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CP Asymmetries in B^0 Decays Beyond the Standard Model*

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ABSTRACT

Of the many ingredients of the Standard Model that are relevant for the analysis of CP asymmetries in B^0 decays, some are likely to hold even beyond the Standard Model while other are sensitive to new physics. Consequently, certain predictions are maintained while other may show dramatic deviations from the Standard Model. Many classes of models may show clear signatures when the asymmetries are measured: four quark generations, Z-mediated flavor changing neutral currents, supersymmetry and "real superweak" models. On the other hand, models of left-right symmetry and multi-Higgs sectors with natural flavor conservation are unlikely to modify the Standard Model predictions.

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Measurements of CP asymmetries in B^0 decays into CP eigenstates [1] are guaranteed to provide us with most valuable information. They will address three fundamental questions:

(*i*) **Is the Kobayashi-Maskawa phase of the three generation Standard Model (SM) the only source of CP violation?**

So far, CP violation has been clearly observed only in the measurement of the ϵ-parameter in the K^0 system. While the experimental value of ϵ can be accommodated in the SM, it does not by itself test this model. CP asymmetries in B^0 decays will provide us with an observation of CP violation in a different system and are subject to a clean theoretical interpretation. Thus, they will clearly test whether the single phase of the CKM matrix is the only source of CP violation.

(*ii*) **What are the exact values of the CKM parameters?**

The parameters of the CKM matrix are important physical quantities that merit careful measurement. The determination of V_{ub} and V_{td} or, equivalently, of s_{13} and δ in the standard parametrization, is limited in accuracy due to theoretical uncertainties in modeling $b \to u$ transitions and in hadronic matrix elements (f_B). CP asymmetries in B^0 decays provide us with a unique way to measure the CKM parameters. They measure relative phases between various combinations of CKM elements. As these asymmetries are expected to be sizable, systematic errors will probably not obscure the signal. Various consistency checks will further reduce such errors. Most important, theoretically, CP asymmetries in B^0 decays are free of hadronic uncertainties.

We emphasize that even in the case that the answers to the above two questions are consistent with the SM, we will still gain most valuable information. However, in this work we are interested in the following question:

(*iii*) **Is there new physics in the quark sector?**

CP asymmetries in B^0 decays test those aspects of the quark sector that are most sensitive to the possible existence of new physics: CP violation, mixing in the neutral meson systems, and unitarity of the CKM matrix.

In the first part of this review, we describe the ingredients of the SM which are relevant to the analysis of CP asymmetries in B^0 decays. We study the prospects of these ingredients being modified in the presence of new physics. In the second part we list the classes of asymmetries that can be cleanly interpreted, and give the SM predictions for these asymmetries. We then explain which of the predictions are likely to be modified with new physics and which are maintained. In the third part, we survey specific models: Four quark generations; Z-mediated flavor changing neutral currents (FCNC); Left-Right Symmetry (LRS); Supersymmetry (SUSY); Multi-Higgs Doublets with natural flavor conservation (NFC); Real superweak contributions to B mixing. We investigate for each specific model whether it is likely to modify the SM predictions and discuss whether these modifications have unique properties.

Previous general discussions of CP asymmetries in B^0 decays beyond the SM can be found in refs. [2 – 4]. References to studies of specific models will be given in chapter 3. A comprehensive analysis of $B - \bar{B}$ mixing beyond the SM is given in ref. [5]. The present status of the SM predictions for CP asymmetries in B^0 decays is described in refs. [6 – 7].

1. The Standard Model Assumptions

The CP asymmetry in neutral B decay, A^{CP}, is the ratio

$$A^{CP}(t) = \frac{\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{CP}) - \Gamma(B^0_{\rm phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{CP}) + \Gamma(B^0_{\rm phys}(t) \to f_{CP})}. \tag{1.1}$$

$B^{(0)}_{\rm phys}$ $[\bar{B}^0_{\rm phys}(t)]$ is a is a time-evolving initially pure B^0 $[\bar{B}^0]$ state. f_{CP} is a final CP eigenstate. $\Gamma(t)$ is the time-dependent decay rate. Two ingredients of the SM are essential for any clean interpretation of a measurement of A^{CP}. (By "clean interpretation" we mean that the measured value of the asymmetry can be translated into a value of a basic parameter of the electroweak sector or its extension with no significant hadronic or other uncertainties.)

