New Physics and Future B Factories

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Abstract

Further experimental and theoretical studies of the physics of flavor and CP violation are well motivated. Within the supersymmetric framework, higher precision measurements will allow to explore classes of models with stronger degree of universality: first, models with no universality, such as alignment or heavy first two squark generations; second, models with approximate universality, such as dilaton dominance or AMSB; and finally models of exact universality, such as GMSB. A broad program, including various rare processes or CP asymmetries in $B$, $D$ and $K$ decays, will provide detailed information about viable extensions of the Standard Model. Some highlights of future $B$-physics experiments (the present $B$-factories with integrated luminosity of $0.5$ ab$^{-1}$, hadron machines, and future high-luminosity $B$-factories) are described.

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I. INTRODUCTION

All existing measurements of flavor and CP violation are consistent with the CKM framework. In particular, the two recent measurements of CP violation in $B$ decays \cite{1,2} have provided the first precision test of CP violation in the Standard Model. Since the model has passed this test successfully, we are able, for the first time, to make the following statement: *The Kobayashi-Maskawa phase is, very likely, the dominant source of CP violation in low-energy flavor-changing processes.*

Still, further experimental and theoretical investigations of flavor and CP violation are well motivated. Here are some of the reasons for the interest in these aspects of high energy physics:

(i) *The flavor puzzle.* The flavor parameters of the Standard Model, that is the fermion masses and mixing angles, are small (except for $m_t$ and $\delta_{\text{KM}}$) and hierarchical. The Standard Model offers no explanation for these puzzling features. Perhaps the special structure of the Yukawa couplings is a hint of new physics.

(ii) *The supersymmetric flavor puzzle.* Flavor changing neutral current processes are highly suppressed in Nature. This experimental fact is nicely accounted for within the Standard Model, where flavor changing neutral currents are absent at tree level. They appear at the loop level, but then they are suppressed very effectively by the small CKM angles and the GIM mechanism. Various extensions of the Standard Model need to have very special flavor structures in order to achieve similarly effective suppression mechanisms. The most striking example is supersymmetry. While tree level FCNC can be forbidden (together with baryon and lepton number violations) by imposing an $R_p$ symmetry, there is no similarly natural and generic way to suppress the loop contributions to flavor and CP violating processes. Experimental studies of flavor physics are then crucial for understanding the mechanism of dynamical supersymmetry breaking.

(iii) *New sources of CP violation.* Almost any extension of the Standard Model provides new sources of CP violation. These sources often allow for significant deviations from the Standard Model predictions. Moreover, various CP violating observables can be calculated with very small hadronic uncertainties. Consequently, CP violation provides an excellent probe of new physics.

(iv) *The strong CP problem.* It is presently not understood why CP violation is so small in the strong interactions. The upper bound on the electric dipole moment of the neutron constrains nonperturbative CP violating QCD effects to be at least ten orders of magnitudes below naive expectations.

(v) *Baryogenesis.* The observed baryon asymmetry of the universe requires that CP is violated, but quantitatively it cannot be accounted for by the Kobayashi-Maskawa mechanism. It is clear then that new sources of CP violation must exist in Nature.

The experimental program of $B$ physics has just entered a new era in precision, in sensitivity and in probing time-dependent CP asymmetries. We are trying to overconstrain the CKM parameters, and to test the Standard Model correlations and (approximate) zeros. Experimental studies of $B$ decays are guaranteed to enrich our understanding of flavor and CP physics:

(i) At the very least, these experiments will significantly improve the determination of the CKM parameters.
(ii) If low-energy supersymmetry is realized in Nature then, as explained above, the study of flavor physics (whether consistent or inconsistent with the Standard Model predictions) will provide unique information about high scale physics. We explain the relations between the mechanism of dynamical supersymmetry breaking and the flavor and CP physics in the next section.

(iii) At best, measurements of rare $B$ decays and related CP violation will allow us to make progress on the road to solving the flavor puzzle and/or the puzzle of baryogenesis. It is important, however, to realize that, in contrast to the fine-tuning problem of electroweak symmetry breaking, here there is no analogous argument that says that the relevant new physics must appear at a scale that is not too far above $m_Z$. The scale of new flavor or CP violating physics may be very high, well beyond the reach of $B$ factories.

II. THE SUPERSYMMETRIC FRAMEWORK

Supersymmetry solves the fine-tuning problem of the Standard Model and has many other virtues. But at the same time, it leads to new problems: baryon number violation, lepton number violation, large flavor changing neutral current processes and large CP violation. The first two problems can be solved by imposing $R$-parity on supersymmetric models. There is no such simple, symmetry-related solution to the problems of flavor and CP violation. Instead, suppression of the relevant couplings can be achieved by demanding very constrained structures of the soft supersymmetry breaking terms. There are two important questions here: First, can theories of dynamical supersymmetry breaking (for a review, see [3]) naturally induce such structures? Second, can measurements of flavor changing and/or CP violating processes shed light on the structure of the soft supersymmetry breaking terms? Since the answer to both questions is in the affirmative, we conclude that flavor changing neutral current processes and CP violating observables will provide clues to the crucial question of how supersymmetry breaks.

