{q}$ , running in the loop. The new flavour mixings in the  $6 \times 6$  down squark mass matrix,

$$\tilde{M}^{d2} = \begin{pmatrix} \tilde{M}_{LL}^{d2} & \tilde{M}_{LR}^{d2} \\ \tilde{M}_{RL}^{d2} & \tilde{M}_{RR}^{d2} \end{pmatrix}, \quad (4)$$

lead to new flavour changing interactions, which, together with the new CP phases, may significantly contribute to  $B_{d,s}$  meson mixings. In Eq. (4), the phenomenological constraints on the off-diagonal squark mixings in  $3 \times 3$  matrices  $\tilde{M}_{LR,RL}^{d2}$  are more stringent than in  $\tilde{M}_{LL,RR}^{d2}$  [34], and we therefore neglect  $\tilde{M}_{LR,RL}^{d2}$  in the following.

The most oftenly used parameterization of squark mixing effects is called the mass insertion method [33,34]. It assumes a flavour diagonal  $\tilde{g}q\tilde{q}$  vertex and also flavour diagonal quark mass matrices and places all the mixing effects, described by the dimensionless parameter  $(\delta_{ij})_{MN}$ ,  $M, N = L, R$ , (see Eq. (2.35) in Ref. [9]), in the squark propagators. This method is the appropriate one when the squark masses are nearly degenerate but the price to be paid for using it, is the introduction of an average squark mass which should be chosen in an appropriate way [34]. The second method, the vertex mixing method, deals with the mass eigenstates of quarks and squarks with off-diagonal  $\tilde{g}q\tilde{q}$  couplings, and considers only the contribution from the lightest squark generation. Thus the mixing effects in this formalism can be characterized by the matrices  $K_L^d = V_L^d \tilde{V}_L^d$  and  $K_R^d = V_R^d \tilde{V}_R^d$ , where  $V_{L,R}^d$  and  $\tilde{V}_{L,R}^d$  are the matrices diagonalizing the quark and squark mass matrices, respectively. Obviously, this is a better approximation when one generation is much lighter than the others. In our numerical calculations we will use both methods depending upon which one is the most appropriate for the concrete application to the case at stake.

The SUSY flavour models were already classified and studied in a comprehensive work, [9]. There are three basic mechanisms to suppress the dangerous FCNC. The first one is the alignment of squark mass matrices along to the quark ones, so that the mixing matrices  $K_{L,R}^d$  are close to unity [15–18]. Motivated by the different behavior of the third family as compared to the first two ones, there have been proposed models with non-abelian flavour symmetries [18–26]. The approximate flavour symmetries are broken by a small factor  $\eta$  which in our numerical estimates is taken to be equal to the Wolfenstein parameter,  $\eta = 0.22$ . Finally, there are models with super-heavy squarks in the first two generations [23,27–32]. To suppress FCNC completely, several of the methods described above may be combined in a single realistic model. It has been pointed out that in order to avoid fine tuning in the electroweak symmetry breaking [27], and to ensure the positivity of the stop mass matrix squared at weak scale [38], there should be bounds on the squark mass parameters in consistent heavy squarks models. These, in turn, constrain the most popular scenarios of generating the multi TeV masses for the first two generation squarks using horizontal  $U(1)$  symmetries [28,30,31]. On the other hand, recently it has been proposed that all the SUSY soft masses might be at multi TeV scale and the lightness of the third generation squarks should be then generated radiatively [39]. In this scenario the right bottom squark remains heavy with mass of several TeV. The analysis of such a model is beyond the scope of the present work. We shall take a purely phenomenological approach and allow squark masses, in particular sbottom masses, to vary from  $\mathcal{O}(100)$  GeV to several TeV and, study the sensitivity of the CP asymmetries to the squark masses.

