

## Search for new physics at a super- $B$ factory

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**Abstract.** The importance of a super- $B$  factory in the search for new physics, in particular, due to CP-odd phase(s) from physics beyond the standard model is surveyed. The first point to emphasize is that we now know how to directly measure all three angles of the unitarity triangle very cleanly, i.e. without theoretical assumptions with irreducible theory error  $\lesssim 1\%$ . However, this requires much more luminosity than is currently available at  $B$ -factories. Direct searches via penguin-dominated hadronic modes as well as radiative, pair-leptonic and semi-leptonic decays are also discussed. Null tests of the SM are stressed as these will play a crucial role especially if the effects of BSM phase(s) on  $B$ -physics are small.

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### 1. Introduction and motivation

The asymmetric  $B$ -factories at KEK and SLAC have performed remarkably well. The accurate measurement of CP asymmetry in  $B^0 \rightarrow J/\psi K^0$  was significant for a variety of reasons. For one thing, it constitutes the first evidence of CP violation outside the  $K$ -system. Unlike the case of  $K$ -decays, though, in  $B \rightarrow J/\psi K^0$  the asymmetry is large [1,2], i.e.  $O(1)$ , which is about three orders of magnitude larger than what is found in  $K$ -decays. Quantitatively, the measured asymmetry provides a striking confirmation of the CKM-paradigm [3] as it is in very good agreement with indirect determinations based on the SM. As such these measurements at the asymmetric  $B$ -factories represent an important milestone in our understanding of CP-violation phenomena.

Indeed, these studies also show that the CKM phase is the dominant contributor to the observed CP asymmetry and the effect of any beyond the standard model (BSM) CP-odd phase(s) (we will collectively denote these as  $\chi_{\text{BSM}}$ ), even if they exist, in  $B \rightarrow J/\psi K^0$  must be small [4]. This great success of the  $B$ -factories now entails a concern for the future as it implies that the effect of  $\chi_{\text{BSM}}$  in  $B$ -physics may be small and their detection may be experimentally quite challenging. At the same time it is important to re-emphasize that there are very good reasons to suggest that  $\chi_{\text{BSM}}$  must exist.

In extensions of the SM, as a rule, it is difficult to avoid new phase(s). Given that three families of quarks exist, in the context of the SM, a CP-odd phase in the CKM matrix occurs naturally. In fact, although it is not impossible to arrange extensions of the SM in such a way that the CP-odd phase of the CKM matrix is zero, these tend to be contrived and not natural.

From the perspective of modern quantum field theory there is nothing sacred about CP asymmetry. As more particles (fermions, gauge bosons or scalars) are introduced in extended models new CP-odd phases arise [5]. More explicitly, this can be seen in specific extensions such as two Higgs doublets [6,7], LRS [8,9], SUSY [10] or models with warped extra dimensions [11]. In the case of two Higgs doublet models (2HDM) with natural flavor conservation there are three neutral Higgs whose exchanges entail a new CP-odd phase [5,12]. In general, in minimal LRS models based on the gauge group  $SU(2)_L \times SU(2)_R \times U(1)$  there can be as many as six new phases. Similarly SUSY can have tens of new phases [10]. Thus while the SM-CKM phase is completely natural, at the same time, there is no good reason to think that more CP-odd phases do not exist.

Furthermore, repeated investigations have suggested that the CKM phase is unable to account for baryogenesis. So far this has provided the only clue for the need of BSM source(s) of CP violation. Indeed, at the same time, it seems that extended models such as 2HDM, LR symmetry, SUSY or warped extra dimensions may be able to account for this crucial requirement of any model of CP violation.

While there are very strong reasons to think that BSM CP phase(s) exist, there is no reliable guidance as to the size of the effects they cause in  $B$ -physics. Indeed, the asymmetry they cause may be small even if the underlying CP-odd phases are not small. In this context, the SM itself teaches a valuable lesson. We know now that the CKM phase is  $O(1)$  yet the asymmetry it produces in  $K$  decays is vanishingly small. The indirect and direct CP violation parameters in  $K_L$  decays are  $\epsilon_K \approx 10^{-3}$  and  $\epsilon'_K \approx 10^{-6}$ . In fact, in decays of the top quark the CKM phase is expected to cause even smaller asymmetries [5,13] (than in  $K$ -decays) and there is virtually no hope of ever being able to detect them in laboratory experiments. It is also well-known that in charm decays the SM causes extremely small CP-violating asymmetries. Thus, it is only in  $B$ -decays that the CKM phase causes large asymmetries. It therefore stands to reason that the CP asymmetries, due to BSM phase(s), in  $B$ -decays, need not be large and may well be quite small.

Interestingly, there are some indications that the SM description of time-dependent CP asymmetry in penguin-dominated  $b \rightarrow s$  decays, such as  $B \rightarrow \phi(\eta', \pi^0 \dots) K^0$ , may not be adequate. Indeed TDCP asymmetries  $O(10\text{-}20\%)$  due to BSM sources cannot at this point be ruled out [14,15].

On the other hand, if the CP asymmetries in  $B$ -physics caused by  $\chi_{\text{BSM}}$  are as small as they were in  $K$ -decays, i.e.  $O(10^{-3})$  then their detection will undoubtedly require very large fluxes of  $B$ -mesons in a clean environment. Assuming a BR of  $O(10^{-3})$ , since it is difficult to find modes (that may be useful for this purpose) with larger BR, it is easy to see that the detection of asymmetries of  $O(10^{-3})$  requires  $\geq 10^{10}$   $B$ -mesons, i.e. a super- $B$  factory as well as precise control of experimental systematics.

The situation with respect to  $\chi_{\text{BSM}}$  is somewhat reminiscent of  $\nu$  mass and oscillations. There was never any good reason to think that  $m_\nu = 0$  just as there are no

good reasons to think that  $\chi_{\text{BSM}} = 0$ . For decades the only experimental indication of the possible need for  $m_\nu \neq 0$  was the deficit of solar  $\nu$ 's. Similarly, the fact that it is difficult to account for baryogenesis with the CKM-phase serves as a beacon for the search for  $\chi_{\text{BSM}}$ . The search for  $\nu$  mass and  $\nu$  oscillations took decades. In fact, the  $\Delta m^2$  region had to be persistently lowered by about three orders of magnitude in the past two decades before neutrino oscillations and  $m_\nu \neq 0$  were established! We can only hope that nature would be kinder for  $\chi_{\text{BSM}}$  in  $B$ -physics but we cannot count on that.

What we can count on is improved determination of the angles of the UT. The important point is that we know now methods which allow us to extract all the angles of the UT (and not just  $\beta$ ) [16] very cleanly, i.e. with intrinsic theory errors that are very small, i.e.  $\leq 1\%$ , but that require substantially more  $B$  mesons than are available at a  $B$ -factory.

If the BSM source(s) cause only small deviations from the SM in  $B$ -physics, then in addition to precision determination of the angles of the UT, searches for NP via *null tests* of the SM could also play an important role. Furthermore, progress in our calculational prowess would also be highly desirable.

## 2. Strategies for improved searches of new physics at a super- $B$ factory

In the light of the important findings of the two asymmetric  $B$ -factories, the strategies for searching for new physics (NP) may be subdivided into three broad categories as follows:

- Indirect searches with theory input.
- Indirect searches without theory input: Elements of a pristine UT.
- Direct searches (TDCP, DIRCP, PRA, TCA, wherever applicable) especially in arenas where the SM predicts vanishing asymmetries.

In particular, *null tests* of the CKM-paradigm become extremely important especially if  $\chi_{\text{BSM}}$  leads to small deviations in  $B$ -physics from the predictions of the SM.

### 2.1 *Indirect searches with theory input*

In the Wolfenstein representation, the four parameters of the CKM matrix are  $\lambda, A, \rho$  and  $\eta$ . Of these,  $\lambda = 0.2200 \pm 0.0026$  [17],  $A \approx 0.850 \pm 0.035$  are known quite precisely;  $\rho$  and  $\eta$  still need to be determined accurately. Efforts have been underway for many years to determine these parameters. The angles  $\alpha, \beta, \gamma$ , of the UT can be determined once one knows the 4-CKM parameters.

A well-studied strategy for determining these from experimental data requires knowledge of hadronic matrix elements. Efforts to calculate several of the relevant matrix elements on the lattice, with increasing accuracy, have been underway for the past many years. A central role is played by the following four inputs [18–20]:

- $B_K$  from the lattice with  $\epsilon_K$  from experiment,

**Table 1.** Illustration of progress from lattice calculations towards constraining CKM-parameters.

Quantity	Old fit (Lat'95)	New fit (BCP4 '01)
$V_{ub}/V_{cb}$	$0.08 \pm 0.02$	$0.085 \pm 0.017$
$V_{cb}$	$0.04 \pm 0.005$	$0.04 \pm 0.002$
$f_B \sqrt{\hat{B}_B}$ (MeV)	$237 \pm 65$	$230 \pm 50$
$\xi$	$1.16 \pm 0.10$	$1.20 \pm 0.10$
$\hat{B}_K$	$0.85 \pm 0.21$	$0.86 \pm 0.15$
$\sin 2\beta_{\text{SM}}$	$0.59 \pm 0.20$	$0.70 \pm 0.10$
$\eta$	$0.32 \pm 0.10$	$0.30 \pm 0.05$
$V_{td}/V_{ts}$	$0.22 \pm 0.05$	$0.185 \pm 0.015$

- $f_B \sqrt{\hat{B}_B}$  from the lattice with  $\Delta m_d$  from experiment,
- $\xi$  from the lattice with  $\Delta m_s/\Delta m_d$  from experiment,
- $(b \rightarrow ul\nu)/(b \rightarrow cl\nu)$  from phenomenology, HQS, lattice + experiment.