A. Flavor and CP Problems

A generic supersymmetric extension of the Standard Model contains a host of new flavor and CP violating parameters. (For reviews of CP violation in supersymmetry see [4,5].) In fact, the Lagrangian of the minimal supersymmetric Standard Model has 124 physical parameters: 80 real ones and 44 imaginary ones [6]. Most of these parameters are related to flavor changing couplings. In addition to the Yukawa terms of the Standard Model, we now have flavor violation in trilinear scalar couplings ($A$-terms) and scalar mass-squared matrices ($\tilde{m}^2$-matrices). In contrast to the SM, we now have also flavor diagonal phases, coming from the bilinear Higgsino coupling (the $\mu$-term), the bilinear Higgs coupling (the $B$-term) and gaugino masses ($m_{\tilde{g}_i}$). Supersymmetry provides an impressive demonstration that low energy flavor physics might be richer than the CKM framework.

The requirement of consistency with experimental data provides strong constraints on many of these parameters. For this reason, the physics of flavor and CP violation has had a profound impact on supersymmetric model building. The supersymmetric flavor problem and the supersymmetric CP problem are well represented by the predictions for the mass
difference ($\Delta m_K$) and CP violation ($\varepsilon_K$) in $K^0 - \bar{K}^0$ mixing and by the electric dipole moment of the neutron ($d_N$).

The supersymmetric contribution to $\Delta m_K$ is dominated by diagrams involving $Q$ ($SU(2)_L$ doublet) and $D$ (down singlet) squarks in the same loop. To simplify our presentation, we assume that there is a single scale $\tilde{m}$ that characterizes all supersymmetry breaking terms, that is, $\tilde{m} \simeq m_{\tilde{g}} \simeq m_{\tilde{Q}} \simeq m_{\tilde{D}}$ (our results depend only weakly on this assumption). We focus on the contribution from the first two squark families (see, for example, [7]):

$$\frac{(\Delta m_K)_{\text{SUSY}}}{(\Delta m_K)_{\text{EXP}}} \sim 10^5 \left( \frac{300 \text{ GeV}}{\tilde{m}} \right)^2 \left( \frac{m_{Q_2}^2 - m_{Q_1}^2}{\tilde{m}^2} \right) \left( \frac{m_{D_2}^2 - m_{D_1}^2}{\tilde{m}^2} \right) \text{Re} \left[ (K_{L}^d)_{12} (K_{R}^d)_{12} \right], \quad (2.1)$$

where $K_L^d$ ($K_R^d$) are the mixing matrices in the gluino couplings to left-handed (right-handed) down quarks and their scalar partners. The constraint from $\varepsilon_K$ can be obtained by replacing $10^5$ with $10^7$.

In a generic supersymmetric framework, we expect $\tilde{m} = \mathcal{O}(m_Z)$, $\Delta m_{Q,D}^2/\tilde{m}^2 = \mathcal{O}(0.1)$ and $(K_{L,R}^d)_{ij} = \mathcal{O}(1)$. (The approximate degeneracy in squark masses is induced by RGE if the soft breaking terms are all induced close to the Planck scale with comparable size.) Then the constraint (2.1) is generically violated by about three orders of magnitude. Eq. (2.1) also suggests three possible ways to solve the supersymmetric flavor problems:

(i) Heavy squarks: $\tilde{m} \gg 300 \text{ GeV}$;

(ii) Universality: $\Delta m_{Q,D}^2 \ll \tilde{m}^2$;

(iii) Alignment: $| (K_{M}^d)_{12} | \ll 1$;

In addition, the related CP problems are alleviated if the relevant phases fulfill $\sin \phi \ll 1$.

Supersymmetry predicts also flavor preserving CP violation. For simplicity, we describe this aspect in a supersymmetric model without additional flavor mixings, i.e. the minimal supersymmetric standard model (MSSM) with universal sfermion masses and with the $A$-terms proportional to the corresponding Yukawa couplings. In such a constrained framework, there are two new physical phases [8,9]: $\phi_A$, which is related to the relative phase between the $A$-terms and the gaugino masses, and $\phi_B$, which is related to the relative phase between the $\mu$-term and the $B$-term. The most significant effect of $\phi_A$ and $\phi_B$ is their contribution to electric dipole moments (EDMs). For $d_N$, we obtain (see, for example, [10]):

$$\frac{d_N}{6.3 \times 10^{-26} \text{ e cm}} \sim 300 \left( \frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \sin \phi_{A,B}, \quad (2.2)$$

where the denominator on the left hand side gives the present experimental upper bound.

In a generic supersymmetric framework, we expect $\tilde{m} = \mathcal{O}(m_Z)$ and $\sin \phi_{A,B} = \mathcal{O}(1)$. Then the experimental bound is generically violated by about two orders of magnitude. This is the Supersymmetric CP Problem. Eq. (2.2) shows two possible ways to solve the supersymmetric CP problem:

(i) Heavy squarks: $\tilde{m} \gtrsim 1 \text{ TeV}$;

(ii) Approximate CP: $\sin \phi_{A,B} \ll 1$
B. Supersymmetry Breaking and Universality

Two scales play an important role in our discussion of supersymmetry: $\Lambda_S$, where the soft supersymmetry breaking terms are generated, and $\Lambda_F$, where flavor dynamics takes place. When $\Lambda_F \gg \Lambda_S$, it is possible that there are no genuinely new sources of flavor and CP violation. This leads to models with exact universality. When $\Lambda_F \lesssim \Lambda_S$, we do not expect, in general, that flavor and CP violation are limited to the Yukawa matrices. This leads to models without universality. In some special cases of supersymmetry breaking with $\Lambda_F \lesssim \Lambda_S$, it is possible that the leading contributions to supersymmetry breaking are universal. But it is difficult to avoid subdominant flavor-dependent contributions. Then we expect approximate universality.