- In the neutral B system the difference in width between the two mass eigenstates is much smaller than the difference in mass, $\Gamma_{12} \ll M_{12}$.

- The direct decay is dominated by a single combination of CKM parameters (or by a single strong phase). This means that the asymmetry is a result of the interference between a direct decay $B \to f_{CP}$ and a process that involves mixing $B \to \bar{B} \to f_{CP}$.

Under these two conditions, A^{CP} depends on only two properties of the decay process: The type of the decaying neutral B, whether B_d or B_s, and the quark sub-process involved in the direct decays. Therefore, we denote an asymmetry in a B_q decay through a quark sub-process i by A^{CP}_{iq}. Under the same conditions, the asymmetries have a simple time-dependence:

$$A^{CP}_{iq}(t) = \text{Im }\lambda_{iq}\sin(\Delta M_q\ t). \tag{1.2}$$

ΔM_q is the mass difference in the B_q system, defined to be positive:

$$\Delta M_q \equiv M[B_q(\text{heavy})] - M[B_q(\text{light})]. \tag{1.3}$$

Im λ_{iq} is the amplitude of the sinusoidal time-oscillation, to be determined by experiment. λ_{iq} is a pure phase. To show what ingredients of the SM are further used to calculate λ_{iq}, we derive the specific prediction:

$$\text{Im }\lambda(B_s \to \rho K_S) = -\sin 2\gamma, \tag{1.4}$$

where γ is an angle in the unitarity triangle (see Fig. 1). The list of ingredients goes as follows:

- The direct decay $\bar{b} \to \bar{u}u\bar{d}$ is dominated by the W-mediated tree level diagram. This gives:

$$\lambda \propto \left(\frac{X}{X^*}\right); \quad X_{\bar{b}\to\bar{u}u\bar{d}} = V_{ub}V_{ud}^*. \tag{1.5}$$

- The mixing in the B_s system is dominated by a box diagram with virtual t-quarks. This gives:

$$\lambda \propto \left(\frac{Y}{Y^*}\right); \quad Y_s = V_{tb}^*V_{ts}. \tag{1.6}$$

- The mixing in the K^0 system is dominated by box diagrams with virtual c-quarks. (As B_s^0 produces a $\bar{K}^0$ and $\bar{B}_s^0$ produces a K^0, interference is possible only with $K-\bar{K}$ mixing.) This gives:

$$\lambda \propto \left(\frac{Z}{Z^*}\right); \quad Z_{\bar{K}} = V_{cd}V_{cs}^*. \tag{1.7}$$

The result is:

$$\lambda(B_s \to \rho K_S) = \left(\frac{V_{ub}V_{ud}^*}{V_{ub}^*V_{ud}}\right)\left(\frac{V_{tb}^*V_{ts}}{V_{tb}V_{ts}^*}\right)\left(\frac{V_{cd}V_{cs}^*}{V_{cd}^*V_{cs}}\right). \tag{1.8}$$

- The following unitarity constraint holds:

$$\mathcal{U}_{sb} \equiv (V_{us}^*V_{ub}) + V_{cs}^*V_{cb} + V_{ts}^*V_{tb} = 0. \tag{1.9}$$

(We put the first term in parentheses as, based on experimental information, we can safely neglect it.) This allows a simplification of (1.8):

$$\lambda(B_s \to \rho K_S) = \left(\frac{V_{ub}V_{ud}^*}{V_{ub}^*V_{ud}}\right)\left(\frac{V_{cb}^*V_{cd}}{V_{cb}V_{cd}^*}\right). \tag{1.10}$$

- The following unitarity constraint holds:

$$\mathcal{U}_{db} \equiv V_{ud}^*V_{ub} + V_{cd}^*V_{cb} + V_{td}^*V_{tb} = 0. \tag{1.11}$$

Geometrically, this relation can be represented by a triangle (see Fig. 1) with angles α, β, γ that are given by:

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]; \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]; \quad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]. \quad (1.12)$$

Thus, we derive the prediction of eq. (1.4):

$$\text{Im}\ \lambda(B_s \to \rho K_S) = -\sin 2\gamma. \quad (1.13)$$

The l.h.s of this equation will be experimentally determined: it is the amplitude of the sinusoidal oscillation in time of A^{CP}. As for the r.h.s, the SM allowed range for $\sin 2\gamma$ will be determined using information on the length of the sides of the triangle. Thus we need to assume, for example:

- Mixing in the B_d system is dominated by a box diagram with virtual t quarks and, therefore, proportional to $|V_{td}V_{tb}|$.