As is well-known, for the past few years, these inputs lead to an important constraint:  $\sin 2\beta_{\text{SM}} \approx 0.70 \pm 0.10$  which was found to be in very good agreement with direct experimental determination (by  $B$ -factories + CDF + ...) via CP-asymmetry measurements from  $b \rightarrow c\bar{c}s$  decays (such as  $B \rightarrow J/\psi K^0$ )  $\sin 2\beta_{\text{expt}} = 0.726 \pm 0.037$  [14,15].

Despite severe limitations (e.g. the so-called quenched approximation) these lattice inputs provide valuable help so that with  $B$ -factory measurements one arrives at an important conclusion that in  $B \rightarrow J/\psi K^0$  the CKM-phase is the dominant contributor; any NP contribution is unlikely to be greater than about 15%.

What sort of progress can we expect from the lattice in the next several years in the (indirect) determination of the UT? To answer this the pace of progress of the past several years are to be considered. Table 1 shows how lattice calculations of matrix elements around 1995 [21] yielded (amongst other things)  $\sin 2\beta \approx 0.59 \pm 0.20$ , whereas the corresponding error decreased to about  $\pm 0.10$  around 2001 [18-20]. In addition to  $\beta$ , such calculations also now constrain  $\gamma (\approx 60^\circ)$  with an error of around  $10^\circ$ .

There are three important developments that should help lattice calculations in the near future:

1. Exact chiral symmetry can be maintained on the lattice. This is especially important for light quark physics.
2. Relatively inexpensive methods for simulations with dynamical quarks (esp. using improved staggered fermions) have become available. This should help overcome limitations of the quenched approximation.
3. About an order of magnitude increase in computing power is imminent. Another factor of about 2-3 is quite likely in the forthcoming years.

In five years or so, errors on lattice determination of CKM parameters should decrease appreciably, perhaps by a factor of 3. So the error in  $\sin 2\beta_{\text{SM}} \pm 0.10 \rightarrow$

$\pm 0.03$ ;  $\gamma \pm 10^\circ \rightarrow 4^\circ$  etc. While this increase in accuracy is very welcome, there are good reasons to believe, that experiment will move ahead of theory in direct determinations of unitarity angles in three to five years. (At present, experiment is already ahead of theory for  $\sin 2\beta$ .)

## 2.2 Indirect searches without theory input: Elements of a superclean unitarity triangle

The starting point is to recognize that measurement of the angle  $\beta$  by the  $B$ -factories with essentially no theoretical assumptions has ushered in a new area.

The basic idea here is very simple. One should use methods that are extremely ‘clean’, i.e. require no theoretical assumptions and directly measure all the angles of the unitarity triangle. Thereby through redundant measurements of this type one can test CKM-unitarity and look for inclusive signals of  $\chi_{\text{BSM}}$ .

In spirit, this is a generalization of the great success of the  $B$ -factories in directly measuring the angle  $\beta$  with time-dependent CP asymmetry studies in  $B^0/\bar{B}^0 \rightarrow J/\psi K^0$ . At the moment the error in the measurement of  $\beta$  is around 5%. However, this is expected to improve quite rapidly as more data are accumulated. The important point for this discussion is that the intrinsic theory error for the method being used is  $\leq 1\%$ .

Let us briefly recall that

- direct CP studies of  $B^\pm \rightarrow 'K^\pm' + D^0, \bar{D}^0$  give  $\gamma$  [22–24],
- time-dependent CP studies in  $B^0 \rightarrow K^0 D^0, \bar{D}^0$  gives  $\gamma$  or  $\alpha$  and  $\beta$  [25,26].

Although the  $\beta$  determination from  $B^0 \rightarrow D^0 K^0$  is not competitive [26] with the  $B \rightarrow J/\psi K^0$  method, it is still useful as it provides a good check of the CKM-paradigm. Note, in particular, that for  $B^\pm$  and for  $B^0$  these methods for extracting angles of the UT using decays to  $D^0$  final states are very clean as they require no theoretical assumptions such as isospin [27].

Furthermore, time-dependent and direct CP studies in all three final states of  $B \rightarrow \pi\pi, \rho\pi, \rho\rho$  should give a very good determination of  $\alpha$  [28].

With these methods of direct determination of the unitarity angles, a very important criterion to bear in mind is the irreducible theory error (ITE). In other words, this is the intrinsic error coming from theoretical assumptions that these methods entail and even with very large data samples it will be very difficult to reduce this error. The  $B \rightarrow KD$  methods for  $\gamma$  are likely to have the smallest ITE, perhaps  $O(0.1\%)$ . The ITE for  $\beta$  with the  $B \rightarrow J/\psi K^0$  mode is also expected to be less than a per cent. The  $\alpha$  determination is less clean due to EWP contamination, resonant substructure, resonance-continuum separation difficulties etc. However, when all three FS ( $\pi\pi, \rho\pi, \rho\rho$ ) are studied (given enough luminosity) it is quite plausible that the remaining ITE for  $\alpha$  also will be quite small, i.e.  $O(1\%)$ .

It is extremely important that we make use of the opportunity afforded to us by as many of these very clean redundant measurements as possible. In order to exploit these methods to their fullest potential and get the angles with errors of order ITE will require a super  $B$ -factory (SBF).

The crucial point that cannot be overemphasized is that just as the feasibility of a clean measurement of  $\beta$  was the central motivating factor for the construction of the asymmetric  $B$ -factories about a decade ago, we should understand that we now know of methods that will allow us to cleanly and directly measure the other two angles,  $\gamma$  and  $\alpha$ . Although this motivation for SBF may not appear ‘sexy’ to some, it is important to understand that it is based entirely on facts; no theoretical assumptions, prejudices or speculations are involved. Therefore, this ought to be a very important driving force for construction of a super  $B$ -factory as these methods do require much larger luminosities than what the current  $B$ -factories can deliver.

Precision measurement of the three angles in itself constitutes a strong enough reason for a SBF, as it represents a great opportunity to precisely nail down the fundamental parameters of the CKM-paradigm.

### 3. Direct searches

We focus mainly on the following types of direct searches:

1. Mixing-induced CP violation in radiative  $B$ -decays: We begin the discussion with this interesting method for searching for NP as it is relatively new and seems very promising.
2. Mixing-induced CP violation in penguin-dominated hadronic final states: This has become very topical in the past two years and is likely to remain an important test of the CKM-paradigm for a long time. Indeed, CPV in  $b \rightarrow s$  decays has the distinction of providing a plausible indication of a non-standard phase that could be causing sizeable deviations in  $B$ -physics from the expectations of the SM.
3. Radiative  $B$ -decays, branching ratios and direct CP: Although the BR measurement has played an important role for almost a decade in limiting the parameter space of NP, it is likely to become less effective. However, direct CP searches are extremely important to pursue for quite some time and will be accompanied, in any case, by more precise measurements of BR’s.
4. Decays with leptonic pairs, e.g.  $B \rightarrow Xl^+l^-$ : Experiments are just beginning to make sensitive measurements of the rate. More accurate determination of the rate as well as forward-backward asymmetries, direct CP, including triple correlation asymmetries are clearly important.
5. Importance of tree-dominated hadronic final states that are especially sensitive to a CP-odd phase from the charged Higgs sector.
6. Semi-leptonic decays into final states with a  $\tau$  lepton: These are especially suited for constraining the charged Higgs-sector. Furthermore, the importance of the transverse polarization asymmetry as a powerful null test of the CKM-paradigm is emphasized.

#### 3.1 *Mixing-induced CP in radiative B-decays*

While the use of the rate and the direct CP asymmetry measurements in radiative decays of the  $B$  have received much attention for a very long time [29], discussions

on mixing-induced (time-dependent) CP in these modes are more recent [30]. This class of CP provides a very clean test of the SM and is very sensitive to the presence of right-handed currents of BSM origin [30].

The key point is that in the SM, the  $\gamma$  in  $b$  decays is predominantly LH whereas the  $\gamma$  in  $\bar{b}$  decays is predominantly RH. Mixing-induced CP cannot occur unless  $B^0$  and  $\bar{B}^0$  decay to the same final state to enable them to interfere. Thus in the SM TDCP asymmetry in radiative  $B$ -decays are expected to be either very small ( $b \rightarrow s$ ) or completely negligible ( $b \rightarrow d$ ).

In the SM TDCP in  $B \rightarrow \gamma[\rho, \omega, K^*, \dots] \propto m_d/m_b$  or  $m_s/m_b$  (in addition to including other suppression factors as well). BSM physics (e.g. LRSM, SUSY) can produce much larger asymmetries as in those models the occurrence of RH currents does not necessarily suffer from the  $m_d(m_s)/m_b$  suppression factor. Implications for these reactions in BSM scenarios have been studied recently in many papers [31].

In general, (for  $q = s, d$ )

$$H_{\text{eff}} = -\sqrt{8}G_{\text{F}} \frac{em_b}{16\pi^2} F_{\mu\nu} \left[ \frac{1}{2} F_{\text{L}}^q \bar{q} \sigma^{\mu\nu} (1 + \gamma_5) b + \frac{1}{2} F_{\text{R}}^q \bar{q} \sigma^{\mu\nu} (1 - \gamma_5) b \right]. \quad (1)$$

In the SM,  $F_{\text{R}}^q/F_{\text{L}}^q \approx m_q/m_b$ . In contrast, for example in a LR model,  $F_{\text{R}}^q/F_{\text{L}}^q$  can be appreciably larger as the presence of RH currents has a  $m_t/m_b$  enhancement for  $F_{\text{R}}^q/F_{\text{L}}^q$  [30].