1. Exact Universality: Gauge Mediated Supersymmetry Breaking

If at some high energy scale squarks are exactly degenerate and the $A$ terms proportional to the Yukawa coupling, then the contributions to FCNC come from RGE and are GIM suppressed, for example,

$$\Delta m_K \propto \text{Re}[(V_{td}V_{ts}^*)^2]Y_t^4 \left(\frac{\log(\Lambda_S/m_W)}{16\pi^2}\right)^2.$$  \hspace{1cm} (2.3)

This contribution is negligibly small.

In models of Gauge Mediated Supersymmetry Breaking (GMSB) [11–13], superpartner masses are generated by the SM gauge interactions. These masses are then exactly universal at the scale $\Lambda_S$ at which they are generated (up to tiny high order effects associated with Yukawa couplings). Furthermore, $A$ terms are suppressed by loop factors. The only contribution to FCNC is then from the running, and since $\Lambda_S$ is low it is highly suppressed. Similarly to $K-\bar{K}$ mixing, the supersymmetric contribution to $D-\bar{D}$ mixing is small and we expect no observable effects. Supersymmetric contributions to $B-\bar{B}$ mixing are, at most, 20% of the SM one and usually much smaller. Such deviations are too small to be signalled by $\Delta m_B$ but can perhaps give observable effects in the CP asymmetries in $B \to \psi K$ decays.

More generally, in any supersymmetric model where there are no new flavor violating sources beyond the Yukawa couplings, FCNC and CP violation in meson decays are hardly modified from the SM predictions [14].

2. Approximate Universality: Gravity, Anomaly and Gaugino Mediation

If different moduli of string theory obtain supersymmetry breaking $F$ terms, they would typically induce flavor-dependent soft terms through their tree-level couplings to Standard Model fields. There are however various scenarios in which the leading contribution to the soft terms is flavor independent. The three most intensively studied frameworks are dilaton dominance, anomaly mediation and gaugino mediation.

**Dilaton dominance** assumes that the dilaton $F$ term is the dominant one. Then, at tree level, the resulting soft masses are universal and the $A$ terms proportional to the
Yukawa couplings [15]. Both universality and proportionality are, however, violated by string loop effects. These induce corrections to squark masses of order $\frac{\alpha_X}{\pi} m_3^{2/3}$, where $\alpha_X = (2\pi(S + S^*))^{-1}$ is the string coupling. There is no reason why these corrections would be flavor blind. The effect of these terms is, however, somewhat suppressed by RGE effects which enhance the universal part of the squark masses by roughly a factor of five, while leaving the off-diagonal entries essentially unchanged. The flavor suppression factor is then [16]

$$\frac{\Delta m_{12}^2}{m^2} \sim \frac{m_{12}^2 \text{one-loop}}{m_g^2} \approx \frac{\alpha_X}{\pi} \frac{1}{25} \approx 4 \times 10^{-4}.$$  

(2.4)

Dilaton dominance relies on the assumption that loop corrections are small. This probably presents the most serious theoretical difficulty for this idea, because it is hard to see how non-perturbative effects, which are probably required to stabilize the dilaton, could do so in a region of weak coupling. In the strong coupling regime, these corrections could be much larger. However, this idea at least gives some plausible theoretical explanation for how universal masses might emerge in hidden sector models. Given that dilaton stabilization might require that non-perturbative effects are important, the flavor suppression might in reality be weaker than the estimate of eq. (2.4).

**Anomaly mediation** (AMSB) provides another approach to solving the flavor problems of supersymmetric theories, as well as to obtaining a predictive spectrum. The conformal anomaly of the Standard Model gives rise to soft supersymmetry breaking terms for the Standard Model fields [17,18]. These terms are generated purely by gravitational effects and are universal. In general, naturalness considerations suggest that couplings of hidden and visible sectors should appear in the Kahler potential, leading to soft masses for scalars already at tree level, and certainly by one loop. As a result, one would expect the anomaly-mediated contributions to be irrelevant. However, in “sequestered sector models” [17], in which the visible sector fields and supersymmetry breaking fields live on different branes separated by some distance, the anomaly mediated contribution could be the dominant effect. This leads to a predictive picture with universal scalar masses. It has been realized, however, that within the framework of string/M theories, the separation of branes is, by itself, not enough to avoid tree-level, non-universal squark and slepton masses [19–21]. Only under special conditions, such as compactification to pure five-dimensional supergravity with end of the world branes, is the anomaly-mediated contribution dominant. Quite generically, however, sub-dominant effects give deviations from universality, e.g. [20]

$$\frac{\Delta m_{12}^2}{m^2} = \mathcal{O} \left( \frac{T}{S} \right),$$  

(2.5)

where $S$ is the dilaton and $T$ is some modulus. On both theoretical and phenomenological grounds, one expects that the ratio $T/S$ is not much smaller than unity, perhaps $T/S \sim 1/3$. Such non-universal contributions may easily violate the $\Delta m_K$ and $\varepsilon_K$ constraints [5]. (Another difficulty of this framework is related to the fact that slepton masses-squared are negative, so modification is required.) Similar comments apply to the framework of **gaugino mediation** ($\tilde{g}$MSB) [22,23]. These models also suppress dangerous tree level contact terms by invoking extra dimensions, with the Standard Model matter fields localized.
on one brane and the supersymmetry breaking sector on another brane. In this case, however, the Standard Model gauge fields are in the bulk, so gauginos get masses at tree level, and as a result scalar masses are generated by running. Again, however, non-universal tree and one loop contributions to scalar masses are generic and significant violations of degeneracy and proportionality are expected.