For any of the asymmetries that we discuss, the analysis goes along similar lines to those presented above. To discuss the sensitivity of the analysis to new physics, we divide the various ingredients into five groups, and comment on each of them in turn.

a. **In neutral B^0 systems, $\Gamma_{12} \ll M_{12}$.**

Within the SM, one can explicitly calculate the two relevant quantities (assuming that a quark-level description is appropriate):

$$\frac{\Gamma_{12}}{M_{12}} = \frac{3\pi}{2}\frac{1}{f_2(y_t)}\frac{m_b^2}{m_t^2} \sim 10^{-2}. \quad (1.14)$$

$f_2(y_t)$ is a slowly varying function of $y_t \equiv m_t^2/M_W^2$, which assumes values in the range $\{3/4, 1/4\}$ for y_t in the range $\{1, \infty\}$. However, it seems that the order of magnitude estimate holds far beyond the SM [3]. For Γ_{12} to be enhanced, one needs a new decay mechanism which significantly dominates over the W mediated decay. This is most unlikely; there seems to be no viable model that suggests such a situation. Therefore, a ratio Γ_{12}/M_{12} significantly higher than in the SM is possible only in models where M_{12} is significantly suppressed. This requires fine-tuning to cancel the known top contribution with some new physics mechanism. Again, we know of no model where a cancellation to two orders of magnitude is predicted. The argument is particularly solid for the B_d system, as it is supported by experimental evidence: $\Delta M/\Gamma \sim 0.7$, while (upper limits on) branching ratios into states which contribute to Γ_{12} are at the level of 10^{-3}.

b. **The relevant decay processes are dominated by the SM W-mediated amplitudes.**

Within the SM, there are contributions from penguin diagrams as well. If the matrix elements for the penguin operator are not significantly enhanced, then these amplitudes are suppressed by a factor of $(\alpha_s/12\pi)\ln(m_t^2/m_b^2)$ compared to the tree-level amplitudes. The situation is particularly promising in the $\bar{b} \to \bar{c}c\bar{s}$ processes, where the CKM combinations for the W-mediated and penguin amplitudes carry the same phase. It seems reasonable that for other processes (except for $\bar{b} \to \bar{u}u\bar{s}$ which we do not consider here) the effect is within 10% or less [8 – 10].

In models beyond the SM, violation of this SM assumption is possible if there is a new decay mechanism which competes with the W-mediated tree-level decay. Unlike our discussion of Γ_{12}, the effect will be important even if it is comparable to the SM diagram (and not necessarily dominating over it). However, experimental measurements of rare processes (*e.g.* $B-\bar{B}$ mixing or $B \to X\ell^+\ell^-$ decays) typically constrain the couplings or the scale of the new physics in a way which renders the contribution from the new physics to tree-level processes very small. For example, amplitudes from new physics at the 1 TeV scale typically give $\lesssim 1\%$ of the SM amplitude.

c. **$K-\bar{K}$ mixing is dominated by box-diagrams with virtual c-quarks.**

Even within the SM there is a non-negligible long-distance contribution. The important ingredient is that the relevant CKM combination is $\arg(Z) = \arg(V_{cd}^* V_{cs})$. The validity of this assumption holds far beyond the SM: Although Z may be modified with new physics, arg(Z) is not [4]. Consider the condition on mixing in the K system from the measurement of the ϵ parameter:

$$\arg(M_{12}/\Gamma_{12})(\text{mod } \pi) = 6.6 \times 10^{-3}. \tag{1.15}$$

Therefore, to an excellent approximation, M_{12} and Γ_{12} carry the same phase (mod π). Assuming that the $K \to 2\pi$ amplitude is proportional to $V_{ud}^* V_{us}$, we may use $\arg(Z) = \arg(V_{ud}^* V_{us})$ independent of the model for mixing. A new mixing mechanism will not be revealed through CP asymmetries in B^0 decays as long as

$$\arg(V_{ud}^* V_{us}) = \arg(V_{cd}^* V_{cs})(\text{mod } \pi). \tag{1.16}$$

Within any three generation model, eq. (1.16) holds to an excellent approximation due to unitarity constraints. Even within extended models, eq. (1.16) is likely to hold, but with contrived models it could be violated.