3.1.1 *Time-dependent CP asymmetry in  $B(t) \rightarrow M^0 \gamma$* : For a state tagged as  $B$  rather than  $\bar{B}$  at  $t = 0$  and with  $\text{CP}|M^0\rangle = \xi|M^0\rangle$ ; with  $\xi = \pm 1$ :

$$A(\bar{B} \rightarrow M^0 \gamma_{\text{L}}) = A \cos \psi e^{i\phi_{\text{L}}}, \quad (2)$$

$$A(\bar{B} \rightarrow M^0 \gamma_{\text{R}}) = A \sin \psi e^{i\phi_{\text{R}}}, \quad (3)$$

$$A(B \rightarrow M^0 \gamma_{\text{R}}) = \xi A \cos \psi e^{-i\phi_{\text{L}}}, \quad (4)$$

$$A(B \rightarrow M^0 \gamma_{\text{L}}) = \xi A \sin \psi e^{-i\phi_{\text{R}}}. \quad (5)$$

Here  $\tan \psi = F_{\text{R}}^q/F_{\text{L}}^q$  and  $\phi_{\text{L,R}}$  are CP-odd weak phases. Thus, with  $\phi_{\text{M}}$  as the mixing phase,  $\Gamma(t) \equiv \Gamma(B(t) \rightarrow M^0 \gamma)$ ,

$$\Gamma(t) = e^{-\Gamma t} |A|^2 [1 + \xi \sin(2\psi) \sin(\phi_{\text{M}} - \phi_{\text{L}} - \phi_{\text{R}}) \sin(\Delta mt)].$$

This leads to a time-dependent CP asymmetry,

$$A(t) \equiv \frac{\Gamma(t) - \bar{\Gamma}(t)}{\Gamma(t) + \bar{\Gamma}(t)} = \xi \sin(2\psi) \sin(\phi_{\text{M}} - \phi_{\text{L}} - \phi_{\text{R}}) \sin(\Delta mt). \quad (6)$$

In the SM:

$$\begin{aligned} \text{for } B^0 : \quad \phi_{\text{M}} &= 2\beta, \\ \text{for } B_s : \quad \phi_{\text{M}} &= 0, \end{aligned} \quad (7)$$

and

$$\begin{aligned}
 \text{for } b \rightarrow s\gamma : \quad \sin(2\psi) &\approx \frac{2m_s}{m_b}, \quad \phi_L = \phi_R \approx 0, \\
 \text{for } b \rightarrow d\gamma : \quad \sin(2\psi) &\approx \frac{2m_d}{m_b}, \quad \phi_L = \phi_R \approx \beta.
 \end{aligned} \tag{8}$$

Thus, in the SM,

$$\begin{aligned}
 B^0 \rightarrow K^{*0}\gamma : A(t) &\approx (2m_s/m_b) \sin(2\beta) \sin(\Delta mt), \\
 B^0 \rightarrow \rho^0\gamma : A(t) &\approx 0, \\
 B_s \rightarrow \phi\gamma : A(t) &\approx 0, \\
 B_s \rightarrow K^{*0}\gamma : A(t) &\approx -(2m_d/m_b) \sin(2\beta) \sin(\Delta mt),
 \end{aligned} \tag{9}$$

where  $K^{*0}$  is observed through  $K^{*0} \rightarrow K_S\pi^0$ . Therefore, the SM predicts a maximum of a few per cent ( $\approx 3\%$ ) TDCP asymmetry in the  $B^0 \rightarrow K^*\gamma$  mode whereas the asymmetry in the  $B^0 \rightarrow \rho\gamma$  mode ought to be completely negligible.

As an illustrative contrast with the SM, let us next consider a simple LRSM based on the EW gauge group,  $G = SU(2)_L \times SU(2)_R \times U(1)$ . As is well-known the left- and right-handed doublets of quarks and leptons occur in this model completely symmetrically, e.g.

$$\begin{pmatrix} u \\ d \end{pmatrix}_{L,R}, \begin{pmatrix} \nu_e \\ e \end{pmatrix}_{L,R}.$$

This class of models has many attractive features, e.g. the  $\nu$  mass arises naturally. Using the  $K_L - K_S$  mass difference one obtains a rather stringent bound  $m_R \geq 1.5$  TeV [32]. Given that  $m_\nu \neq 0$  (and TeV is no longer such an imposing scale as it seemed in the early 80's) the model ought to be reconsidered as an effective low energy theory [9]. Taking,  $\langle \Phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$  and setting  $|\kappa'/\kappa| = m_b/m_t$  leads to a striking simplification [9]:

- $\Rightarrow$  The CKM angle hierarchy arises quite readily
- $\Rightarrow (CKM)_R = (CKM)_L$
- $\Rightarrow \delta_R = \delta_L$

endowing the model with a 'natural' origin for the so-called 'manifest' LR symmetry and considerable predictive power.

The  $W_L - W_R$  mixing is described by

$$\begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix} = \begin{pmatrix} \cos \zeta & e^{-i\omega} \sin \zeta \\ -\sin \zeta & e^{-i\omega} \cos \zeta \end{pmatrix} \begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix}.$$

Although  $\zeta$  is small,  $\leq 3 \times 10^{-3}$  [33,34], it is considerably offset by the helicity enhancement factor  $m_t/m_b$ . Radiative  $B$ -decays previously examined in the LRSM showed [35]

$$F_L \propto F(x) + \eta_{\text{QCD}} + \zeta \frac{m_t}{m_b} e^{i\omega} \tilde{F}(x),$$

$$F_R \propto \zeta \frac{m_t}{m_b} e^{-i\omega} \tilde{F}(x),$$

**Table 2.** Mixing-induced CP asymmetries in radiative exclusive  $B$ -decays in the SM and in the LRSM.

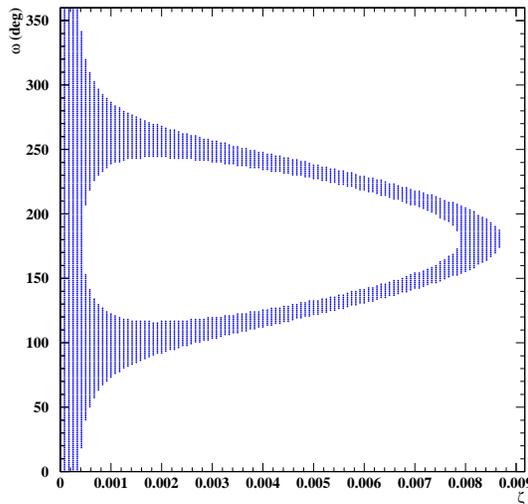
Process	SM	LRSM
$A(B \rightarrow K^* \gamma)$	$2(m_s/m_b) \sin 2\beta \sin(\Delta m_t)$	$\sin 2\omega \cos 2\beta \sin(\Delta m_t)$
$A(B \rightarrow \rho \gamma)$	$\approx 0$	$\sin 2\omega \sin(\Delta m_t)$

where  $x = (m_t/m_{W_1})^2$ ,  $\eta_{\text{QCD}} = -0.18$ . Also assuming  $\frac{\text{BR}(B \rightarrow X_s \gamma)_{\text{exp.}}}{\text{BR}(B \rightarrow X_s \gamma)_{\text{SM}}} = 1.0 \pm 0.1 \Rightarrow |\sin(2\omega)| = 0.67$  (see figure 1) one obtains the predictions for time-dependent CP shown in table 2.

Thus, whereas in the SM negligible TD asymmetries are predicted, in the LRSM they can be  $O(50\%)$  even if  $\text{BR}(B \rightarrow X_s \gamma)$  is in very good agreement with the SM.

The rarer radiative decay  $B \rightarrow \rho \gamma$  provides an even more striking contrast between the predictions of the SM and a model with LR currents such as the LRSM. In the SM, mixing-induced CP is even more dramatically suppressed as the quark mass ratio now gets replaced by  $m_d/m_b$ . In addition, the CP-odd weak phase factor of  $\sin 2\beta$  is replaced by a factor of  $O(\lambda^2)$  so that in the SM, CP asymmetry is expected to be  $\leq 10^{-3}$ , making it a very useful (essentially) *null test*. In the LRSM  $B \rightarrow \rho \gamma$  can have a TDCP asymmetry of order tens of per cents.

Let us briefly mention the current experimental effort to search for this class of asymmetry in radiative  $B$ -decays. Both BaBar and BELLE have demonstrated



**Figure 1.** Presently allowed values of  $\zeta$  and  $\omega$  from  $\text{BR}(B \rightarrow X_s \gamma)$ , deduced by setting  $\text{EXP}/\text{SM} = 0.71 \pm 0.36$  (i.e. to 90% CL), are included in the shaded area and in the blank internal area. Only the shaded region would be allowed when agreement between the SM prediction and experiment at the 10% level is attained [38].

the feasibility of time-dependent CP asymmetry measurement in  $B \rightarrow K^*[K^* \rightarrow K_s\pi^0]\gamma$  [36,37]. With some  $100\text{--}200 \times 10^6$   $B$ -pairs each, they both obtain results consistent with zero with statistical errors of  $O(0.6)$  [15,36,37]. In the next five years or so, it is expected that the luminosities will increase by factors of perhaps 5–10. This would reduce this error to perhaps around  $O(0.2)$ . If a positive result of such a size is seen then that would of course unambiguously imply new physics. However, for the experiments to reach the sensitivity of the predicted SM asymmetry, which is an important goal, would require higher luminosity only accessible to a SBF [39–41].

### 3.2 Search for $\chi_{\text{BSM}}$ via penguin-dominated hadronic final states

This test of the SM has received considerable attention in the past year or so. Initially, both BELLE and BaBar saw a large negative central value (with large errors) for  $\sin 2\beta$  from pure penguin modes. However, in Summer'03 with somewhat improved statistics the BaBar central value shifted and became quite consistent with the SM while BELLE's value became more precise and less consistent with the SM. The present (Summer'04) experimental status is summarized in table 3. The combined result for  $b \rightarrow s$  modes from BELLE and BaBar deviates by about  $3.5\sigma$  from the SM.