3. No Universality: Supersymmetric Horizontal Symmetries

Various frameworks have been suggested in which flavor symmetries, designed to explain the hierarchy of the Yukawa couplings, impose at the same time a special flavor structure on the soft supersymmetry breaking terms that helps to alleviate the flavor and CP problems. Alignment models do not assume any squark degeneracy. Instead, flavor violation is suppressed because the squark mass matrices are approximately diagonal in the quark mass basis. This is the case in models of Abelian flavor symmetries, in which the off-diagonal entries in both the quark mass matrices and in the squark mass matrices are suppressed by some power of a small parameter, $\lambda$, that quantifies the breaking of some Abelian flavor symmetry. A natural choice for the value of $\lambda$ is $\sin \theta_C$, so we will take $\lambda \sim 0.2$. One would naively expect the first two generation squark mixing to be of the order of $\lambda$. However, the $\Delta m_K$ constraint is not satisfied with the ‘naive alignment’, $K_{12}^d \sim \lambda$, and one has to construct more complicated models to achieve the required suppression [24,25]. As concerns $D - \bar{D}$ mixing, models of alignment are very predictive. It is unavoidable in this framework that, to a very good approximation,

$$|(K_L^u)_{12}| = \sin \theta_C.$$  

(2.6)

Consequently, the supersymmetric contributions to $\Delta m_D$ are close to the present experimental bound. Furthermore, there is no reason for the related CP violating phase to be small. Thus, large CP violating effects could be observed in the doubly-Cabibbo-suppressed $D \to K\pi$ decays. The effects in $B - \bar{B}$ mixing are smaller: one expects $|(K_L^d)_{13}| \sim |V_{ub}|$, leading to a few percent effects on CP asymmetries in neutral $B$ decays. We conclude that one can construct models in which an Abelian horizontal symmetry solves the supersymmetric problems of flavor and CP. These models are however not the generic ones in this framework. They can be tested through measurements of mixing and CP violation in the neutral $D$ system and searched for through small but perhaps non-negligible effects in CP violation in neutral $B$ decays.

Non-Abelian horizontal symmetries can induce approximate degeneracy between the first two squark generations, thus relaxing the flavor and CP problems [26]. (A review of $\epsilon_K$ in this class of models can be found in [4].) The approximate degeneracy between the first two squark generations suppresses also the supersymmetric contributions to $D - \bar{D}$ mixing. Small but perhaps observable deviations from the Standard Model predictions for CP asymmetries in $B$ decays are possible. Similar to models of Abelian flavor symmetries, one can construct models of non-Abelian symmetries in which the symmetry solves both the $\epsilon_K$ and the $d_N$ problems. These models are however not the generic ones in this framework.

Finally, one can construct models of heavy first two generation squarks. Here, the basic mechanism to suppress flavor changing processes is actually flavor diagonal: $m_{\tilde{q}_{1,2}} \sim$
20 TeV. Naturalness does not allow higher masses, but this mass scale is not enough to satisfy even the $\Delta m_K$ constraint [27], and one has to invoke alignment, $K^{d}_{12} \sim \lambda$. This is still not enough to satisfy the $\varepsilon_K$ constraint, and a somewhat small phase is required. Two more comments are in order: First, in this framework, gauginos are significantly lighter than the first two generation squarks, and so RGE cannot induce degeneracy. Second, the large mass of the squarks is enough to solve the EDM related problems, and so it is only the $\varepsilon_K$ constraint that motivates a special phase structure.

C. Flavor and CP Violation as a Probe of Supersymmetry

We have seen that supersymmetric flavor models can be roughly divided to three classes:

(i) Models of exact universality, where the only effects of flavor violation and CP violation come from the Yukawa sector and enter through RGE.

(ii) Models of approximate universality, where there are genuinely new sources of flavor and CP violation which are, however, subleading to the dominant universal structure.

(iii) Models without universality, where horizontal symmetries (or large masses) suppress flavor and CP violation.

The latter class is the easiest to explore through flavor and CP violation, since it gives the largest effects. With more precise measurements we can probe stronger degrees of universality.

We would like to emphasize the following points:

(i) For supersymmetry to be established, a direct observation of supersymmetric particles is necessary. Once it is discovered, then measurements of CP violating observables will be a very sensitive probe of its flavor structure and, consequently, of the mechanism of dynamical supersymmetry breaking.

(ii) It seems possible to distinguish between models of exact universality and models with genuine supersymmetric flavor and CP violation. The former tend to give $d_N \lesssim 10^{-31}$ e cm while the latter usually predict $d_N \gtrsim 10^{-28}$ e cm.