d. $B - \bar{B}$ **mixing is dominated by box-diagrams with virtual** t**-quarks.**

The SM box-diagram is suppressed by being fourth-order in the weak coupling and by small mixing angles (the GIM mechanism). Thus, it is not unlikely that new physics contributions, even when suppressed by a high energy scale, will compete with or even dominate over the SM diagram. Indeed, in many models, a new such mechanism for mixing of neutral B's is suggested. If this is the case, there are two possibilities:

(i) The phase of the new mixing mechanism is the same as that of the SM mechanism. Consequently, the SM predictions for A^{CP} will not be violated, even though there is new physics in the relevant processes.

(ii) The phase of the new mixing mechanism is different from the SM mechanism. Consequently, CP asymmetries in B^0 decays may be very different from the SM predictions. They no longer measure the relative phase between the CKM combinations that determine the decay and the mixing. Instead they measure the relative phase between the CKM combination that determines the decay and the phase from new physics that determines the mixing. As these new phases have no experimental constraints, their effect could be rather dramatic, *e.g.* give maximal asymmetry where the SM predicts zero asymmetry.

e. **The three generation CKM matrix is unitary.**

The relevant unitarity constraints are:

$$\mathcal{U}_{qb} \equiv \sum_{k=1}^{3} V_{kb} V_{kq}^* = 0; \quad q = d, s. \tag{1.17}$$

We would like to argue that there is a connection between the three generation unitarity constraints and mixing in the B system. More specifically, if $\mathcal{U}_{sb} \neq 0$ [$\mathcal{U}_{db} \neq 0$], there will be significant contributions from beyond the SM to $B_s - \bar{B}_s$ [$B_d - \bar{B}_d$] mixing [4]. If the full spectrum of colored fermions consists of the three known generations of quarks, the 3×3 CKM matrix is unitary, and all the constraints hold. There are two basic ways to extend the quark sector, thus allowing a violation of the unitarity constraints:

1. Adding sequential quarks, namely left-handed doublets and right-handed singlets. With n generations, the CKM matrix is a sub-matrix of an $n \times n$ unitary mixing matrix. The relevant unitarity constraints of eq. (1.17) are replaced by:

$$\mathcal{U}_{qb} = -\sum_{k=4}^{n} V_{kb} V_{kq}^*. \tag{1.18}$$

At the same time, the u_k quark contributes to $B_q - \bar{B}_q$ mixing through box-diagrams proportionally to $(V_{kb} V_{kq}^*)^2$. This contribution is enhanced by m_k^2/m_t^2.

2. Adding non-sequential quarks. The charged current mixing matrix is non-unitary, and consequently there are flavor changing neutral currents. The best-known example is the model with an $SU(2)_L$ singlet of charge -1/3 quark. In this

case, the unitarity constraints are modified to

$$\mathcal{U}_{qb} = U_{qb}, \tag{1.19}$$

where U_{qb} is a flavor-changing coupling of the Z^0 gauge boson. At the same time, there is a contribution to $B_q - \bar{B}_q$ mixing from tree-level Z-mediated diagrams, proportional to $(U_{qb})^2$. This contribution is enhanced because it appears at tree-level.

The conclusion is that a small violation of the unitarity constraints usually gives a significant new contribution to $B - \bar{B}$ mixing. For CP asymmetries in B^0 decays, this second effect is the one that may give substantial deviations from the SM predictions.

To summarize: When we survey models of new physics for possible violation of the SM predictions for CP asymmetries in B^0 decays, the main questions to be asked are:

1. Is there a possibility of a new mechanism for mixing of neutral B's?
2. Does this mechanism carry new phases?

We also check the following aspects:

3. Is unitarity of the 3×3 CKM matrix violated?
4. Are there significant new contributions to the direct $B \to f_{CP}$ decays?

2. Modifications of the SM Predictions

Our study involves those classes of asymmetries for which, within the SM, the direct decay is expected to be dominated by a single combination of CKM parameters. The asymmetries are denoted by Im λ_{iq}. The sub-index $i = 1, \ldots, 5$ denotes the quark sub-process. The sub-index $q = d, s$ denotes the type of decaying meson, B_q. In Tables I and II we list CP asymmetries in B_d and B_s decays, respectively. The list of hadronic final states gives examples only. Other states may be more favorable experimentally. We always quote the CP asymmetry for CP-even states, regardless of the specific hadronic state listed.

