On Supersymmetric CP Violation

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We discuss the discovery potential for New Physics of various measurements of CP violation. If nature is supersymmetric, then the flavor problem is even more mysterious than in the standard model. We show how we can learn about the mechanism that solves the supersymmetric flavor problem from measurements of mixing and CP violation in $K$, $D$ and $B$ decays.

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1. Introduction

One of the most intriguing aspects of high energy physics is CP violation. On the experimental side, it is one of the least tested aspects of the Standard Model. There is only one (complex) CP violating parameter that is unambiguously measured \( \epsilon \), that is the \( \epsilon \) parameter in the neutral \( K \) system. A genuine testing of the Kobayashi-Maskawa picture of CP violation in the Standard Model awaits the building of \( B \) factories that would provide a second, independent measurement of CP violation. On the theoretical side, the Standard Model picture of CP violation has two major difficulties. First, CP violation is necessary for baryogenesis, but the Standard Model CP violating processes are much too weak to produce the observed asymmetry of the Universe. Simple extensions of the Standard Model do provide large enough sources of CP violation that can be consistent with the observed asymmetry. Second, an extreme fine-tuning is needed in the CP violating part of the QCD Lagrangian in order that its contribution to the electric dipole moment of the neutron does not exceed the experimental upper bound. This suggests that an extension of the Standard Model, such as a Peccei-Quinn symmetry or a horizontal symmetry that guarantees \( m_u = 0 \), is required.

The implications of baryogenesis for CP violation are particularly interesting. GUT baryogenesis, while providing very plausible mechanisms for Sakharov’s requirements (\( B \) nonconserving interactions, violation of both C and CP, and departure from thermal equilibrium), runs into serious difficulties. In particular, any baryon asymmetry produced prior to inflation is washed out by inflation. For GUT scale baryogenesis to occur after inflation requires a high reheat temperature \( T_{\text{rh}} \). Constraints from structure formation, \( T_{\text{rh}} \lesssim 10^{12} \text{ GeV} \ll m_{\text{GUT}} \) and (within supergravity models) from Nucleosynthesis constraints, \( T_{\text{rh}} \lesssim 10^{10} \text{ GeV} \left( m_{\text{grav}}/100 \text{ GeV} \right) \), make this unlikely. Moreover, electroweak processes at \( T = \mathcal{O}(\text{TeV}) \) might completely wash out an earlier generated baryon asymmetry with initially vanishing \( B - L \). These problems suggest that the processes that are responsible to the observed baryon asymmetry have taken place at temperatures of the order of the electroweak scale.

Remarkably, the Standard Model itself has the potential of dynamically generating baryon asymmetry. However, departure from thermal equilibrium can only occur at
the electroweak epoch if there is a sufficiently strong first order phase transition. This requires a light SM Higgs, below the experimental bound, or an extension of the Higgs sector. More important to our discussion is the fact that CP violation in the Standard Model is far too small \cite{10,11}. It allows at best $n_B/s \simeq 10^{-20}$, and perhaps a lot less. Simple extensions of the Standard Model, such as the Minimal Supersymmetric Standard Model or Two Higgs Doublet Models, have extended Higgs sectors that do allow a first order phase transition, and new sources of CP violation that could be consistent with the observed $n_B/s$, but only if the new phases are not too small.

The conclusion then is that it is not unlikely that there exist large, new sources of CP violation at the electroweak scale. This makes the experimental search for CP violation in all its possible low energy manifestations a very exciting direction of research. We note, however, that CP violating phases that can account for the baryon asymmetry are most likely to be probed in measurements of electric dipole moments. It is very difficult to induce large enough baryogenesis with flavor dependent phases of the type that may affect CP asymmetries in $B^0$ decays.

In this work, we focus on supersymmetry as an example of New Physics which potentially affects CP violation. We will discuss in detail CP violation in neutral meson mixing. We will not discuss the implications of supersymmetry on electric dipole moments. We would like to mention, however, that supersymmetric theories have at least two new flavor-diagonal CP violating phases \cite{12,13}. While these phases could generate the observed baryon asymmetry \cite{14}, they also typically give an electric dipole moment of the neutron that is two orders of magnitude above the experimental bound. Most supersymmetric models simply fine tune the new phases to zero (though models with naturally small phases have been constructed \cite{15,21,13}). If supersymmetry exists in Nature, and if the supersymmetric phases are indeed responsible for baryogenesis, the phases cannot be much below the bound. This means that the on-going search for $d_N$ may well yield a signal. Alternatively, improved upper bounds on $d_N$ become more and more of a serious problem to the supersymmetric framework.
2. CP Violation in Neutral Meson Systems