		Model	(13) mixing				(23) mixing		
			$LL$	$RR$	$m_{\tilde{q}}$ (GeV)	$h_{max}$	$LL$	$RR$	$h_{max}$
Mass insertion	A	[15]	$\eta^3$	$\eta^3$	550	1.2	$\eta^2$	$\eta^4$	0.016
		[16], [18] a	Too small		1400	—	$\eta^2$	1	1.05
		[17]	$\eta^3$	$\eta^7$	260	0.18	Small CP angle		
	B	[18] b	$\eta^3$	$\eta^{3/2}$	1400	1.3	$\eta^2$	$\eta^{1/2}$	1.05
		[20], [23] b	$\eta^3$	$\eta^3$	550	1.2	$\eta^2$	$\eta^2$	0.96
		[21]	$\eta^2$	$\eta^4$	330	1.1	$\eta^3$	$\eta^5$	0.002
		[25]	$\eta^3$	$\eta^4$	260	1.2	$\eta^2$	$\eta^4$	0.07
Vertex mixing	B+C	[23] a	$\eta^3$	$\eta^3$	830	1.3	$\eta^2$	$\eta^2$	0.97
	C	[29],[31]	$\eta^3$		450	1.2	$\eta^2$		0.89

Table 1

SUSY models which solve the FCNC problem with A–alignment, B–non-abelian symmetries and C–heavy squarks in first two generations. The mixing parameter  $\eta$  in  $LL$  and  $RR$  squark mass matrices is taken to be  $\eta = 0.22$  in our numerical estimates. The lower bounds on  $m_{\tilde{q}}$  coming from the measurement of  $\Delta M_{B_d}$  are presented for each model. The maximal values of  $h = |M_{12}^{SUSY}/M_{12}^{SM}|$  in  $B_d$  and  $B_s$  systems for each model are calculated for the given lower bound on  $m_{\tilde{q}}$ .

It is important to notice that from all the models listed above, some either are not able to pass all the phenomenological constraints set by  $\epsilon_K$ ,  $\Delta M_K$ ,  $d_e$  and  $d_n$  or do not have specific prediction for the squark mass matrix textures (for discussion see Ref. [9]). The models which have interesting predictions for B-physics, are summarized in Table 1. In the first column of this table, we specify the appropriate method for the estimation of the SUSY box contribution in each model, while in the second column, we specify the mechanism used to suppress FCNC. For a detailed description of each of these models, we refer the reader to the original literature which is listed in the third column. The predictions for the (23) and (13) flavour mixings in the mass matrices  $\tilde{M}_{LL,RR}^d$  are also given for each model.

## 4 Numerical results

In the SM the quantity  $M_{12}^{SM}$  has been calculated including NLO QCD corrections (for references see [1]) and reads

$$M_{12}^{SM} = \frac{G_F^2}{12\pi^2} \eta_{QCD} B_{B_q} f_{B_q}^2 M_{B_q} M_W^2 (V_{tq} V_{tb}^*)^2 S_0(z_t), \quad (5)$$

where

$$S_0(z_t) = \frac{4z_t - 11z_t^2 + z_t^3}{4(1-z_t)^2} - \frac{3z_t^3 \ln z_t}{2(1-z_t)^3}, \quad (6)$$

with  $z_t = m_t^2/m_W^2$ . Recent updated values for the bag parameter,  $B_{B_d}$ , and the decay constant,  $f_{B_d}$ , are  $B_{B_d} = 1.29 \pm 0.08 \pm 0.06$  and  $f_{B_d} = 175 \pm 25$  MeV, respectively, and the QCD correction factor  $\eta_{QCD}$  takes the value  $\eta_{QCD} = 0.55 \pm 0.01$  [1]. The meson masses we have used for the numerical estimation are,  $M_{B_d} = 5.279$  GeV,  $M_{B_s} = 5.369$  GeV, and the value of the top quark mass,  $m_t(m_t) = 165$  GeV, is taken from [1]. For the CKM mixing elements we use the following values  $|V_{td}V_{tb}^*| = 0.0084$  and  $|V_{ts}V_{tb}^*| = 0.040$ .