TABLE I

CP Asymmetries in B_d Decays

Class (iq)	Quark sub-process	Final state (example)	SM prediction
$1d$	$\bar{b} \to \bar{c}c\bar{s}$	ψK_S	$-\sin 2\beta$
$2d$	$\bar{b} \to \bar{c}c\bar{d}$	D^+D^-	$-\sin 2\beta$
$3d$	$\bar{b} \to \bar{u}u\bar{d}$	$\pi^+\pi^-$	$\sin 2\alpha$
$4d$	$\bar{b} \to \bar{s}s\bar{s}$	ϕK_S	$-\sin 2\beta$
$5d$	$\bar{b} \to \bar{s}s\bar{d}$	$K_S K_S$	0

TABLE II

CP Asymmetries in B_s Decays

Class (iq)	Quark sub-process	Final state (example)	SM prediction
$1s$	$\bar{b} \to \bar{c}c\bar{s}$	$D_s^+D_s^-$	0
$2s$	$\bar{b} \to \bar{c}c\bar{d}$	ψK_S	0
$3s$	$\bar{b} \to \bar{u}u\bar{d}$	ρK_S	$-\sin 2\gamma$
$4s$	$\bar{b} \to \bar{s}s\bar{s}$	$\eta'\eta'$	0
$5s$	$\bar{b} \to \bar{s}s\bar{d}$	ϕK_S	$\sin 2\beta$

From our general analysis in the previous section, it follows that in most models of new physics:

- λ_{iq} is of the form ($|\lambda_{iq}| = 1$):

$$\lambda_{iq} = \left(\frac{X_i}{X_i^*}\right)\left(\frac{Y_q}{Y_q^*}\right)\left(\frac{Z_{iq}}{Z_{iq}^*}\right). \qquad (2.1)$$

  The X_i-factor depends on the quark sub-process amplitude. The Y_q-factor depends on the mixing amplitude of the decaying meson. The Z_{iq}-factor (which differs from 1 only for final states with an odd number of neutral kaons) depends on the $K-\bar{K}$ mixing amplitude.

- The X_i factor is given by

$$\begin{aligned} X_1 &\equiv X(\bar{b}\to\bar{c}c\bar{s}) = V_{cb}V_{cs}^*, \\ X_2 &\equiv X(\bar{b}\to\bar{c}c\bar{d}) = V_{cb}V_{cd}^*, \\ X_3 &\equiv X(\bar{b}\to\bar{u}u\bar{d}) = V_{ub}V_{ud}^*. \end{aligned} \qquad (2.2)$$

  For classes $i = 4,5$, the dominant direct decay mechanism within the SM is the penguin amplitude. We include them in the tables for completeness, but will not discuss them in detail. A detailed analysis is given in ref. [11].

- The Z_{iq} factor is given by:

$$\begin{aligned} Z_{2d} &= Z_{3d} = Z_{5d} = Z_{1s} = Z_{4s} = 1, \\ Z_{1d} &= Z_{4d} = Z_{2s}^* = Z_{3s}^* = Z_{5s}^* = V_{ud}^*V_{us}. \end{aligned} \qquad (2.3)$$

On the other hand:

◇ arg[Y_d] and arg[Y_s] may differ significantly from the SM values, if there are new contributions to the mixing of neutral B's, and if these contributions carry new phases.

◇ The unitarity constraints on $\mathcal{U}_{db}$ and $\mathcal{U}_{sb}$ may be significantly violated in models of extended quark sector.

Within the SM, the asymmetries measure angles in the complex plane between various combinations of the charged current mixing matrix, as those determine both b decays and $B_q - \bar{B}_q$ mixing. These angles are calculated within the SM on the basis of direct measurements and unitarity of the CKM matrix. Within models of new physics, unitarity of the charged current mixing matrix may be lost, but this is not the main reason for the asymmetries being modified. The reason is rather that, when $B_q - \bar{B}_q$ mixing has significant contributions from new physics, the asymmetries measure different quantities, namely angles between combinations of elements of the charged current mixing matrix determining b decays and elements of mixing matrices in sectors of new physics (squarks, multi-Higgs, etc.) which determine $B_q - \bar{B}_q$ mixing.