Recall that in the SM,  $B^0, \bar{B}^0$  decays that are dominated by  $b \rightarrow s$  penguin transitions are expected to have a negligible CP-odd phase [42,43]. Since the  $B \rightarrow J/\psi K^0$ -like ( $b \rightarrow c\bar{c}s$ ) decays also receive no CP-odd weak phase, the time-dependent CP asymmetry measurements of these two seemingly significantly different FS should have the same CKM-phase originating from  $B^0 - \bar{B}^0$  mixing, i.e.  $\sin 2\beta$ .

Note though that the  $u$ -quark contribution inside the penguin loop, or for that matter the corresponding tree ( $b$  to  $u$ ) contributions do, in principle, carry a non-zero CP-odd weak phase, i.e.  $\gamma$ . To that extent the time-dependent CP asymmetry measured via  $b$  to  $s$  'penguin-dominated' modes may differ from that seen in  $B \rightarrow J/\psi K^0$  modes. For many of the modes of interest, the tree contribution is color and Cabibbo suppressed; for those cases one finds [43]  $T/P$  to be  $O(\lambda^2) \approx 0.04$ . Thus, theoretical estimates of these deviations in the modes listed above seem to be  $O(\text{a few } \%)$ . Since light-quarks are involved some dynamical enhancement may well make these deviations somewhat larger. However, naively it seems difficult for the  $\sin 2\beta$  measured via these 'penguin' modes to deviate by more than 10% from the value measured in the  $J/\psi K^0$  method.

As was emphasized in [43], in addition to  $B \rightarrow \phi K^0$  several other modes in which the  $T/P$  ratio is very small (i.e. less than a few per cent), such as  $\eta'$  ( $\pi^0, \omega, \rho^0, \dots$ )  $K_S^0$  can all be used for testing the CKM-paradigm. In each of these modes the magnitude of time-dependent CP asymmetry should equal  $\sin 2\beta$  to a very good approximation. The sign of the expected asymmetry in the SM can of course be fixed by the CP eigenvalue of the final state.

3.2.1 *Highlights of the current experimental status* [14,15,43]: Table 3 summarizes the experimental studies of the time-dependent CP in penguin-dominated modes. At the moment, the evidence for a significant difference from the  $J/\psi K^0$  (i.e. the

**Table 3.** Experimental status of search of time-dependent CP in some penguin-dominated modes [14,15]. NT means no tree, CST is color suppressed tree and CAT is color allowed tree.

Final state	Type of tree	BELLE	BaBar
$\phi K^0$	NT	$0.06 \pm 0.33 \pm 0.09$	$0.50 \pm 0.25^{+0.07}_{-0.04}$
$\eta' K_s^0$	CST	$0.65 \pm 0.18 \pm 0.04$	$0.27 \pm 0.14 \pm 0.03$
$f_0 K_s$	CST	$-0.47 \pm 0.41 \pm 0.08$	$0.95^{+0.23}_{-0.32} \pm 0.10$
$\pi^0 K_s$	CST	$0.30 \pm 0.59 \pm 0.11$	$0.35^{+0.30}_{-0.33} \pm 0.04$
$\omega K_s$	CST	$0.75 \pm 0.64^{+0.13}_{-0.16}$	
$K^+ K^- K_s^0$	CAT	$0.49 \pm 0.18^{+0.17}_{-0.04}$	$0.55 \pm 0.22 \pm 0.12$
Average		$0.43^{+0.12}_{-0.11}$	$0.42 \pm 0.10$

$b \rightarrow c\bar{c}s$ ) determination:  $\sin(2\phi_1) = 0.726 \pm 0.037$  (weighted average) [14,15] is not yet compelling. However, each experiment sees an interesting  $\approx 2.5\sigma$  effect, when all such modes are combined. For a cleaner theoretical interpretation, though, in the long run, it is better to separate modes that receive color-allowed tree (CAT) contributions from those that do not receive any tree contribution or at most receive a color-suppressed tree contribution. (In table 3, the  $K^+ K^- K_s^0$  mode may also be different from the rest due to the fact that it is a three-body mode.) The above results are based on a combined total of about  $500 \times 10^6$   $B$ -pairs between the two experiments. With the expected increase in luminosity by a factor of 5–10 in the next few years, the current error (around 0.12) should decrease to around 0.05 making it a very meaningful test. Again, for a cleaner theoretical interpretation and a decisive test the error on individual modes should be reduced below  $O(\lambda^2 \approx 0.05)$ . This is very likely to require a SBF and should be one of the most interesting applications of such a machine [39,41].

3.2.2 *Model-independent remarks:* For a model-independent discussion, we can divide NP sources contributing to  $B \rightarrow \phi K_s$  into two types and discuss briefly the implications of each:

I. NP leads to modification of  $b \rightarrow s$  form-factor(s) [45]:

$$\Lambda_\mu^{bs} = \bar{s}_i T_{ij}^\alpha [-iF(q^2)(q^2 \gamma_\mu - q_\mu \not{q})L + m_b q_\mu \epsilon_\nu \sigma^{\mu\nu} G(q^2)R] b_j$$

with

$$F(q^2) = e^{i\delta_{st}} F_{SM} + e^{i\lambda_F} F_x;$$

$$G(q^2) = G_{SM} + e^{i\lambda_G} G_x,$$

where  $\delta_{st}$  is the strong phase generated by the absorptive part resulting from the  $c\bar{c}$  cut for  $q^2 > 4m_c^2$  [46];  $\lambda_F$  and  $\lambda_G$  are the CP-odd non-standard phases. For simplicity, the CKM phase in  $b \rightarrow s$  is assumed to be negligibly small. Of course,  $glu \rightarrow q\bar{q}$  interactions as dictated by QCD are always possible and are implied. So,  $glu \rightarrow s\bar{s}$  leads to the  $\phi K_s^0$  anomaly; but at the same time has serious ramifications

for  $\eta'K_s$ . In fact, recall that such a BSM modification was introduced to enhance the rate for  $B \rightarrow \eta'X_s(K)$ , possibly leading to non-standard direct CP-violation signals [45]. Also note that, for example,  $gluon \rightarrow c\bar{c}, \dots$  is inevitable.

Thus, it is clear that this type of new physics should lead to deviations from SM in numerous channels, in particular, all FS with (net)  $\Delta S = \pm 1$  are susceptible to effects of NP: rates, DIRCP, TDCP, TCA should all be modified. The effects will not be restricted to  $\phi K^0$  but will also be present in  $\phi K^\pm, \phi K^*$  (TCA),  $K\bar{K}K(X); \pi^0 K_s, \eta'K_s, \eta'K^\pm \dots; \sin(2\beta)$  via  $D^+D^-$  should *not* equal that from  $J/\psi K^0$ ; also DIRCP in  $D_s D^-(D^0)$ , TCA in  $D_s^* D^* \dots$ . Similarly  $\gamma X_s(K^*, K\pi \dots); l^+l^- X_s(K, K^*, K\pi \dots)$  should also show deviations at some level depending on the detailed implementation of the BSM.

II. Another model-independent way to incorporate NP is to assume an effective 4-Fermi interaction in the  $b \rightarrow s\bar{s}s$  vertex:

$$L_{4f}^{b3s} = G_{b3s} e^{i\chi_{b3s}} [\bar{s}\Gamma_\mu b][\bar{s}\Gamma'_\mu s].$$

$G_{b3s}$  is the effective 4-Fermi coupling, assumed real;  $\chi_{b3s}$  is the associated non-standard CP-odd phase. This is much more restrictive and yet such NP should effect not just TDCP in  $B \rightarrow \phi K^0$  but also DIRCP in  $B \rightarrow \phi K^0(K^\pm, K^* \dots)$  and TCA in  $B \rightarrow \phi K^*$ ; similarly  $K\bar{K}K(X); \eta'K_s(K^\pm, K^*)$  should receive BSM contributions.

Thus we can draw some general conclusions:

1. It is impossible to isolate NP only in TDCP in  $B \rightarrow \phi K^0$ .
2. All channels affected by II are also affected by I (but not vice versa).
3. Many of these NP effects will occur in the  $B_s$  system as well; e.g.  $\Delta m_s$ , TDCP in  $\phi\phi, \phi\eta'(\eta)$  and TCA in  $\phi K\bar{K}(X)$ .

3.2.3 *Some implications of BSM<sub>s</sub> invoked to explain  $\phi K_s$* : Here are some illustrative examples that emphasize possible corroborative evidence if one assumes that a large deviation from the SM is found in  $b \rightarrow s$  TDCPV:

I. Huang and Zhu [47] studied 2HDM (Mod III) and found that TDCPA ( $S_{\phi K}$ ) can occur with either sign but DIRCPA  $C_{\phi K} > 0$ .

II. Raidal [48] in LRSM with a relatively low-scale for  $m_{W_R}$  and with at least one new CP-odd phase found large TDCPA in  $B \rightarrow K^*(\rho)\gamma; QP$  in  $B_s \rightarrow \phi\phi$  (also  $\eta\rho, \pi^0\rho$ ).

III. Hiller [49] and Atwood and Hiller [50] proposed flavor-changing  $sZ'b$  with a complex coupling. This led to large non-standard effects in the BR and  $A_{FB}$  of  $b \rightarrow sl^+l^-; B_s \rightarrow \mu\mu; \Delta m_s$ .

IV. Khalil and Kou [51] emphasized that SUSY can (interestingly) account for different asymmetries in  $B \rightarrow \phi K_S^0$  and  $B \rightarrow \eta'K_S^0$ . In particular, they emphasized that the parity of the two final states is not the same and as a result in BSM scenarios such as SUSY  $\phi K_S^0$  and  $\eta'K_S^0$  can have different asymmetries. In their SUSY scenario, DIRCP will occur even in  $B^\pm$  decays; non-standard helicity will arise in  $b \rightarrow s\gamma$  and thus, for example, TDCPA in  $B \rightarrow K^*\gamma$  may also occur [52].