The dominant contribution to  $M_{12}^{SUSY}$  comes from the  $\Delta B = 2$  box diagrams with  $\tilde{q}$ ,  $\tilde{g}$  running in the loop. This can be calculated either in the scenario of vertex mixing [35] or using mass insertion [33,34]. The latter method is widely used in literature while the former, which should be more suitable for models with super heavy squarks, is not. The LO [40] and NLO [41] QCD corrections to  $\Delta F = 2$  processes in SUSY models are calculated using mass insertion method. There are no calculations of QCD corrections using the vertex mixing method. Since one of the aims of this paper is to compare the results in vertex mixing and mass insertion we neglect QCD corrections here and work at the level of electroweak box diagrams. Because the QCD corrections are known to *enhance* the SUSY contribution significantly (for the Wilson coefficients using mass insertion see, e.g., Ref. [11]), the results in this work should be regarded as a *conservative* estimate of the SUSY contribution to CP asymmetries. Moreover, as what matters in CP asymmetries are the ratios of amplitudes, QCD corrections tend to cancel.

Within the vertex mixing approximation,  $M_{12}^{SUSY}$  is given by [35]

$$M_{12}^{VM} = -\frac{\alpha_s^2}{216m_{\tilde{q}}^2} \frac{1}{3} B_{B_q} f_{B_q}^2 M_{B_q} \left\{ ((K_L^d)_{3i}^2 + (K_R^d)_{3i}^2) (66\tilde{f}_4(x) + 24xf_4(x)) + \right. \quad (7)$$

$$\left. (K_L^d)_{3i}(K_R^d)_{3i} \left[ \left( 36 - 24 \left( \frac{M_{B_q}}{m_b + m_q} \right)^2 \right) \tilde{f}_4(x) + \left( 72 + 384 \left( \frac{M_{B_q}}{m_b + m_q} \right)^2 \right) xf_4(x) \right] \right\},$$

$$f_4(x) = \frac{2 - 2x + (1+x)\ln x}{(x-1)^3}, \quad \tilde{f}_4(x) = \frac{1 - x^2 + 2x\ln x}{(x-1)^3}, \quad (8)$$

where  $x = m_{\tilde{g}}^2/m_{\tilde{q}}^2$ ,  $i = 1, 2$  for  $B_d$  and  $B_s$ , respectively and we take  $(K_{L,R}^d)_{33} \sim 1$ . Within the mass insertion notation,  $M_{12}^{SUSY}$  takes the form [34]

$$M_{12}^{MI} = -\frac{\alpha_s^2}{216m_{\tilde{q}}^2} \frac{1}{3} B_{B_q} f_{B_q}^2 M_{B_q} \left\{ ((\delta_{3i})_{LL}^2 + (\delta_{3i})_{RR}^2) (66\tilde{f}_6(x) + 24xf_6(x)) + \right. \quad (9)$$

$$\left. (\delta_{3i})_{LL}(\delta_{3i})_{RR} \left[ \left( 36 - 24 \left( \frac{M_{B_q}}{m_b + m_q} \right)^2 \right) \tilde{f}_6(x) + \left( 72 + 384 \left( \frac{M_{B_q}}{m_b + m_q} \right)^2 \right) xf_6(x) \right] \right\},$$

$$f_6(x) = \frac{6(1+3x)\ln x + x^3 - 9x^2 - 9x + 17}{6(x-1)^5}, \quad (10)$$

$$\tilde{f}_6(x) = \frac{6x(1+x)\ln x - x^3 - 9x^2 + 9x + 1}{3(x-1)^5}. \quad (11)$$

For our numerical estimates we use  $\alpha_s(m_b) = 0.222$ ,  $m_b(m_b) = 4.4$  GeV and  $x = m_{\tilde{g}}^2/m_{\tilde{q}}^2 = 1$ , unless stated otherwise.