We are mainly interested in pairs of decay processes that are related by a CP transformation. If $B$ and $\bar{B}$ are CP conjugate mesons and $f$ and $\bar{f}$ are CP conjugate states, then we denote by $A$ and $\bar{A}$ the two CP conjugate decay amplitudes:

$$ A = \langle f | H | B \rangle, \quad \bar{A} = \langle \bar{f} | H | \bar{B} \rangle. \quad (2.1) $$

We define $p$ and $q$ ($|p|^2 + |q|^2 = 1$) as the components of the two neutral interaction eigenstates $B^0$ and $\bar{B}^0$ in the mass eigenstates $B_1$ and $B_2$:

$$ |B_1\rangle = p |B^0\rangle + q |\bar{B}^0\rangle, \quad |B_2\rangle = p |B^0\rangle - q |\bar{B}^0\rangle. \quad (2.2) $$

We define a quantity $\lambda$,

$$ \lambda = \frac{q}{p} \frac{\bar{A}}{A}. \quad (2.3) $$

The three quantities $|\bar{A}/A|$, $|q/p|$ and – for final CP eigenstates – $\lambda$ are independent of phase conventions and correspond to three distinct types of CP violation.

(i) CP violation in decay:

$$ |\bar{A}/A| \neq 1. \quad (2.4) $$

This is a result of interference between various decay amplitudes that lead to the same final state. It can be observed in charged meson decays. The processes that are likely to have non-negligible effects are decays with suppressed tree contributions, e.g. $B \to \rho K$, decays with no tree contributions, e.g. $B \to \phi K$ and $B \to KK$, and radiative decays. A theoretical calculation of this type of CP violation,

$$ \left| \frac{\bar{A}}{A} \right| = \left| \sum_i A_i e^{i\delta_i} e^{-i\phi_i} \right| \left| \sum_i A_i e^{i\delta_i} e^{+i\phi_i} \right|, \quad (2.5) $$

requires knowledge of strong phase shifts $\delta_i$ and absolute values of amplitudes $A_i$ to extract the weak, CP violating phases $\phi_i$. Consequently, it involves large hadronic uncertainties.

(ii) CP violation in mixing:

$$ |q/p| \neq 1. \quad (2.6) $$
This is a result of the mass eigenstates being non-CP eigenstates. It can be observed in semileptonic neutral meson decays. A theoretical calculation of this type of CP violation, 

\[ \left| \frac{q}{p} \right|^2 = \left| \frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}} \right|, \]  

(2.7)

requires knowledge of \( B_K \) in the \( K \) system or \( \Gamma_{12} \) in the \( B \) system. Consequently, it involves large hadronic uncertainties.

(iii) CP violation in the interference of mixing and decay:

\[ \lambda \neq 1. \]  

(2.8)

In particular, we mean here \( |\lambda| = 1 \) and \( \text{Im}\lambda \neq 0 \). This is a result of interference between the direct decay into a final state and the first-mix-then-decay path to the same final state. It can be observed in decays of neutral mesons into final CP eigenstates. A theoretical calculation of this type of CP violation could be theoretically very clean, provided that two conditions are met:

a. \( A \) is dominated by a single weak phase, so that CP violation in decay has no effect.

b. \( \text{Im}\lambda \gg 10^{-3} \), so that the effect of CP violation in mixing is negligible.

The \( K \to \pi^+\pi^- \) decays satisfy the first condition, but \( \text{Im}\lambda(K \to \pi\pi) \sim 10^{-3} \), which is the reason why we do not have a very clean determination of the Kobayashi-Maskawa phase from the \( K \) system. On the other hand, both conditions are satisfied in various \( B \) decays, e.g. \( B \to \psi K_S \) and (with isospin analysis) \( B \to \pi\pi \). This is why \( B \) factories would enable us to determine \( \sin 2\alpha \) and \( \sin 2\beta \) very cleanly.

We conclude that CP asymmetries in neutral \( B \) decays are a unique tool for discovering New Physics: due to their theoretical cleanliness, they are sensitive to New Physics even if it gives a contribution that is comparable to the Standard Model one. Other CP violating observables in meson decays (and, similarly, the electric dipole moment of the neutron) can clearly signal New Physics only if the new contribution is much larger than that of the Standard Model.