### 3.2.4 Summary on $B \rightarrow \phi K^0$ :

- Many beyond the SM scenarios can accommodate fairly large deviations of the asymmetry in  $B \rightarrow \phi K^0$  from the SM expectation.
- It is virtually impossible to confine the effects of a new phase to  $B \rightarrow \phi K^0$ , large TDCPA, DIRCP, TCA effects should be seen in a multitude of channels. In particular, TCA and other anomalous effects in  $\phi K^*$ ,  $\pi^0 K_s$ ,  $KKK(n\pi)$ ,  $\eta' K(n\pi)$ ,  $\gamma K^*(n\pi)$ ,  $l^+ l^- K(n\pi)$  should be vigorously studied.
- Future experimental efforts should target definitive measurements of asymmetry of  $O(\approx \text{theo. errors}) \approx \lambda^2$ , i.e. about 5% in as many of these individual channels as possible. Given a BR  $\approx 10^{-5}$  and assuming a 10% detection efficiency implies that about  $10^{10} B\bar{B}$  pairs are required for a convincing ( $5\sigma$ ) signal, i.e. a super- $B$  factory.
- Modes that seem to be dominated by penguins but that receive color-allowed tree contribution, e.g.  $K^+ K^- K_s$  should not be combined with those that only receive color-suppressed tree contributions.

### 3.3 Radiative $B$ -decays, BR and direct CP

Another very interesting rare  $B$  mode, whose importance has been recognized for a very long time [29] is  $B \rightarrow X_s \gamma$ . Recall the current experimental status, (World Ave.) BR ( $B \rightarrow X_s \gamma$ ) =  $(3.34 \pm 0.38) \times 10^{-4}$  [53]. In comparison, the SM (NLO) predicts  $(3.57 \pm 0.30) \times 10^{-4}$  [29,54], which is in good agreement.

As is well-known, this leads to important constraints on numerous extensions of the SM such as, 2HDM's, supersymmetric or extra-dimension models, etc. [29]. To further improve the theoretical prediction requires NNLO calculations, a very demanding and challenging task. Therefore, improvement in the experimental determination of the BR may appear somewhat unnecessary. However, larger data samples and improved statistics are in any case essential for a better determination of  $a_{\text{CP}}^{B \rightarrow X_s \gamma}$ , BR ( $B \rightarrow X_d \gamma$ ) and  $a_{\text{CP}}^{B \rightarrow X_d \gamma}$ , which are very well-motivated. The exclusive counterparts of these reactions also deserve continuing efforts.

In this context, note that  $a_{\text{CP}}^{B \rightarrow X_d \gamma} = -0.004 \pm 0.051 \pm 0.038$  [53]. Thus, the current experimental limit on  $a_{\text{CP}}^{B \rightarrow X_s \gamma}$  needs improvement by a factor of 5–10 to reach sensitivity to the SM (i.e.  $a_{\text{CP}}^{B \rightarrow X_s \gamma} \approx 0.6\%$ ). This should be possible at a SBF. Clearly precise measurements of this asymmetry constitute a very important test of the SM.

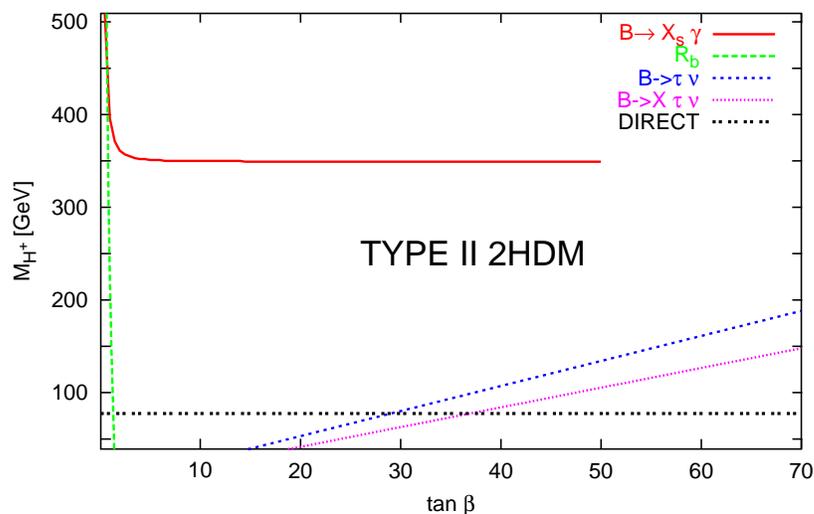
Furthermore, let us recall that due to accidental cancellations, in 2HDMs  $a_{\text{CP}}^{B \rightarrow X_s \gamma}$  is also  $< 0.6\%$ , however, it can be much larger in SUSY supergravity inspired models [55,56].

Interestingly, SM predicts  $a_{\text{CP}}^{B \rightarrow X_d \gamma}$  to be much larger ( $\approx -16\%$ ) ([56]; see table 4).

3.3.1 *Illustrative examples of constraints on models from BR[ $B \rightarrow X_s \gamma$ ]*: For the past many years, BR( $B \rightarrow X_s \gamma$ ) has been extremely useful in constraining the parameter space of a wide variety of non-standard models. Here are few examples that serve to illustrate this point.

**Table 4.** Direct CP asymmetries in radiative  $b$  decays in and beyond the SM [56].

Model	$a_{\text{CP}}^{B \rightarrow X_s \gamma} (\%)$	$a_{\text{CP}}^{B \rightarrow X_d \gamma} (\%)$
SM	0.6	-16
2HDM (Model II)	$\approx 0.6$	$\approx -16$
3HDM	-3 to +3	-20 to +20
T2HDM	$\approx 0$ to +0.6	$\approx -16$ to +4
Supergravity [55]	$\approx -10$ to +10	-(5-45) and (2-21)
SUSY with squark mixing [57]	$\approx -15$ to +15	
SUSY with $R$ -parity violation [58]	$\approx -17$ to +17	

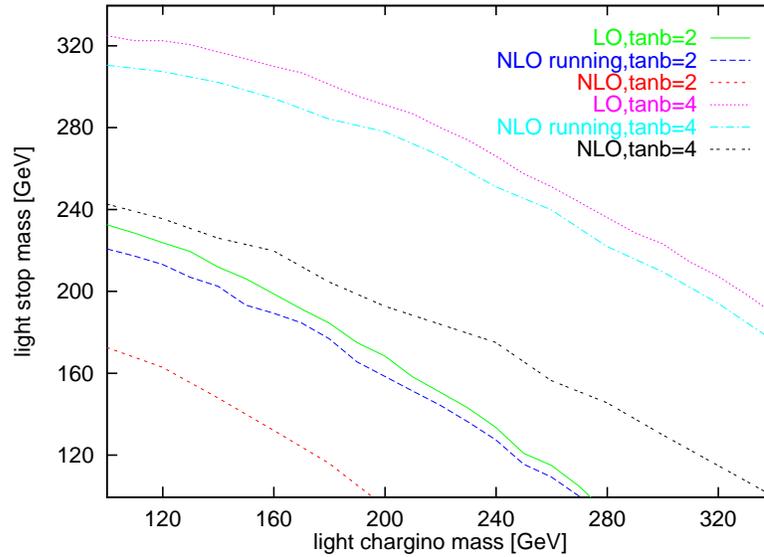


**Figure 2.** Direct and indirect lower bounds on  $M_{H^+}$  from different processes in the Type II 2HDM as a function of  $\tan \beta$  [29,59].

Figure 2 shows constraints on the  $\tan \beta - m_H$  plane resulting from  $B \rightarrow X_s \gamma$  along with other processes. The sensitivity of  $B \rightarrow X_s \gamma$  is very impressive. Note that  $B \rightarrow \tau \nu, X \tau \nu$  cannot compete with  $B \rightarrow X_s \gamma$  unless  $\tan \beta$  is very large; see [59] for further details.

Figure 3 illustrates constraints on the SUSY parameter space of stop-chargino masses.

**3.3.2 Direct CP violation in radiative  $B$  decays in and beyond the SM:** As discussed above even if improved measurement of the branching fraction do not lead to better constraints on the parameter space of BSM's, direct CP asymmetry can still be a very powerful way to search for new physics; see table 4. In the  $B \rightarrow X_s \gamma$  mode, asymmetries much larger than the SM are possible in SUSY extensions. However, due to an accidental cancellation [56] in a class of two Higgs doublet models the asymmetries do not change much from the SM.



**Figure 3.** Upper bounds on the lighter chargino and stop masses from  $B \rightarrow X_s \gamma$  data in a scenario with a light charged Higgs mass; for  $\tan \beta = 2$  (three lower curves) and 4 (three upper plots) the LL, NLL-running and NLL results (from top to bottom) are shown [29,60].