To begin with, we have to take into account the constraint on the squark masses coming from the measurement  $\Delta M_{B_d} = 0.470 \pm 0.019$  ps<sup>-1</sup>. In order to do so we require that our calculated  $\Delta M_{B_d} = 2|M_{12}^d|$  coincides, within errors, with the experimental value. The errors are completely dominated by the errors of  $B_{B_d}$  and  $f_{B_d}$ . The lower bounds on the squark masses,  $m_{\tilde{q}}$ , for  $\eta = 0.22$  and for a fixed value of  $\theta$ ,  $\theta = \pi/2$ , (that takes into account the case where the SUSY CP violation is large) for each model are presented in Table 1. The interpretation of each of these numbers depends on the method used to calculate the SUSY contribution. For the mass insertion method (squark masses are nearly degenerate) this is the average squark mass, while for the vertex mixing method (squarks of the first two generation are decoupled) it bounds the sbottom masses.

In principle, one can get bounds on the squark masses and mixings also from the measurement of  $b \rightarrow s\gamma$  branching ratio. However, as we neglect the  $LR$  mixings in Eq. (4) here, the bound on the (23) squark mixing in  $LL$  is at best of order  $\mathcal{O}(1)$  for  $m_{\tilde{q}} = 500$  GeV [34], even assuming that the SUSY contribution to the branching ratio is less than 10%. Comparing this bound with the model predictions in Table 1 we conclude that  $b \rightarrow s\gamma$  does not impose constraints on our results.

Comparing the squark mass bounds in Table 1, it follows that in models with the same  $LL$  and  $RR$  mixings the vertex mixing method gives much larger contribution to  $M_{12}$  than the mass insertion one (compare models [15], [20], [23] b with [23] a). Since the models we have considered here have very different predictions for the squark mixings the mass bounds vary from the direct Tevatron bound  $m_{\tilde{q}} \gtrsim 260$  GeV to 1.4 TeV.

For the given squark mass bounds, the maximum allowed values of  $h = |M_{12}^{SUSY}/M_{12}^{SM}|$  for both  $B_{d,s}$  systems in each model are also given in Table 1. For the models [16] and [18] a, as there is no bound coming from  $\Delta M_{B_d}$  and in order to be conservative, we give  $h$  in the  $B_s$  system for  $m_{\tilde{q}} = 1.4$  TeV. As it is evident from the results shown in the table, the SUSY contribution dominates in all the models besides model [17], where it can be still measurable in the  $B_d$  system. As each model predicts different squark mixings the maximum  $h$  is different in the  $B_d$  and  $B_s$  systems.

The largest SUSY contribution to the  $B_d$ - $\bar{B}_d$  mixing is predicted within models [18] b and [23] a, and that to the  $B_s$ - $\bar{B}_s$  mixing by the models [16], [18] a and b, and [23] a. To study how large squark masses can possibly be probed in the prospective CP experiments we plot in Fig. 1 the dependence of  $h$  on  $m_{\tilde{q}}$  in these models ( $B_d$  in Fig. 1 (a) and  $B_s$  Fig. 1 (b)). The solid curve in Fig. 1 (a) is for model [18] b while in Fig. 1 (b) it is for all