(iii) The proximity of $a_{\psi K}$ to the SM predictions is obviously consistent with models of exact universality. It disfavors models of heavy squarks such as that of ref. [27]. Models of flavor symmetries allow deviations of order 20% (or smaller) from the SM predictions. For such new physics to be convincingly established, the hadronic uncertainties that affect the SM allowed range of $a_{\psi K}$ will be required to be reduced well below this level [28].

(iv) Alternatively, the fact that $K \rightarrow \pi \nu \bar{\nu}$ decays are not affected by most supersymmetric flavor models [29–31] is an advantage here. The Standard Model correlation between $a_{\pi \nu \bar{\nu}}$ and $a_{\psi K}$ is a much cleaner test than a comparison of $a_{\psi K}$ to the CKM constraints.

(v) The neutral $D$ system provides a stringent test of alignment. Observation of CP violation in the $D \rightarrow K \pi$ decays will make a convincing case for new physics.

III. HIGHLIGHTS OF HIGHER LUMINOSITY B FACTORIES

Considering possible outcomes of future measurements, there are different time-scales to look at. Until 2005 or so, BABAR [32] and BELLE expect to collect $\sim 0.5$ ab$^{-1}$ of data each. On this timescale the Tevatron [33] will also yield important information, most crucially $B_s$...
mixing. In the second half of the decade dedicated hadronic $b$ factories will start to operate, and the $e^+e^-$ machines may undergo upgrades to luminosities in the $10^{35} - 10^{36}$ cm$^{-2}$ sec$^{-1}$ range [34,35].

We remind the reader that the cross section of $B$ production in the $e^+e^-$ machines is $1.2$ nb, so that a luminosity of $3 \times 10^{33}$ cm$^{-2}$ sec$^{-1}$ gives $1.8 \times 10^7 B^0\bar{B}^0$ pairs (and a similar number of $B^+B^-$ pairs) in a year. For comparison, the corresponding cross section in BTeV is about $100$ µb, so that a luminosity of $2 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$ gives $2 \times 10^{11}$ $b\bar{b}$ pairs. In LHC-B the cross section is even larger.

### A. $B_s$ mixing and $|V_{ub}|$

In the Standard Model these measurements will determine the two sides of the unitarity triangle. Soon after $B_s$ mixing is observed, the experimental error on $\Delta m_d/\Delta m_s$ is expected to be reduced below the 1% level. Thus, the uncertainty of $|V_{td}/V_{ts}|$ will be dominated by the error of $(f_{B_d}/f_{B_s})\sqrt{B_{B_d}/B_{B_s}}$ from lattice QCD. This is presently at the 4 – 5% level in unquenched calculations with two light quark flavors [36], and it is important to reduce this source of uncertainty using simulations with three light flavors.

For the determination of $|V_{ub}|$ from inclusive semileptonic $B$ decays, the reconstruction of $q^2$ and $m_X$ (lepton–neutrino invariant mass and hadronic invariant mass) offers probably the smallest theoretical error [37]. The error in determining $|V_{ub}|$ from exclusive semileptonic $B$ decays will be controlled by the accuracy of unquenched lattice calculations. With $0.5$ ab$^{-1}$, a determination of $|V_{ub}|$ at the 5 – 10% level should be possible. Confidence in such a precision will come from consistency between different model independent determinations.

### B. $a_{\pi\pi}$ and $a_{\rho\pi}$

Measuring the CP asymmetries in $b \to u\bar{u}d$ transitions will add a significant constraint on the unitarity triangle. The simplest process involving a final CP eigenstate is $B \to \pi^+\pi^-$. The problem here is that the penguin contribution is nonnegligible compared to the tree contribution, $r_{PT}^{\pi\pi} \equiv P_{\pi\pi}/T_{\pi\pi} = O(0.3)$, where $P_{\pi\pi}$ and $T_{\pi\pi}$ are defined through the CKM decomposition,

$$A(B^0 \to \pi^+\pi^-) = T_{\pi\pi}V_{ub}^*V_{ud} + P_{\pi\pi}V_{tb}^*V_{td}. \quad (3.1)$$

One needs to know $r_{PT}^{\pi\pi}$ to extract the value of the CP violating phase from the CP asymmetry in $B \to \pi\pi$. This is the problem of penguin pollution.

A variety of solutions to this problem have been proposed. One type of approach is to exploit the fact that the (strong) penguin contribution to $P_{\pi\pi}$ is pure $\Delta I = \frac{1}{2}$, while the tree contribution to $T_{\pi\pi}$ contains a piece which is $\Delta I = \frac{3}{2}$. Isospin symmetry allows one to form a relation among the amplitudes $B^0 \to \pi^+\pi^-$, $B^0 \to \pi^0\pi^0$, and $B^+ \to \pi^+\pi^0$ and another one for the charge conjugate processes. A simple geometric construction then allows one to disentangle the unpolluted $\Delta I = \frac{3}{2}$ amplitudes, from which the CP violating phase may be extracted cleanly [38]. The key experimental difficulty is that one must measure accurately...
the flavor-tagged rate for $B^0 \to \pi^0\pi^0$. Since the final state consists of only four photons, and the branching fraction is expected to be of $\mathcal{O}(10^{-6})$, this is very hard.