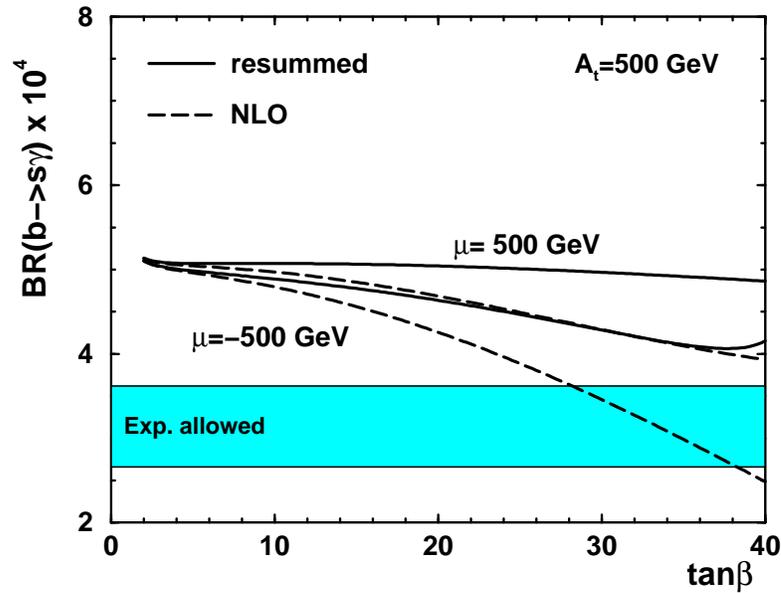
For the more suppressed  $b \rightarrow d$  transition, the direct CP asymmetry in the SM is expected to be much larger, around 16%. In this mode, new (BSM) CP-odd phase(s) can decrease or increase the asymmetry compared to SM expectations.

Given that the asymmetry in  $b \rightarrow d$  is some 15 times bigger than in  $b \rightarrow s$ , even though the BR of  $b \rightarrow d$  is expected to be smaller by roughly the same factor, detection of the  $b \rightarrow d$  asymmetry may well require fewer number of  $B$ 's [56]. Recall that a precise measurement of the branching fraction for the mode  $B \rightarrow \rho(\omega)\gamma$  is also a good way of better determining  $|V_{td}|/|V_{ts}|$ . Eventually, this will require careful, precise calculation of the  $SU(3)$  breaking effects for the corresponding form factors presumably using lattice methods.

The importance of studying radiative inclusive and exclusive modes at SBF can hardly be overemphasized.

### 3.4 $B$ -decays to lepton pairs ( $B \rightarrow Xl^+l^-$ )

Another very interesting rare  $B$  mode, whose importance has been recognized for a very long time [62], is  $B \rightarrow Xl^+l^-$ . BELLE and BaBar have recently started to see this mode with,  $BELLE + BaBar \Rightarrow BR(B \rightarrow X_s l^+ l^-) = (6.2 \pm 1.1^{+1.6}_{-1.3}) \times 10^{-6}$  [53]. SM (NLO) predicts  $(4.2 \pm 0.7) \times 10^{-6}$  [29]. In passing, we also recall the first SM [LO] prediction [62],  $\approx 6 \times 10^{-6}$  for  $m_t = 175$  GeV. Since this mode is somewhat rarer compared to  $B \rightarrow X_s \gamma$  its detection took longer. It ought to be clear though that it also is nevertheless very important:



**Figure 4.** Comparison of the theoretical NLL predictions within a special MSSM scenario *with* the resummed large  $\tan\beta$  terms; the charged Higgs boson mass is 200 GeV and the light stop mass is 250 GeV. The values of  $\mu$  and  $A_t$  are indicated in the plot, while the gluino, heavy stop and down-squark masses are set at 800 GeV; see [29,61].

- Inclusive ( $X_s, X_d$ ), exclusive ( $K, K^*, \pi, \rho \dots$ ) BR's and CP asymmetries will continue to provide valuable information on SM parameters and constraints on BSM physics as better data becomes available from  $B$  and super- $B$  factories.
- As an example note the special richness of  $K^*(\rho)$  final states that provide numerous ( $T_N$  even and odd) CP-violating observables [63]; see table 5.
- While an exhaustive study may well be beyond the reach of even a super- $B$  factory, very clean predictions of the CKM-paradigm [64]

$$A_{\text{CP}}^{X_s} = -(0.19^{+0.17}_{-0.19})\%; \quad A_{\text{CP}}^{X_d} = (4.40^{+3.87}_{-4.45})\%$$

should certainly be an important target of  $B$ -facilities.

Note also the interesting predictions for the corresponding exclusive modes [63],  $B \rightarrow K^*(\rho)l^+l^-$ , given in table 5.

### 3.5 Tree dominated (hadronic) FS: e.g $J/\psi K(K^*)$

These decay modes are extremely sensitive to  $\chi_{\text{BSM}}$  from an extended scalar sector [65]. In addition, as [65] emphasizes, they have the significant advantage of possessing a very clean experimental signal in neutral as well as in charged  $B$  decays and also have large BRs. CLEO, BELLE and Babar [66] have looked for these non-SM

**Table 5.** Estimates of the average CP-violating asymmetries  $A_k$  in units of  $10^{-4}$  ( $10^{-2}$ ) for the  $B \rightarrow K^*$  ( $B \rightarrow \rho$ ) transition [63]. Note also that 7–9 are triple correlation ( $T_N$  odd) asymmetries, others are  $T_N$  even;  $A_{CP}$  is PRA.

	$A_{CP}$	$A_3$	$A_4$	$A_5$	$A_6$	$A_7$	$A_8$	$A_9$
$K^*$	2.7	-0.6	-2.0	5.2	-4.6	0	0.6	-0.04
$\rho$	-1.7	0.1	0.4	-1.4	1.2	0	-0.1	0.006

effects. For example, for the  $B^\pm \rightarrow J/\psi K^\pm$  mode, the PRA is found to be less than around 5%. Clearly it is important to improve these bounds to look for a BSM-CP-odd phase, especially one from charged Higgs exchange.

To illustrate how such effects may arise, we may consider a ‘two Higgs doublet model for the top quark (T2HDM)’ [67,68], which is very well-motivated.

1. In this model the large  $m_{\text{top}}$  value is accommodated naturally by postulating that the second Higgs doublet, with a much larger VEV compared to the first, couples only to the top quark giving rise naturally to  $\tan\beta \gg 1$ .

This is accomplished via the Lagrangian:

$$L_{\text{Yukawa}} = -\bar{L}_L \phi_1 E l_R - \bar{Q}_L \phi_1 F d_R - \bar{Q}_L \bar{\phi}_1 G \mathbf{I}^{(1)} u_R - \bar{Q}_L \bar{\phi}_2 G \mathbf{I}^{(2)} u_R + \text{h.c.}$$

Here  $\phi_{1,2}$  are the two Higgs doublets;  $E, F$  and  $G$  are  $3 \times 3$  Yukawa matrices giving masses respectively to the charged leptons, the down- and up-type quarks;  $\mathbf{I}^{(1)} \equiv \text{diag}(1, 1, 0)$  and  $\mathbf{I}^{(2)} \equiv \text{diag}(0, 0, 1)$  are the two orthogonal projectors onto the first two and third family respectively.  $Q_L$  and  $L_L$  are the usual left-handed quark and lepton doublets.

2. It is best to view the T2HDM as a low energy effective theory (LEET) that parametrizes through the Yukawa interactions some high energy dynamics, which generate the top quark mass as well as the weak scale.
3. In addition to large  $\tan\beta$  the model has restrictive FCNC (since it belongs to type III) amongst only the up-type quarks.
4. A distinctive feature is that  $b \rightarrow c$  couplings becomes complex with non-standard CP violation in many  $B$ -decays, including the ‘gold-plated’ mode,  $B^0 \rightarrow J/\psi K^0$ .  $B$ -factory measurements now imply that such a non-standard phase is sub-dominant.
5. A good way to search for the presence of a small  $\chi_{\text{BSM}}$  is to search for direct CP asymmetry in the experimentally clean channel,  $B^\pm \rightarrow J/\psi K^\pm$  where the SM predicts completely negligible PRA [65].
6. A possible drawback of PRA in  $J/\psi K$  is that the needed strong-phase *may* not be large. For this reason it is very important to study TCA in  $B \rightarrow J/\psi K^*$  [69].
7. It is important to understand that the presence of complex (non-standard) (tree) couplings (e.g.  $b \rightarrow c$ ) has important consequences for  $b \rightarrow s(d)$  penguins. Thus penguin-dominated hadronic FS as well as radiative, pair leptonic and semileptonic FS become useful testing grounds.

### 3.6 Constraining the Higgs sector with $B \rightarrow D^{(*)}\tau\nu_\tau$

Semileptonic  $B$  decays involving  $\tau$  leptons provide important avenues to search for BSM physics, especially of the type involving an extended charged Higgs sector, CP-conserving or CP violating. The T2HDM discussed in the preceding section is a fine example of such a model. Below are some important points.

1. The  $q^2$  ( $q \equiv p_B - p_D$ ) distribution is rather sensitive to  $\tan\beta/m_H$ , much more so than the integrated rate.
2. Unlike  $B \rightarrow X_s\gamma$ , in  $B \rightarrow D^{(*)}\tau\nu_\tau$  the charged Higgs contribution does not cancel against the contribution from other SUSY partners.
3. The transverse polarization ( $p_\tau^t$ ) of  $\tau$  is an extremely sensitive and uniquely clean probe of a CP-odd  $H^\pm$  phase;  $\langle p_\tau^t \rangle_{\text{SM}} = 0$ .

3.6.1 (*CP-conserving*) *Constraints on Higgs sector with  $B \rightarrow D\tau\nu_\tau$* : This reaction has received considerable attention in the past several years [70–73]. Note that:

1. The needed semileptonic form factors ( $F_0, F_1$  and  $F_s$ ) should be determined accurately via  $B \rightarrow D\ell\nu$  and  $B \rightarrow D\mu\nu$ ;
2. For illustrative purposes we invoke heavy quark symmetry (HQS), which gives all three form factors in terms of the Isgur–Wise function;
3. Although  $1/m_Q$  corrections to individual form factors are appreciable, their ratios receive very small residual corrections. We use [74] and parametrize the remaining errors.