In view of these observations, let us examine which of the predictions of Tables I and II are likely to hold and which may be violated with new physics [4, 11].

The predictions

$$\text{Im } \lambda_{1d} = \text{Im } \lambda_{2d}, \quad \text{Im } \lambda_{1s} = \text{Im } \lambda_{2s}, \tag{2.4}$$

do not depend on the mixing mechanism for neutral $B's$. Instead, they depend only on the mechanism for tree-level decays and for $K - \bar{K}$ mixing. They will hold as long as $\arg[X_1] + \arg[Z_{1q}] = \arg[X_2] + \arg[Z_{2q}]$. As explained above, this relation will hold in all but some very contrived models with both new mechanism for $K - \bar{K}$ mixing and extended quark sector.

The predictions

$$\text{Im } \lambda_{1d} = \text{Im } \lambda_{4d}, \quad \text{Im } \lambda_{1s} = \text{Im } \lambda_{4s}, \tag{2.5}$$

do not depend on the mixing mechanism for neutral $B's$. Instead, they depend only on the mechanism for direct decays and the unitarity constraint $\mathcal{U}_{sb} = 0$. They are likely to be violated in any model with $\mathcal{U}_{sb} \neq 0$. Similarly, certain relations between asymmetries in classes $i = 2, 3$ and $i = 5$ will be violated if $\mathcal{U}_{db} \neq 0$.

The prediction

$$\text{Im } \lambda_{1s} = 0 \tag{2.6}$$

depends on the mechanism for tree-level decays, on the unitarity constraint $\mathcal{U}_{sb} = 0$ and on the mechanism for B_s mixing. It is likely to be violated in models with new phases in $B_s - \bar{B}_s$ mixing.

The predictions

$$\text{Im } \lambda_{2d} = -\sin(2\beta), \quad \text{Im } \lambda_{3d} = \sin(2\alpha), \tag{2.7}$$

depend on the mechanism for tree-level decays, on the unitarity constraint $\mathcal{U}_{db} = 0$ and on the mechanism for B_d mixing. They are likely to be violated in models with new phases in $B_d - \bar{B}_d$ mixing.

Finally, we note that the three angles deduced from measurements of the Im λ_{1d}, Im λ_{3d} and Im λ_{3s} will sum up to 180^o whenever the amplitude for $B_s - \bar{B}_s$ mixing is real [4]. This is independent of whether they correspond to the angles of the unitarity triangle or not.

3. Models of New Physics

We now briefly survey relevant models of new physics. As explained in previous sections, we look for violation of the unitarity constraints:

$$\mathcal{U}_{db} = 0; \quad \mathcal{U}_{sb} = 0, \tag{3.1}$$

and, more important, for new contributions to $B_q - \bar{B}_q$ mixing which are at least comparable to the SM contribution:

$$M_{12}^t(B_q) = \frac{G_F^2}{12\pi^2}\eta M_B(B_B f_B^2) M_W^2 y_t f_2(y_t)(V_{tb}^* V_{tq})^2. \tag{3.2}$$

1. **Four quark generations** [12 – 15]:

There are no new tree-level contributions to b decays. Thus, Γ_{12} remains unmodified and the direct tree-level decays are still dominated by the W-mediated diagrams. Unitarity of the CKM matrix is violated:

$$\mathcal{U}_{qb} = -V_{t'b}V^*_{t'q}. \tag{3.3}$$

There could be significant new contributions to $B_q - \bar{B}_q$ mixing. For example, a box-diagram with virtual t' quarks contributes:

$$M^{t'}_{12}(B_q) = \frac{G_F^2}{12\pi^2}\eta M_B(B_B f_B^2)M_W^2 y_{t'} f_2(y_{t'})(V^*_{t'b}V_{t'q})^2. \tag{3.4}$$

The full (4×4) mixing matrix has three independent phases, which could appear in M_{12}.