Second, one might attempt to calculate the penguin matrix elements. Model-dependent analyses are not adequate for this purpose, since the goal is the extraction of fundamental parameters. Precise calculations of such matrix elements from lattice QCD are far in the future, given the necessity for a treatment allowing for final state interactions, the large energies of the $\pi$’s, and the need for an unquenched calculation. Recently, new QCD-based analyses of the $B \to \pi\pi$ matrix elements have been proposed [39,40].

The third type of approach is to use measurements of $B \to K\pi$ decays to determine $|P_{K\pi}|$. Once $|P_{K\pi}|$ is known, flavor $SU(3)$ is used to relate $|P_{K\pi}|$ to $|P_{\pi\pi}|$. It may also be possible to relate $B_d \to \pi^+\pi^-$ to $B_s \to K^+K^-$ (which is expected to be measured at the Tevatron) using $SU(3)$ [41]. The problem with these approaches is that some $SU(3)$ breaking corrections remain a source of irreducible uncertainty.

An alternative is to perform an isospin analysis of the process $B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$ [42–45]. Here one must study the time-dependent asymmetry over the entire Dalitz plot, probing variously the intermediate states $\rho^\pm\pi^\mp$ and $\rho^0\pi^0$. The advantage here is that the final states with two $\pi^0$’s need not be considered. On the other hand, thousands of cleanly reconstructed events would be needed. It is yet unclear how well this can be done. With integrated luminosity of 0.5 ab$^{-1}$, it is possible that a meaningful measurement will be achieved.

C. $B \to DK$ and $B \to D^*\pi$

One method of extracting the CP violating phase $\gamma$ that seems theoretically clean involves $B \to KD^0(\overline{D^0})$ decays [46,47]. The relevant quark transitions are $b \to c\bar{u}s$ and $b \to \bar{c}us$. The method requires high statistics and is probably realistic with 10 ab$^{-1}$.

The final state $D^{*+}\pi^-$ is common to $B^0$ and $\overline{B^0}$ decays. Therefore, the decay rates are sensitive to interference effects between the direct decay and the first-mix-then-decay paths, which in turn have interesting dependence on CP violating phases [48]. By measuring the four time-dependent decay rates, $B^0, \overline{B^0} \to D^{*\pm}\pi^\mp$ one can determine the amplitude ratio and the CP violating phase $2\beta + \gamma$ in a theoretically clean way.

The problem in this measurement is that

$$A(\bar{b} \to \bar{u}cd) \sim \frac{V_{ub}^*V_{cd}}{V_{cb}^*V_{ud}} \sim \lambda^2.$$ (3.2)

Thus the interference effects are small and hard to measure. Despite this difficulty, its theoretical cleanliness makes this a potentially very important measurement. With integrated luminosity of 0.5 ab$^{-1}$ the error of $\sin(2\beta + \gamma)$ is expected to be $0.15 - 0.20$ [34,49]. A similar measurement of the four time dependent rates $B_s, \overline{B_s} \to D_s^{\pm}\pi^\mp$ measures $2\beta_s + \gamma$. The advantage of this mode is that, unlike Eq. (3.2), the two amplitudes are comparable in size. The disadvantage is that because the large Cabibbo allowed $B_s \to D_s\pi$ background must be suppressed, this measurement will probably only be doable at LHCb/BTeV.

An interesting, related proposal was made in ref. [50]. The idea is to measure the angle $\gamma$ using CP tagged decays, $B_{CP} \to DK_S$. Such a measurement can only be done in a very high
luminosity $e^+e^-$ $B$ factory. If such a future collider also operates at the $\Upsilon(5S)$ resonance, it may be possible to cleanly determine $\gamma$ from time-integrated measurements of CP tagged $B_s \to D_s K$ decays as well [51].

**D. $B_s \to \psi\phi$ and $\psi\eta^{(')}$**

The CP asymmetry in these processes is the analog of $a_{\psi K}$ and measures the relative phase between $B_s$ mixing and $b \to c\bar{c}s$ decay. This is $\sin 2\beta_s$, which is presently constrained in the SM to be between 0.026 and 0.048 [52]; a larger asymmetry would be a clear sign of new physics. The expected error at CDF is about 1.6 times that of $\sin 2\beta$, further diluted by one minus twice the CP-odd fraction the $\psi\phi$ final state. Although this CP-odd contribution is expected to be small, it can be avoided by using the decay modes $B_s \to \psi\eta^{(')}$, which are pure CP-even.

**E. $a_{\phi K_S}$**

Within the Standard Model, where the Kobayashi-Maskawa phase is the only source of CP violation in meson decays, there are strong correlations between various CP asymmetries. One of the best known examples is that of the CP asymmetries in $B \to \psi K_S$ and $B \to \phi K_S$. The two decays proceed via different quark transitions, $b \to c\bar{c}s$ for the first, and $b \to s\bar{s}s$ for the latter. Yet, the Standard Model predicts that the two CP asymmetries are equal to within a few percent. This is a result of the fact that $V_{cb}V_{cs}^*$ and $V_{tb}V_{ts}^*$ are almost aligned. Within extensions of the Standard Model, the correlation can often be lost due to significant new contributions to the $b \to s\bar{s}s$ transition. For example, in supersymmetric models there could be squark-gluino penguin diagrams that compete with the SM quark–$W$ diagrams. The comparison of the two CP asymmetries can therefore cleanly signal new physics [53].