Theoretical study [73] shows that the differential spectrum is clearly more sensitive (see figure 6). Note  $[(\text{GeV}) \tan\beta/m_H] = [0, 0.1, 0.3]$  for  $\bar{\rho}/\bar{\rho}_{\text{SM}} = 1, 80\%, 50\%$ , respectively. The differential rate is given by

$$\frac{d\Gamma_\tau}{dt} = f(r_\tau, r_D, t, \zeta(t), \delta_H(t))$$

where,  $r_D = m_D^2/m_B^2$ ,  $r_\tau = m_\tau^2/m_B^2$ ,  $t = q^2/m_B^2$ ,

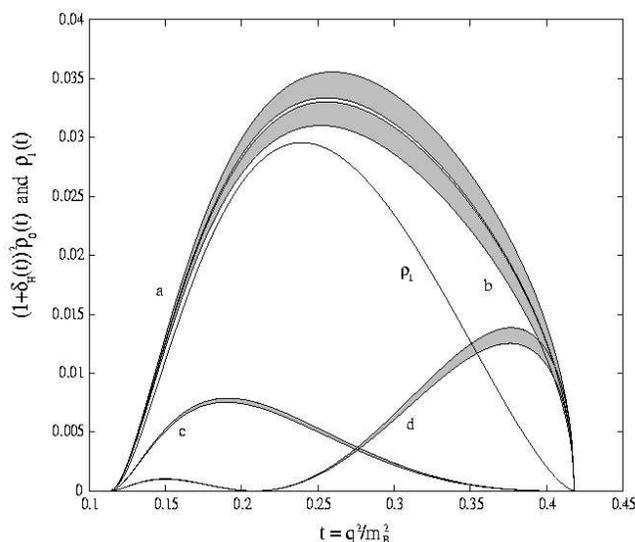
$$\delta_H(t) = - \left[ \frac{\tan\beta}{m_H} \right]^2 \frac{m_b m_B^2 t}{m_B - m_D} \left[ 1 + \frac{m_c}{m_b} \cot^2\beta \right] \frac{F_s(t)}{F_0(t)}$$

It is difficult to go below 0.06 in  $t$  (see figure 5) due to residual uncertainties in the ratio of form factors.

One can also try to improve the constraints using the technique of optimized observables [75,76]. Effects of QCD corrections have also been studied [72].

3.6.2 *Transverse  $\tau$  polarization in  $B \rightarrow \tau\nu_\tau X$* : This is an extremely sensitive observable for probing the presence of a CP-odd phase ( $\chi_{\text{BSM}}^{H^\pm}$ ) from charged Higgs exchange present in e.g. the T2HDM, discussed in the preceding sections. Also recall that due to CPT,  $Q\text{P}$  observables can be split into two categories [77].

- $T_N$  even, (e.g.  $\langle E_\tau \rangle$  or PRA)  $\Rightarrow \propto \text{Im}$  Feynman amplitude, i.e.  $\sin\delta_{\text{st}}$ ;  $\delta_{\text{st}}$  is the CP-even ‘strong’ phase.
- $T_N$  odd, (e.g.  $\langle p_\tau^t \rangle$ )  $\Rightarrow \propto \text{Re}$  Feynman amplitude, i.e.  $\cos\delta_{\text{st}}$ , where,



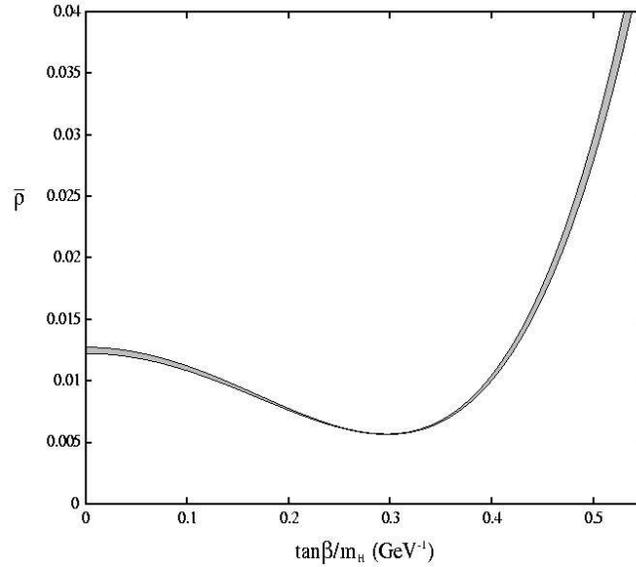
**Figure 5.** Spin-0 and spin-1 contributions to the differential distribution for  $B \rightarrow D\tau\nu$  in the standard model and in two-Higgs doublet models with  $[\text{GeV} \frac{\tan\beta}{m_H}] = 0$  (the SM), 0.06, 0.25, 0.35 for curves a, b, c, d respectively. The shaded regions indicate the theoretical uncertainty due to the uncertainties in the form-factors. The solid curve corresponds to the spin-1 contribution,  $\rho_1(t)$  [73].

$$p_\tau^t \equiv \frac{S_\tau \cdot p_\tau \times p_X}{|p_\tau \times p_X|}.$$

Thus,  $\langle E_\tau \rangle, A_{\text{PRA}}$  require an imaginary part of a Feynman amplitude and are proportional to  $(\alpha_s/\pi) \approx 0.1$ . Also, for  $\langle E_\tau \rangle, A_{\text{PRA}}$ , W-H interference requires the amplitude to be proportional to  $\text{Tr}[\gamma_\mu L(\not{p}_\tau + m_\tau)(L, R)\not{p}_\nu]$ . This yields another suppression factor,  $\propto m_\tau/m_B$ . Therefore,  $\langle p_\tau^t \rangle / \langle E_\tau \rangle, \langle p_\tau^t \rangle / A_{\text{PRA}} \approx 30$  [78]. The effect of power corrections was studied in [79] and tends to reduce this enhancement.

Experimental detection of  $P_\tau^t$ , via decay correlation in  $\tau \rightarrow \pi\nu, \mu\nu\nu, \rho\nu$  etc. is expected to be much harder than measuring an energy or rate asymmetry. Clearly rate and/or energy asymmetries should also be studied especially if detection efficiencies for those are higher. Fake asymmetries due to FSI can arise if only  $\tau^-$  or  $\tau^+$  is studied. Genuine (i.e. CP-violating)  $p_\tau^t$  will switch sign from  $\tau^-$  to  $\tau^+$ .

Although from a theoretical standpoint, these semileptonic modes with  $\tau$  in the final states are rather unique and extremely clean, their experimental study is a very difficult challenge. The main problem is that due to large backgrounds, at the moment, the only way to see these modes is with the use of fully reconstructed tagged events. Unfortunately the tagging efficiency is only  $\mathcal{O}(0.4)\%$  [41]. Combining this with the detection efficiency and the branching ratio ends up leaving too few events to have a serious impact on the allowed parameter space.



**Figure 6.** Normalized integrated width for  $B \rightarrow D\tau\nu$  as a function of  $\tan\beta/m_H$ . The shaded region indicates the theoretical uncertainty originating from the uncertainty in the form-factors [73].

#### 4. Crucial benchmarks in the hunt for $\chi_{\text{BSM}}$

In the hunt for  $\chi_{\text{BSM}}$  and NP a very good strategy may be to aim for some specific targets. Below are some representative samples:

- Determination of all three angles of UT with errors  $\approx O(\text{ITE})$ .
- Precise determination of  $a_{\text{CP}}(B \rightarrow X_s\gamma)$  (the SM expectation is around 0.6%).
- Precise determination of  $a_{\text{CP}}(B \rightarrow X_sl^+l^-)$  (the SM expectation is  $< 0.5\%$ ).
- Precise determination of  $\text{BR}(B \rightarrow X_d\gamma)$  (the SM expectation is around  $10^{-5}$ ).
- Precise determination of  $\sin 2\beta$ , in penguin-dominated final states, i.e.  $(\phi, \eta', \pi^0, \rho^0, \omega)K_s$ .
- Precise determination of TDCPA (S) for  $K_s^*\gamma$  (the SM expectation is  $\approx 3\%$ ).

The super- $B$  factory should be able to meet many if not all of these goals. Through such a strategy, a SBF would provide several approaches to uncovering  $\chi_{\text{BSM}}$ , irrespective of what the underlying theory is.

#### 5. Summary and outlook

$B$ -factories have started on an important hunt. One crucial milestone has already been attained. Not only is the KM phase confirmed, its dominant role in  $B \rightarrow$

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**Table 6.** Final states and observables in  $B$ -decays useful in searching for effects of new physics. Reliability of SM predictions and sensitivity to extensions of the SM are each indicated by stars (5 = best).

Final state	Observable	Theoretical cleanliness	Sensitivity to NP
$\gamma[K_s^*, \rho, \omega]$	TDCP	5*	5*
$K_s[\phi, \pi^0, \omega, \eta', \eta, \rho^0]$	TDCP	4.5*	5*
$K^*[\phi, \rho, \omega]$	TCA	4.5*	5*
$[\gamma, l^+l^-][X_s, X_d]$	DIRCP	4.5*	5*
Same	Rates	3.5*	5*
$J/\psi K$	TDCP, DIRCP	4*	4*
$J/\psi K^*$	TCA	5*	4*
$D(*)\tau\nu_\tau$	TCA ( $p_i$ )	5*	4*
Same	Rate	4*	4*

$J/\psi K^0$  is established! However, very good theoretical arguments still suggest that a BSM phase ( $\chi_{\text{BSM}}$ ) should exist. In the light of  $B$ -factory results it is likely that the effects of  $\chi_{\text{BSM}}$  on  $B$ -physics are subtle. Therefore, we will need large numbers of  $B$ 's to find  $\chi_{\text{BSM}}$ . A super- $B$  factory with  $10^{10}$   $B$ 's will allow [39] the following:

1. Very clean determination of all three angles of the UT with errors around ITE, i.e.  $O(1\%)$  compared to the current level of (at least) around 20%. This is the most compelling rationale for a SBF as it will allow a thorough understanding of the CKM-paradigm and the workings of the SM in the flavor sector. Of course, it is also an excellent way to search for  $\chi_{\text{BSM}}$ .
2. Search of small deviations using input from theory will require a systematic collective effort. Theory (especially lattice) needs improvement but also continuum methods. If deviations from the UT due to  $\chi_{\text{BSM}}$  are not too small, around say 5–10%, then this strategy has a chance.
3. More importantly, SBF will allow numerous direct searches for  $\chi_{\text{BSM}}$  via
  - TDCPA in  $\phi K_s, \eta' K_s, \pi^0 K_s, \rho K_s, \omega K_s, K^* \gamma, \rho \gamma, \dots$
  - DIRCPA including TCA in  $\phi K^\pm, \phi K^*, \eta'(\eta) X_{s,d}(K\rho), J/\psi K(*), \gamma X_{s,d}(K^*, \rho, \dots), l^+l^- X_{s,d}(K^*, \rho, \dots), \tau\nu_\tau X_c[D(*)]$ .