3. The \( K \) System

The smallness of Flavor Changing Neutral Current (FCNC) processes (particularly \( \Delta m_K \)) and of CP violation (particularly \( \epsilon \)) in the \( K \) system provides severe tests and puts
stringent constraints on extensions of the Standard Model. In this section we discuss the impact of $K$ physics on supersymmetric models building. But first, we explain which types of CP violation contribute to $\epsilon$ and to $\epsilon'$.

3.1. The $\epsilon$ and $\epsilon'$ Parameters

The two CP violating quantities measured in the neutral $K$ system are

$$\eta_{00} = \frac{\langle \pi^0 \pi^0 | H | K_L \rangle}{\langle \pi^0 \pi^0 | H | K_S \rangle}, \quad \eta_{+-} = \frac{\langle \pi^+ \pi^- | H | K_L \rangle}{\langle \pi^+ \pi^- | H | K_S \rangle}.$$  \hspace{1cm} (3.1)

We define

$$A_{00} = \langle \pi^0 \pi^0 | H | K^0 \rangle, \quad \bar{A}_{00} = \langle \pi^0 \pi^0 | H | \bar{K}^0 \rangle,$$

$$A_{+-} = \langle \pi^+ \pi^- | H | K^0 \rangle, \quad \bar{A}_{+-} = \langle \pi^+ \pi^- | H | \bar{K}^0 \rangle,$$  \hspace{1cm} (3.2)

$$\lambda_{00} = (q/p)(\bar{A}_{00}/A_{00}), \quad \lambda_{+-} = (q/p)(\bar{A}_{+-}/A_{+-}).$$

Then

$$\eta_{00} = \frac{1 - \lambda_{00}}{1 + \lambda_{00}}, \quad \eta_{+-} = \frac{1 - \lambda_{+-}}{1 + \lambda_{+-}}.$$  \hspace{1cm} (3.3)

These quantities get contributions from all three types of CP violation. It is interesting then to understand the relative magnitude of each effect and the possibility of separating them. For this purpose, it is convenient to discuss $\epsilon$ and $\epsilon'$ instead of $\eta_{00}$ and $\eta_{+-}$.

The $\epsilon$ parameter is defined by

$$\epsilon \equiv \frac{1}{3}(\eta_{00} + 2\eta_{+-}) = \frac{1}{1 + \lambda_0},$$  \hspace{1cm} (3.4)

where $\lambda_0$ corresponds to the decay into final $(\pi\pi)_{I=0}$ state, and the second equation holds to first order in $A_2/A_0$. As, by definition, only one strong channel contributes to $\lambda_0$, there is no contribution to (3.4) from CP violation in decay. A careful analysis shows that $\text{Re}\epsilon$ is related to CP violation in mixing ($|q/p| \neq 1$) while $\text{Im}\epsilon$ is related to CP violation in the interference of mixing and decay ($\arg[(q/p)(\bar{A}_{00}/A_{00})] \neq 0$). The two effects are comparable in magnitude.

The $\epsilon'$ parameter is defined by

$$\epsilon' \equiv \frac{1}{3}(\eta_{+-} - \eta_{00}) \approx \frac{1}{6}(\lambda_{00} - \lambda_{+-}).$$  \hspace{1cm} (3.5)
The effect of $|q/p| \neq 1$ is negligible, so that to a good approximation there is no contribution to (3.5) from CP violation in mixing. A careful analysis shows that $\text{Re} \epsilon'$ is related to CP violation in decay while $\text{Im} \epsilon'$ is related to CP violation in the interference of mixing and decay [22]. The two effects are comparable in magnitude.

3.2. Supersymmetry: Universality and Alignment

Supersymmetric extensions of the Standard Model predict large new contributions to FCNC processes. Squarks and gluinos contribute to $\Delta m_K$ and to $\epsilon$ through box diagrams. A possible suppression due to large quark and gluino masses is easily compensated for by three enhancement factors:

(i) matrix elements of new four-quark operators are enhanced due to their different Lorentz structure;

(ii) the weak coupling of the Standard Model diagrams is replaced by the strong coupling;

(iii) the GIM mechanism does not operate for generic squark masses.