While $a_{\phi K_S}$ has already been measured, this is not the case for $a_{\psi K_S}$. The problem here is the small branching ratio [54],

$$B(B \to \phi K_S) = (8.1^{+3.3}_{-2.5} \pm 0.8) \times 10^{-6}. \quad (3.3)$$

With 0.5 ab$^{-1}$, the accuracy in the CP asymmetry is expected to be $\delta a_{\phi K_S} \sim 0.25$ [34]. The theoretical uncertainty in $a_{\phi K_S} \simeq a_{\psi K_S}$ is of order $\lambda^2 \sim 0.04$. Measuring $a_{\phi K_S}$ with such a small uncertainty requires $\sim 20\text{ ab}^{-1}$, or about two years at a $10^{36}$ cm$^{-2}$ sec$^{-1}$ $e^+e^-$ machine. This measurement may also be done at hadron colliders, but no detailed study is available.

This test of new physics would benefit from measurements of $B^+ \to \phi\pi^+$ and $B^+ \to K^+K^+$ which will constrain rescattering effects [55].

Before there is sufficient data for measuring $a_{\phi K_S}$, comparison of $a_{\psi K_S}$ with the asymmetry measured in $b \to c\bar{c}d$ modes, such as $B \to D^{(*)}D^{(*)}$, is also interesting. The sensitivity to new physics contributions to the decay amplitude is, however, smaller.

**F. $A_{SL}$**

CP violation in $B$ mixing can be measured, for example, in semileptonic decays: $A_{SL} = \left[ \frac{\Gamma(B^0(t) \to \ell^+) - \Gamma(B^0(t) \to \ell^-)}{\Gamma(B^0(t) \to \ell^+) + \Gamma(B^0(t) \to \ell^-)} \right]$ is proportional to
the relative phase between $\Gamma_{12}$ and $M_{12}$, analogous to $\text{Re}(\varepsilon_K)$ in the kaon sector. The SM predicts the relative phase to be small, suppressed by $m_{\text{c}}^2/m_W^2$ in $B_d$ mixing, and by an additional factor of $\lambda^2$ in $B_s$ mixing. The best present constraint, based on $\sim 20\,\text{fb}^{-1}$ data, is $A_{\text{SL}} = (0.48 \pm 1.85) \times 10^{-2}$ [56], while the SM prediction is at the $10^{-3}$ level [52],

$$-1.3 \times 10^{-3} < A_{\text{SL}}(\text{SM}) < -0.5 \times 10^{-3}. \quad (3.4)$$

While measuring $A_{\text{SL}}$ at the SM level seems impossible even at a very high luminosity $B$ factory, new physics could significantly enhance the asymmetry and make it observable. A model independent analysis (with the only assumption that tree level decays are dominated by SM processes) yields [52]

$$-0.004 < A_{\text{SL}}(\text{NP}) < +0.04. \quad (3.5)$$

G. $D^0 - \bar{D}^0$ mixing

Time dependent measurements of $D \rightarrow K\pi$ decays are sensitive to $D^0 - \bar{D}^0$ mixing. It is expected that, with an integrated luminosity of $0.5\,\text{ab}^{-1}$, one can be sensitive to the mixing parameters $x = \Delta m / \Gamma$ and $y = \Delta \Gamma / 2\Gamma$ at the level of $x^2 + y^2 \sim 10^{-5}$. We emphasize that a signal at that level, that is, $x, y \sim 0.003$, may come from the Standard Model long distance contributions (see, e.g. [57]). To disentangle new physics from Standard Model contributions, it is crucial to measure separately $x, y$, the relevant strong phase and, most important for this purpose, CP violation [58]. Such a program may require a high luminosity $B$-factory.

H. Rare Decays

Various rare decays provide useful measurements of the CKM parameters as well as possible probes of new physics. At present, inclusive rare decays are under better theoretical control than the exclusive ones, and Table I summarizes some of the most interesting modes. A clean theoretical interpretation of the latter requires that we know the corresponding form factors. (Note, however, that CP asymmetries are independent of the form factors.) While useful relations between various form factors can be derived from heavy quark symmetry, ultimately unquenched lattice calculations will be needed for a clean theoretical interpretation of exclusive decays. Rare $b \rightarrow s$ and $b \rightarrow d$ decays are sensitive in the SM to $|V_{td}|^2$ and $|V_{ts}|^2$, respectively. Thus the $b \rightarrow d$ rates are expected to be about a factor of $|V_{td}/V_{ts}|^2 \sim \lambda^2$ smaller than their $b \rightarrow s$ counterparts. As a guesstimate, in $b \rightarrow q l_1 l_2$ decays one expects $10 - 20\% \, K^*/\rho$ and $5 - 10\% \, K/\pi$.

In our introduction we highlighted the fact that with the measurement of $a_{\psi K}$ the KM mechanism of CP violation has passed its first precision test. We should emphasize that in the last year we have been learning that the CKM contributions to rare decays are also likely to be the dominant ones. Support to this statement comes, for example, from the measurement of $B(B \rightarrow X_s \gamma)$ which agrees with the SM at the $15\%$ level [59], the measurement of $B \rightarrow K\ell^+\ell^-$ which is in the ballpark of the SM expectation [60,61], and the
non-observation of direct CP violation in $b \to s\gamma$ at the 0.2 level [62,63]. These new results make it less likely that we will observe orders-of-magnitude enhancement of rare $B$ decays. It is more likely that only precision measurements and a broad program will be able to find signals of new physics.