Table 6 presents a list of the many interesting and powerful ways to directly search for  $\chi_{\text{BSM}}$  and NP. We also indicate how reliably the SM predictions can be calculated (indicated by stars with five representing the best) and also sensitivity to NP, which is again indicated similarly by stars. The SM predicts negligible asymmetries in many cases of interest.

A super- $B$  factory will allow constraints on  $\chi_{\text{BSM}}$  to improve by 1–2 orders of magnitude thereby refining our understanding of flavor-physics to an unprecedented level. In the hunt for  $\chi_{\text{BSM}}$  several of these provide compelling benchmarks. Without reaching these our understanding of SM-CKM paradigm is seriously incomplete. A SBF would provide multiple possible paths to  $\chi_{\text{BSM}}$ , irrespective of what the underlying theory is, whether it is SUSY, extra dimensions or some altogether different

possibility. The most tantalizing prize of a super- $B$  factory is the discovery of a  $\chi_{\text{BSM}}$ , which could significantly illuminate our understanding of baryogenesis.

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### References

- [1] BELLE Collaboration: K Abe *et al*, hep-ex/0208025
- [2] BaBar Collaboration: B Aubert *et al*, hep-ex/0207042
- [3] N Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963)  
M Kobayashi and T Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973)
- [4] See e.g. A Soni, hep-ph/0307107, to be published in *Proceedings of PASCOS'03*
- [5] For a review see D Atwood *et al*, *Phys. Rep.* **347**, 1 (2001), hep-ph/0006032
- [6] T D Lee, *Phys. Rev.* **D8**, 1226 (1973)
- [7] S Weinberg, *Phys. Rev. Lett.* **37**, 657, (1976)
- [8] R N Mohapatra and J C Pati, *Phys. Rev.* **D11**, 566 (1975)
- [9] K Kiers *et al*, hep-ph/0205082
- [10] Y Grossman, Y Nir and R Rattazzi, hep-ph/9701231
- [11] K Agashe, G Perez and A Soni, hep-ph/0406101; hep-ph/0408134
- [12] W Bernreuther, T Schroder and T N Pham, *Phys. Lett.* **B279**, 389 (1992)
- [13] G Eilam, J L Hewett and A Soni, *Phys. Rev. Lett.* **67**, 1979 (1991)
- [14] See the plenary talk of Marcello Giorgi (BaBar) at the International High Energy Physics Conference, Beijing (August 04)
- [15] See the plenary talk of Yoshi Sakai (BELLE) at the International High Energy Physics Conference, Beijing (August 04)
- [16] Note  $(\beta, \alpha, \gamma) \equiv (\phi_1, \phi_2, \phi_3)$
- [17] S Eidelman *et al*, *Phys. Lett.* **B592**, 1 (2004)
- [18] D Atwood and A Soni, hep-ph/0103197
- [19] M Ciuchini *et al*, hep-ph/0012308
- [20] A Hocker *et al*, hep-ph/0104062
- [21] See A Soni, *Proceeding of Lattice'95*, hep-lat/9510036 (esp. p. 14)
- [22] M Gronau and D Wyler, *Phys. Lett.* **B265**, 172 (1991)
- [23] D Atwood, I Dunietz and A Soni, *Phys. Rev. Lett.* **78**, 3257 (1997)  
D Atwood, I Dunietz and A Soni, *Phys. Rev.* **D63**, 036005 (2001)  
D Atwood and A Soni, hep-ph/0312100
- [24] A Giri, Y Grossman, A Soffer and J Zupan, hep-ph/0303187
- [25] M Gronau and D London, *Phys. Lett.* **B253**, 483 (1991)
- [26] D Atwood and A Soni, arXiv:hep-ph/0206045
- [27] D Atwood and A Soni, hep-ph/0212071
- [28] E Snyder and H R Quinn, *Phys. Rev.* **D48**, 2139 (1993)
- [29] T Hurth, *Rev. Mod. Phys.* **75**, 1159 (2003)
- [30] D Atwood, M Gronau and A Soni, *Phys. Rev. Lett.* **79**, 185 (1997)
- [31] C-K Chua and W-S Hou, hep-ph/0110106

*Search for NP at a super-B factory*

- T Gotto *et al*, hep-ph/0306093  
M Gronau and D Pirjol, hep-ph/0205065
- [32] G Beall, M Bander and A Soni, *Phys. Rev. Lett.* **48**, 848 (1982)
- [33] G Beall and A Soni, *Proceedings of Electroweak Session of Moriond* (La, Plagna, 1983)
- [34] L Wolfenstein, *Phys. Rev.* **D29**, 2130 (1984)
- [35] K Fujikawa and A Yamada, *Phys. Rev.* **D49**, 5890 (1994)  
K S Basu, K Fujikawa and A Yamada, *Phys. Lett.* **B333**, 196 (1994)  
P Cho and M Misiak, *Phys. Rev.* **D49**, 5894 (1994)
- [36] BaBar: B Aubert *et al*, hep-ex/0405082
- [37] BELLE: K-F Chen, talk at ICHEP2004, Beijing, China
- [38] This figure is from the unpublished notes of [30]
- [39] See also, A Soni, invited plenary talk at the 5th High Workshop on Higher Luminosity B Factory, Izu, Japan, September 24–26 (2003), <http://belle.kek.jp/superb/workshop/2003/HL05/program.htm>
- [40] See also, M Neubert, hep-ph/0405105
- [41] See also, A G Akeroyd *et al*, hep-ex/0406071
- [42] Y Grossman and M Worah, *Phys. Lett.* **395**, 241 (1997)
- [43] D London and A Soni, *Phys. Lett.* **407**, 61 (1997)
- [44] T Browder, hep-ex/0312024, *Proceedings of Lepton-Photon '03 (FNAL)*
- [45] D Atwood and A Soni, *Phys. Rev. Lett.* **79**, 5206 (1997)
- [46] M Bander, D Silverman and A Soni, *Phys. Rev. Lett.* **43**, 242 (1979)
- [47] C-S Huang and S-H Zhu, hep-ph/0307354
- [48] M Raidal, hep-ph/0208091
- [49] G Hiller, hep-ph/0308180
- [50] D Atwood and G Hiller, hep-ph/0307251
- [51] S Khalil and E Kou, hep-ph/0307024
- [52] For a different SUSY analysis see, M Ciuchini *et al*, hep-ph/0308013 and references therein
- [53] M Nakao, hep-ex/0312041
- [54] A Buras and M Misiak, hep-ph/0207131
- [55] T Goto *et al*, hep-ph/9812369  
M Aoki, G-C Cho and N Oshimo, hep-ph/9811251
- [56] K Kiers, A Soni and G-H Wu, hep-ph/0006280
- [57] C-K Chua and X-G He, hep-ph/9808431  
A Kagan and M Neubert, hep-ph/9803368
- [58] E J Chun, K Hwang and J S Lee, hep-ph/0005013
- [59] P Gambino and M Misiak, hep-ph/0104034
- [60] M Ciuchini *et al*, hep-ph/9806308
- [61] M Carena, hep-ph/0010003
- [62] W-S Hou, R S Willey and A Soni, *Phys. Rev. Lett.* **58**, 1608 (1987)
- [63] F Kruger *et al*, hep-ph/9907386
- [64] A Ali and G Hiller, hep-ph/9812267
- [65] Guo-Hong Wu and A Soni, hep-ph/9911419
- [66] CLEO: V Savinov, hep-ex/0110031  
BELLE: K Abe *et al*, hep-ex/0211047  
BaBar: B Aubert *et al*, hep-ex/0408036
- [67] A Das and C Kao, *Phys. Lett.* **B372**, 106 (1996)
- [68] K Kiers, A Soni and G-H Wu, hep-ph/9810552
- [69] D London, Sinha, Sinha, hep-ph/0207007

- [70] B Grzadkowski and W-S Hou, *Phys. Lett.* **B283**, 427 (1992)
- [71] M Tanaka, *Z. Phys.* **C67**, 321 (1995)
- [72] Y Grossman, H E Haber and Y Nir, *Phys. Lett.* **B357**, 630 (1995)
- [73] K Kiers and A Soni, *Phys. Rev.* **D56**, 5786 (1997)
- [74] M Neubert, *Phys. Rep.* **245**, 259 (1994)
- [75] D Atwood and A Soni, *Phys. Rev.* **45**, 2405 (1992)
- [76] J Gunion, B Grzadkowski and X-G He, *Phys. Rev. Lett.* **77**, 5172 (1996)
- [77] D Atwood *et al*, *Phys. Rep.* **347**, 1 (2001)
- [78] D Atwood, G Eilam and A Soni, *Phys. Rev. Lett.* **71**, 492 (1993)
- [79] Y Grossman and Z Ligeti, *Phys. Lett.* **B347**, 399 (1995)