2. Z**-mediated flavor changing neutral currents (FCNC)** [16]:

There are tree-level Z-mediated contributions to b decays. Experimental constraints imply that they are below 10% of the W diagram for $i = 1$, but could be as large as 20% for $i = 2, 3$. Although Γ_{12} has new contributions from Z mediated diagrams, it is not expected to be enhanced. The direct decays are still dominated by the W-mediated diagrams, but the theoretical analysis of $b \to d$ processes may be less solid. Unitarity of the CKM matrix is violated:

$$\mathcal{U}_{qb} = U_{qb}, \tag{3.5}$$

where U_{qb} is a non-diagonal Z-coupling. There could be significant new contributions to $B_q - \bar{B}_q$ mixing from tree-level diagrams:

$$M^{Z}_{12}(B_q) = \frac{\sqrt{2}G_F}{12}\eta M_B(B_B f_B^2)(U^*_{qb})^2. \tag{3.6}$$

There are new independent phases in the neutral current mixing matrix which could appear in M_{12}.

3. **Multi-Higgs doublets with natural flavor conservation (NFC):**

There are tree-level ϕ^+-mediated contributions to b decays. Experimental limits on the mass of the charged Higgs imply that they are negligible. Thus, there is no significant effect on Γ_{12} and on the direct decays. Unitarity of the CKM matrix is maintained. There could be significant new contributions to $B_q - \bar{B}_q$ mixing from box-diagrams with charged Higgs. In a general n-doublet model with NFC, the couplings of the physical charged scalars to quarks are given by [17]:

$$\mathcal{L} = \sum_{k=2}^{n} \frac{g_2 \phi_k^+}{2\sqrt{2} M_W} \bar{U}[-(Y_{1k}/Y_{11}) M_u V(1-\gamma_5) + (Y_{2k}/Y_{21}) V M_d (1+\gamma_5)] D + h.c. \quad (3.7)$$

Y is the matrix that rotates the mass eigenstates charged scalars to the interaction eigenbasis. Without loss of generality we took ϕ_1^+ to be the Goldstone boson. The Y-matrix introduces new phases which are not related to those of V_{CKM}. However, the leading contribution from ϕ_k^+-exchange diagrams to $B - \bar{B}$ mixing comes from the term proportional to m_t. This gives $(Y_{1k} V_{td})(Y_{1k} V_{tb})^*$, and has exactly the same phase as the SM W-exchange contribution. Consequently, $\arg(M_{12})$ remains unmodified.

It is amusing to note that in the multi-scalar models with NFC and with spontaneous CP violation (SCPV), where $\delta_{KM} = 0$ (so that the unitarity triangle becomes a line), CP asymmetries in classes $i = 1, 2, 3$ all vanish. (This was shown in detail for $B \to \psi K_S$ in ref. [18]. A more general discussion of the $\delta_{KM} = 0$ case is given in ref. [2].) However, it seems that with the new limits on scalar masses from LEP, this class of models is phenomenologically excluded.

4. **Left-Right Symmetry (LRS)** [19 – 20]:

There are tree-level W_R-mediated contributions to b decays. Experimental limits on the mass of W_R imply that they are negligible. Thus, there is no significant effect on Γ_{12} and on the direct decays. Unitarity of the CKM matrix is maintained. The experimental limits on $M(W_R)$ from $K - \bar{K}$ mixing and the relations between the mixing matrices for W_L and W_R interactions imply that there could be no significant new contributions to $B_q - \bar{B}_q$ mixing. The only way to evade these conclusions is by giving up the left-right symmetry (namely, a model of $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetry but no discrete $L \leftrightarrow R$ symmetry), and even then one needs to fine-tune the quark sector parameters.

5. **Supersymmetry (SUSY)** [21]:

There are no new tree-level contributions to b decays. Thus, Γ_{12} remains unmodified and the direct tree-level decays are still dominated by the W-mediated diagrams. Unitarity of the CKM matrix is maintained. There could be significant new contributions to $B_q - \bar{B}_q$ mixing from box-diagrams with intermediate gluinos and squarks. Whether these box diagrams carry phases that are different from those of the SM box diagrams depends on the specific SUSY model. In the *minimal* SUSY model, only left-handed squarks (namely, superpartners of left-handed quarks) contribute. The couplings $\tilde{g}\tilde{d}_{Li}\tilde{d}_{Lj}$ are proportional to the CKM element V_{ij} and thus no new phases are introduced:

$$M_{12}^{\tilde{g}}(B_q) = \frac{\alpha_s^2}{27m_{\tilde{g}}^2} B f_B^2 M_B (V_{td}V_{tb}^*)^2 \Delta S_t(m_{\tilde{d}}, m_{\tilde{b}}, m_{\tilde{g}}). \tag{3.8}$$