(i) $B \to X_{s,d}\gamma$ or $B \to K^{*}\gamma$: provide strong limits on $m_{H^{\pm}}$ in 2HDM models, and constrain various supersymmetric models. The CP asymmetry provides additional constraints on new physics. The best limits are $-0.27 < A_{CP}(B \to X_{s}\gamma) < 0.10$ [62] and $-0.17 < A_{CP}(B \to K^{*}\gamma) < 0.08$ [63] at the 90% CL. In the former case the SM prediction is firmly below 0.01. The photon spectrum, which is not sensitive to new physics, is important for determinations of $|V_{ub}|$ and the $b$ quark mass.

(ii) $B \to X_{s,d}\ell^{+}\ell^{-}$ or $B \to K^{(*)}\ell^{+}\ell^{-}$: sensitive probes of new physics that modifies the $bsZ$ coupling. Of particular interest are the forward-backward asymmetry, the forward-backward CP asymmetry and the CP asymmetry in the rate. Remarkably, the location where the forward-backward asymmetry in $B \to K^{*}\ell^{+}\ell^{-}$ vanishes (near $q^2 = 4\text{GeV}^2$ in the SM) also provides model independent information on short distance parameters [64].

(iii) $B \to X_{s,d}\ell^{+}\ell^{-}$ or $B \to K^{(*)}\ell^{+}\ell^{-}$: probe new physics that modifies the $bsZ$ coupling, or contain unconstrained couplings between three 3rd generation fermions [66]. This mode is particularly clean (in some sense the $B$ physics analog of $K \to \pi\nu\bar{\nu}$) but experimentally very challenging.

(iv) $B \to \ell\bar{\nu}$: measures $f_B|V_{ub}|$ in the SM and is sensitive to new physics, such as charged Higgs.

(v) There are many additional useful probes of new physics, such as direct CP violation, lepton number or lepton flavor violation, $B \to \ell^{+}\ell^{-}$, etc.

| Decay mode | Approximate SM rate | Present status | Number of events assuming SM rates |
|------------|---------------------|----------------|-----------------------------------|
| $B \to X_{s}\gamma$ | $3.5 \times 10^{-4}$ | $(3.2 \pm 0.5) \times 10^{-4}$ | 11K 220K |
| $B \to K^{*}\gamma$ | $4.2 \pm 0.5 \times 10^{-5}$ | < 7.7 \times 10^{-4} | 6K 120K 170 25K |
| $B \to X_{s}\ell^{+}\ell^{-}$ | $4 \times 10^{-5}$ | < 6.5 \times 10^{-6} | 8 160 |
| $B \to X_{s}\mu^{+}\mu^{-}$ | $2 \times 10^{-7}$ | 5 \times 10^{-6} | 17 350 |
| $B \to K^{*}\ell^{+}\ell^{-}$ | $4 \times 10^{-9}$ | 7 \times 10^{-6} | 300 6K few K |
| $B \to K^{0}\ell^{+}\ell^{-}$ | $(9.5 \pm 2.7) \times 10^{-7}$ | < 10^{-8} \‡ | 100 2K 100 4K |

TABLE I. Rare decays [65]. Future estimates should be taken with some caution. The CDF/D0 column corresponds to 2 fb^{-1}, the LHCb/BTeV one to 1 year of running. \‡ Expected upper bounds.
IV. NEW PHYSICS AND FUTURE B FACTORIES

There are three important goals that can be achieved with future B-factories and will make flavor violating and/or CP violating processes excellent probes of new physics:

(i) Better precision in the measurements of processes related, for example, to the determination of $|V_{ub}|$ or of $|V_{td}/V_{ts}|$, will allow to observe small deviations from the Standard Model predictions.

(ii) Higher statistics will allow the measurement of (or improved upper bounds on) rare decays.

Within the framework of supersymmetry, the improvement in precision and sensitivity means that we will be able to explore stronger levels of universality. Models without universality, such as alignment models, may give effects of $O(\lambda)$ and are already being probed by present measurements. Models of approximate universality, such as dilaton dominance (or $U(2)$ models for the first two generations), may induce effects of $O(\alpha_s/\pi)$ (or $O(\lambda^2)$), and will begin to be probed when the experimental and theoretical accuracy reaches the few percent level. Models of exact universality, such as GMSB, give only small and calculable deviations and in large parts of their parameter space give predictions that are similar to the SM.

(iii) A Broad program will allow to learn detailed features of new physics and consequently to distinguish between various models within each class.

For example, the information from $D - \bar{D}$ mixing and $B - \bar{B}$ mixing probes whether the effects of new physics are restricted to either of the up or down sectors. The comparison of $a_{\phi K_S}$ and $a_{\psi K_S}$ probes whether the effects of new physics are restricted to either of the $\Delta B = 1$ and $\Delta B = 2$ processes. The information from $K \rightarrow \pi\nu\bar{\nu}$ decays can be confronted with that from $B$ factories to teach us whether the effects are largest for the third generation or significant also for the first two generations. The information from electric dipole moments can be added to that from $B$ factories to reveal whether new CP violation is flavor diagonal or flavor changing or both.

A new era in the study of flavor physics and CP violation has just begun. The coming decade is expected to significantly enrich our understanding of these aspects and hopefully teach us about new physics.

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