The resulting contributions are so large, even for squark masses as heavy as 1 TeV, that $\Delta m_K$ and $\epsilon$ severely constrain the form of squark mass matrices $[23-26]$. A convenient way to present these constraints is the following. Define $K_d^L$ to be the mixing matrix in the coupling of gluinos to left-handed down quarks and ‘left-handed’ down squarks and similarly $K_d^R$ (for simplicity, we neglect here L-R mixing among squarks). Define $\bar{m}^2$ to be the average squark mass. Then, $\Delta m_K$ and $\epsilon$ constrain the following quantities:

$$(\delta_{MM}^d)_{12} \approx (K_{MM}^d)_{11} (K_{MM}^d)^* \frac{\bar{m}_{d_{M2}}^2 - \bar{m}_{d_{M1}}^2}{m^2}, \quad M = L, R.$$ (3.6)

With $m_{\tilde{d}} = m_{\tilde{g}} = 500$ GeV, ref. [26] quotes

$$\Delta m_K \Rightarrow \sqrt{|\text{Re}(\delta_{LL}^d)_{12}^2|} \lesssim 4 \times 10^{-2}, \quad \sqrt{|\text{Re}(\delta_{LL}^d)_{12}(\delta_{RR}^d)_{12}|} \lesssim 3 \times 10^{-3};$$

$$\epsilon_K \Rightarrow \sqrt{|\text{Im}(\delta_{LL}^d)_{12}^2|} \lesssim 3 \times 10^{-3}, \quad \sqrt{|\text{Im}(\delta_{LL}^d)_{12}(\delta_{RR}^d)_{12}|} \lesssim 2 \times 10^{-4}.$$ (3.7)

The natural expectation in a generic supersymmetric model is that mixing angles, mass splittings and phases are of $O(1)$, namely $\text{Re} (\delta_{MM}^d)_{12} = O(1)$ and $\text{Im} (\delta_{MM}^d)_{12} = O(1)$, which would violate (3.7) by some four orders of magnitude. Two ways of achieving $(\delta_{MM}^q)_{ij} \ll 1$ (for $i \neq j$) have been suggested:
1. **Universality** [27-28]: The supersymmetry breaking scalar masses are universal among generations, so that the mass matrices $\tilde{M}^2_{d_L}$, $\tilde{M}^2_{d_R}$ are proportional to 1 and thus diagonal in any basis. This is achieved in models where the supersymmetry breaking is communicated by supergravity [29-31]; in models where supersymmetry is broken at a low scale and communicated through the Standard Model gauge interactions [32-33]; no-scale supergravity and other models [34-35]; and (for the first two generations) in models of non-Abelian horizontal symmetries [36-38,17].

2. **Alignment** [39]: The squark mass matrices have a structure, but they have a reason to be diagonal in the basis set by the quark mass matrix. This is achieved in models of Abelian horizontal symmetries [39,40] or dynamically [41].

Ref. [42] describes a systematic experimental program to determine the mechanism of supersymmetry breaking by direct measurements in $pp$ and $e^+e^-$ colliders. Here, we wish to show that FCNC and CP violating processes provide complementary means of achieving these goals.

The suppression of FCNC and of CP violation is very different between the two frameworks. If universality holds at the Planck scale, then at the electroweak scale

\[(K^d_L)^{22}(K^d_L)^{\ast}_{12} = V_{cs}V_{cd}^\ast, \quad \frac{\tilde{m}^2_{d_L2} - \tilde{m}^2_{d_L1}}{\tilde{m}^2} = O \left( \frac{\ln \frac{m_Z}{m^2}}{16\pi^2} \right) \Rightarrow (\delta^{d}_{LL})_{12} \sim 10^{-5}, \] (3.8)

safely below the bounds. (In the $\tilde{d}_R$ sector, the splittings are negligible.) On the other hand, in models of alignment,

\[(K^d_M)^{22}(K^d_M)^{\ast}_{12} \sim \sin \theta_c, \quad \frac{\tilde{m}^2_{d_M2} - \tilde{m}^2_{d_M1}}{\tilde{m}^2} = O(1) \Rightarrow (\delta^{d}_{LL})_{12} \sim 10^{-1}, \] (3.9)

which is too large. (By “∼” we mean an order of magnitude estimate and a possible phase of $O(1)$.) However, there exist a sub-class of such models where holomorphy plays an important role and induces approximate zeros in the down quark mass matrix. As a result, $M^d$ is very close to being diagonal and the Cabibbo mixing comes from the up sector. In specific examples in ref. [40],

\[(\delta^{d}_{LL})_{12} \sim (K^d_L)^{22}(K^d_L)^{\ast}_{12} \sim 10^{-4}, \] (3.10)

consistent with the constraints from $\Delta m_K$ and (even with phases of $O(1)$) from $\epsilon$. 