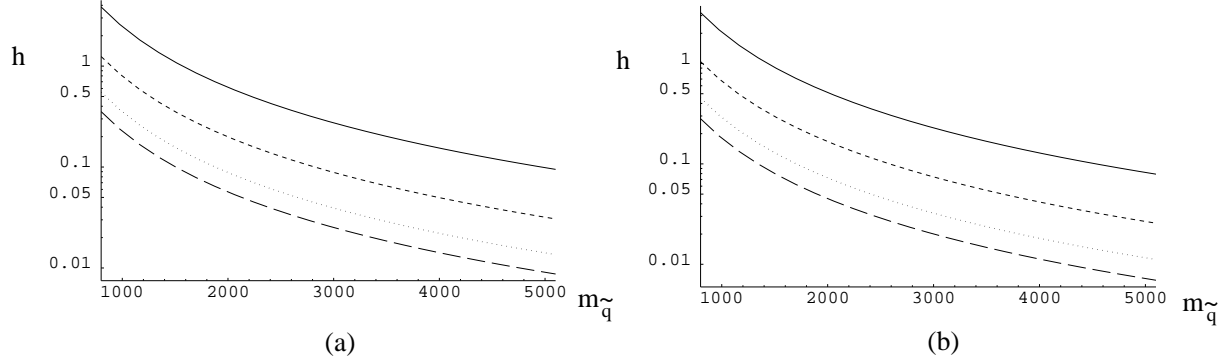


Fig. 1.  $h = |M_{12}^{SUSY}/M_{12}^{SM}|$  as a function of  $m_{\tilde{q}}$  (in GeV) for  $x = 1$  for  $B_d$  (figure (a)) and  $B_s$  (figure (b)) systems. The solid curves are for the model [18] b (figure (a)) and for the models [16], [18] a,b (figure (b)). The dotted curves denote always models [20], [23] b, the long dashed curves models [29], [31], and the short dashed curves model [23] a.

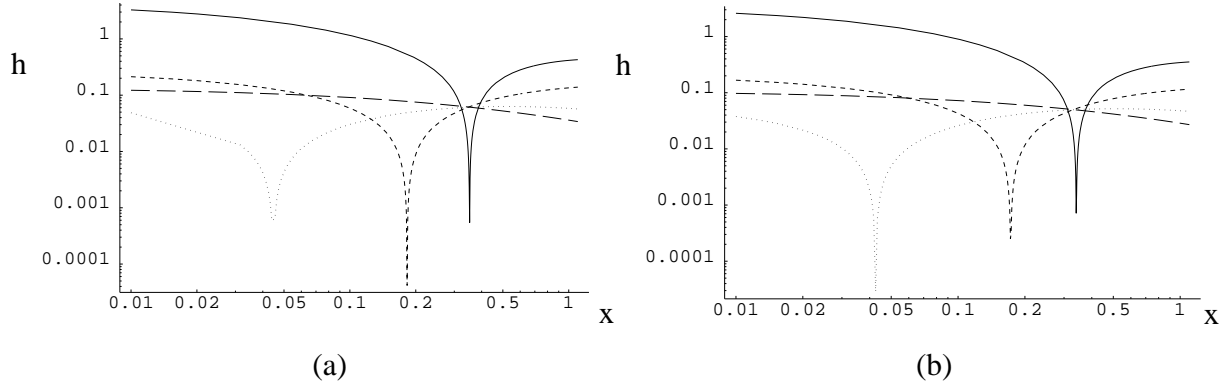


Fig. 2.  $h = |M_{12}^{SUSY}/M_{12}^{SM}|$  as a function of  $x = m_{\tilde{g}}/m_{\tilde{q}}$  for  $m_{\tilde{q}} = 2.5$  TeV for  $B_d$  (figure (a)) and  $B_s$  (figure (b)) systems. The notation is the same as in Fig. 1.

the models in [16,18] because their predictions coincide. The dotted curves denote always models [20], [23] b, the long dashed curves models [29], [31], and the short dashed curves model [23] a. Numerically  $h$  is sizable, i.e. it has values of order 0.1, up to squark masses of several TeV as can be seen from the graphs.

To account for the case with very heavy squarks we plot, in Fig. 2,  $h$  as a function of  $x$  for a fixed value  $m_{\tilde{q}} = 2.5$  TeV. The models and notation are the same as in Fig. 1. Because of the large squark mixings,  $h$  is always largest in model [18] b. However, in models where the first two squark generations are decoupled (models [23] a, [29,31] ) and where the vertex mixing method is used, the value of  $h$  is in general increased for small values of  $x$ . Therefore, models with large sbottom masses (gluinos are expected to be light) can still be tested in future experiments.