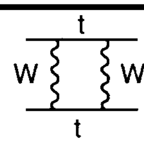
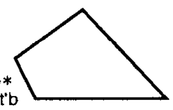
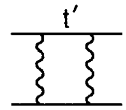
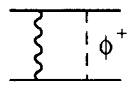
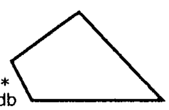
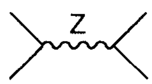
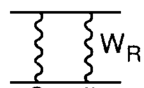
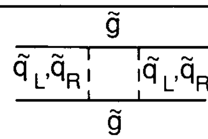
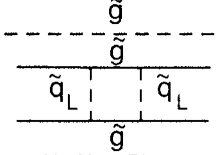
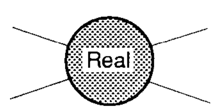
The function ΔS_t can be found, for example, in ref. [5]. Thus CP asymmetries are not modified in minimal SUSY models. However, in less restrictive SUSY models, there are contributions from box-diagrams with right-handed squarks as well. The mixing matrices are not related to V_{CKM} and carry, in general, new phases [22]. We emphasize that (unlike our discussion of LRS models), the difference between minimal and extended SUSY models is only in simplicity and predictive power, but not in the basic theoretical principles, and thus extended models are not less motivated than the minimal ones.

6. **"Real Superweak" models** [2]:

This generic framework assumes that $\Delta B = 1$ processes are dominated by the SM amplitudes, but $\Delta B = 2$ processes may have significant new contributions. The only assumption additional to our general discussion in chapter 1 is that these new contributions are real. This means that the phases from the direct decays ($\arg X$) remain the same as in the SM. As for the mixing, while the phase in B_s mixing ($\arg Y_s$) remains the same, the phase in B_d mixing ($\arg Y_d$) is reduced. Consequently, this model predicts no modification of the SM prediction for asymmetries in B_s decays; a reduction in the asymmetry in $B \to \psi K_S$; and a modification (in either direction) of the asymmetry in $B \to \pi^+\pi^-$. This model demonstrates a general feature noted in ref. [4]: Even though the measurements of $B \to \psi K_S$ and $B \to \pi^+\pi^-$ do not measure β and α anymore, the angles deduced from these measurements will sum up with γ (deduced correctly from $B_s \to \rho K_S$) to 180^o. This is guaranteed by the B_s mixing amplitude being real.

A summary of our conclusions is given in Table III. The second column describes, for each model, whether unitarity of the three generation CKM matrix is maintained (a triangle) or violated (a quadrangle). The third column gives an example of a new contribution to $B_q - \bar{B}_q$ mixing. Unless otherwise mentioned, the contribution could be large and carry new phases.

The measurement of CP asymmetries in B^0 decays should constitute a whole program: the more classes of asymmetries measured, the better we understand the detailed nature of new physics which may account for deviations from the SM predictions.

Model	CKM Unitarity	B - $\bar{B}$ Mixing	SM Predictions for A^{CP}
SM			
Four Quark Generations			Modified
Multi-Scalar with NFC (General)			Unmodified
(+ SCPV)		No New Phases	All Asymmetries Vanish
Z-Mediated FCNC			Modified
LRS		 Small	Unmodified
SUSY (General)			Modified
(Minimal)		 No New Phases	Unmodified
"Real Superweak"			Modified for B_d Unmodified for B_s

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22. See *e.g.* Y. Nir, Nucl. Phys. B273 (1986) 567.

FIGURE CAPTIONS

Figure 1. The unitarity triangle. Relevant classes of CP asymmetries are indicated for each angle (see Tables I and II).

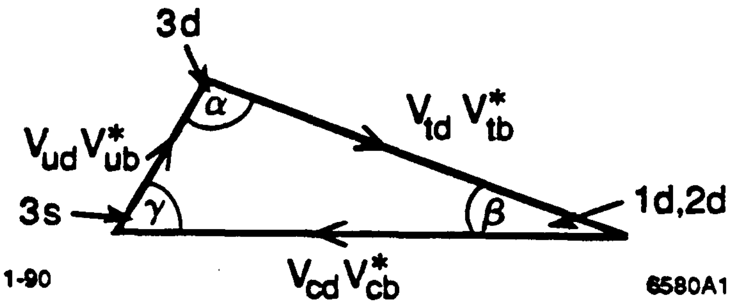

Fig. 1