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The information from $K$ physics is now built into the various supersymmetric models, by incorporating either universality or alignment improved by holomorphy (or a combination of the two mechanisms \cite{43}). Below we show how measurements of FCNC and/or CP violation in $D$ and $B$ decays may distinguish between these two possibilities.

4. The $D$ System

Neither mixing nor CP violation in the $D$ system have been observed. The Standard Model predicts mixing well below the experimental bound and negligible CP violation. Therefore, if mixing is observed in the near future, it will be a clear signal of New Physics. Below, we explain how $\Delta m_D$ can potentially play a decisive role in distinguishing between universality and alignment in supersymmetric theories. But first we analyze the effects of CP violation on the search for mixing in the neutral $D$ system.

4.1. CP Violation in Neutral $D$ decays

The best bounds on $D - \bar{D}$ mixing come from measurements of $D^0 \rightarrow K^+ \pi^-$ \cite{44}. However, these bounds are still orders of magnitude above the Standard Model prediction for the mixing. If the value of $\Delta m_D$ is anywhere close to present bounds, it should be dominated by New Physics. Then, new CP violating phases may play an important role in $D - \bar{D}$ mixing. In this section, we investigate the consequences of CP violation from New Physics in neutral $D$ mixing \cite{45}.

As in section 2, we define

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle,$$

$$A \equiv \langle K^+ \pi^- |H|D^0\rangle, \quad B \equiv \langle K^+ \pi^- |H|\bar{D}^0\rangle,$$

$$\bar{A} \equiv \langle K^- \pi^+ |H|\bar{D}^0\rangle, \quad \bar{B} \equiv \langle K^- \pi^+ |H|D^0\rangle,$$

$$\lambda = \frac{p}{q} \frac{A}{B}, \quad \bar{\lambda} = \frac{q}{p} \frac{\bar{A}}{\bar{B}}.$$  \hspace{1cm} (4.2)

The following approximations can be safely made:

(i) $\Delta M \ll \Gamma, \Delta \Gamma \ll \Gamma, |\lambda| \ll 1$ (all experimentally confirmed).
(ii) $\Delta \Gamma \ll \Delta M$ (which is very likely if $\Delta M$ is close to the bound).

We further make the following very reasonable assumptions:

(iii) CP violation in decay is negligible, $|A/\bar{A}| = |B/B| = 1$.

(iv) CP violation in mixing is negligible, $|p/q| = 1$.

The two assumptions together imply also $|\lambda| = |ar{\lambda}|$.

The consequence of (i) – (iv) is the following form for the (time dependent) ratio between the doubly Cabibbo suppressed (DCS) and Cabibbo-allowed decay rates ($D^0(t)$ [$\bar{D}^0(t)$] is the time-evolved initially pure $D^0$ [$\bar{D}^0$] state):

$$\frac{\Gamma[D^0(t) \to K^+\pi^-]}{\Gamma[D^0(t) \to K^-\pi^+]} = |\lambda|^2 + \frac{\Delta M^2}{4} t^2 + \text{Im}(\lambda) t,$$

$$\frac{\Gamma[\bar{D}^0(t) \to K^-\pi^+]}{\Gamma[\bar{D}^0(t) \to K^+\pi^-]} = |\lambda|^2 + \frac{\Delta M^2}{4} t^2 + \text{Im}(\bar{\lambda}) t. \tag{4.4}$$

This form is valid for time $t$ not much larger than $\frac{1}{\Gamma}$. The time independent term is the DCS decay contribution; the term quadratic in time is the pure mixing contribution; and the term linear in time results from the interference between the DCS decay and the mixing amplitudes. Note that both the const($t$) and the $t^2$ terms are equal in the $D^0$ and $\bar{D}^0$ decays. However, if CP violation in the interference of mixing and decay is significant, $\text{Im}(\lambda) \neq \text{Im}(\bar{\lambda})$ and the linear term is different for $D^0$ and $\bar{D}^0$.

The experimental strategy should then be as follows: (a) Measure $D^0$ and $\bar{D}^0$ decays separately. (b) Fit each of the ratios to constant plus linear plus quadratic time dependence. (c) Combine the results for $|\lambda|^2$ and $\Delta M^2$. (d) Compare $\text{Im}(\lambda)$ to $\text{Im}(\bar{\lambda})$.