## 5 Discussion and conclusions

As discussed in Section 2, the measurements of non-leptonic CP asymmetries through different  $B_d$  and  $B_s$  decay modes, allow one to discriminate between new physics and the SM description of CP violation arising solely from the CKM phase. Our studies show that these measurements can also discriminate between the different SUSY models. According to Eq. (3), it follows from Table 1, that SUSY can completely dominate the CP asymmetries to be measured in B-factories and LHC-B. This is so even once the very strong bounds on the squark masses in Table 1 are properly taken into account. Large effects in non-leptonic CP asymmetries in  $B_d$  system can be expected almost for any prediction of the relative size of the  $LL$  and  $RR$  mixings. This should be compared with the leptonic asymmetries where new physics can be probed only if  $LL = RR$  [9]. As the different models, in general, have different predictions for the (13) and (23) mixings of the squark mass matrices (which may differ from the CKM mixing structure), the comparison of the CP asymmetries in  $B_d$  and  $B_s$  allows a clear discrimination between models. For example, models [16] and [18] a can give large contributions to CP asymmetries only in  $B_s$  decays while the rest of the models can modify either  $B_d$  or both mesons decays.

It is also instructive to compare the mass insertion method with the vertex mixing one. It follows from Table 1 that in models with super heavy squarks in the first two generations, the SUSY contribution for the same value of  $m_{\bar{q}}$  is larger than in other models. This is because in models with nearly degenerate squarks, the GIM mechanism is operative while in heavy squark models, only the  $b$  squarks contribute. Also, the results in the vertex mixing case are much more independent of the relative magnitude of  $LL$  and  $RR$  mixings (compare, for example, models [29,31] with models [21,25]) implying that the new physics should affect the CP asymmetries in super heavy squark models more strongly.

Finally, it remains to be answered how large the squark masses can be and still give measurable effects in CP asymmetries. This question becomes very interesting in light of the results of Ref. [12]. These authors claim that LEP2 results may indicate that colored particles have masses of few TeV. Even in a very disadvantageous scenario, where the SUSY effects can be as low as 10%, i.e.  $h = 0.1$ , but provided that the phase  $\theta$  is large enough, there will be still observable effects in upcoming B-factories as shown in Section 2. As can be seen from Fig. 1 (a),  $m_{\bar{q}} \lesssim 5.1$  TeV and  $m_{\bar{b}} \lesssim 3$  TeV in models [18] b and [23] a, respectively, can be probed for  $\eta = 0.22$ . The  $B_s$  decays (Fig. 1 (b)) are somehow less sensitive, implying  $m_{\bar{q}} \lesssim 4.5$  TeV and  $m_{\bar{b}} \lesssim 2.6$  TeV in models [16], [18] a,b and [23] a, respectively. If the sensitivity of the future experiments would turn out to be better than 10% then, higher masses can possibly be probed. For smaller values of  $\eta$  the mass reach scales linearly. These results have important and far reaching implications on the heavy squark models. As discussed, in some models the right bottom squarks might have masses of several TeV. Have the new large SUSY CP phases happen in this sector, our results would imply (plots in Fig. 2) that TeV masses can still give observable effects in B-factories.

In conclusion, we have shown that, with the squark mixing parameter  $\eta = 0.22$  and with large new SUSY CP phases, the CP asymmetry measurements in upcoming B-factories, HERA-B and LHC-B can be completely dominated by the SUSY contribution in almost every SUSY flavour model that we have considered. Discrimination between the different models can be done by comparing the results of the different decay modes. Assuming that SUSY effects at the level of 10% are still measurable, namely a  $|M_{12}^{SUSY}/M_{12}^{SM}| \sim 0.1$  can be tested, in some models the sensitivity is enough to explore squark masses up to  $\sim 5$  TeV. This implies that the models with heavy squarks have a great chance of being tested in future experiments.

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