The comparison of the linear term should be very informative about the interplay between strong and weak phases in these decays. There are four possible results:

1. $\text{Im}(\lambda) = \text{Im}(\bar{\lambda}) = 0$: Both strong phases and weak phases play no role in these processes.
2. $\text{Im}(\lambda) = \text{Im}(\bar{\lambda}) \neq 0$: Weak phases play no role in these processes. There is a different strong phase shift in $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$.
3. $\text{Im}(\lambda) = -\text{Im}(\bar{\lambda})$: Strong phases play no role in these processes. CP violating phases affect the mixing amplitude.
4. $|\text{Im}(\lambda)| \neq |\text{Im}(\bar{\lambda})|$: Both strong phases and weak phases play a role in these processes.
In all these cases, the magnitude of the strong and the weak phases can be determined from the values of $|\lambda|$, $\text{Im}(\lambda)$ and $\text{Im}(\bar{\lambda})$.

Finding either quadratic or linear time dependence would be a signal for mixing in the neutral $D$ system. However, a non-vanishing linear term does not by itself signal CP violation in mixing, only if it is different in $D^0$ and $\bar{D}^0$. The linear term could be a problem for experiments: if the phase is such that the interference is destructive, it could partially cancel the quadratic term in the relevant range of time, thus weakening the experimental sensitivity to mixing [45]. On the other hand, if the mixing amplitude is smaller than the DCS one, the interference term may signal mixing even if the pure mixing contribution is below the experimental sensitivity [46-47].

4.2. Supersymmetry: Universality and Alignment

The constraints from $\Delta m_D$ analogous to (3.7) are [26]:

$$\Delta m_D \Rightarrow \sqrt{|\text{Re}(\delta_{LL}^u)^2_{12}|} \lesssim 1 \times 10^{-1}, \quad \sqrt{|\text{Re}(\delta_{LL}^u)_{12}(\delta_{RR}^u)_{12}|} \lesssim 2 \times 10^{-2}. \quad (4.5)$$

In models of universality,

$$(K_L^u)^{22}(K_L^u)^{12} = \mathcal{O}\left(\frac{\ln m_{\tilde{u}L}}{m_{\tilde{u}L}}\right) V_{us}V_{cs}^* \frac{\tilde{m}_{\tilde{u}L2} - \tilde{m}_{\tilde{u}L1}}{\tilde{m}_t^2} = \mathcal{O}\left(\frac{m_t^2}{m_W^2}\right) \Rightarrow (\delta_{LL}^u)_{12} \sim 10^{-5}, \quad (4.6)$$

safely below the bounds. On the other hand, in models with alignment, if $-\text{as required by the } K \text{ system and achievable with holomorphy } - (K_L^u)^{12} \ll \sin \theta_c$, then necessarily [39]

$$(K_L^u)^{22}(K_L^u)^{12} \sim \sin \theta_c \Rightarrow (\delta_{LL}^u)_{12} \sim 10^{-1}, \quad (4.7)$$

(we take the mass splitting to be of $\mathcal{O}(1)$). Models of quark-squark alignment predict that $\Delta m_D$ is close to the experimental bound. Furthermore, the supersymmetric contribution to the mixing could carry a new, large CP violating phase. Such a phase has interesting implications for the search of $D - \bar{D}$ mixing, as described in the previous subsection.

5. The $B$ System

5.1. Beyond the Standard Model - General [48]

CP asymmetries in $B$ decays are a sensitive probe of new physics in the quark sector, because they are likely to differ from the Standard Model predictions if there are sources of
CP violation beyond the CKM phase of the Standard Model. New Physics can contribute in two ways:

(i) If there are significant contributions to $B - \bar{B}$ mixing (or $B_s - \bar{B_s}$ mixing) beyond the box diagram with intermediate top quarks; or

(ii) If the unitarity of the three-generation CKM matrix does not hold, namely if there are additional quarks.

Actually, there is a third way in which the Standard Model predictions may be modified even if there are no new sources of CP violation:

(iii) The constraints on the CKM parameters change if there are significant new contributions to $B - \bar{B}$ mixing and to $\epsilon_K$ (see e.g. [49]).

On the other hand, the following ingredients of the analysis of CP asymmetries in neutral $B$ decays are likely to hold in most extensions of the Standard Model:

(iv) $\Gamma_{12} \ll M_{12}$. This is not only theoretically very likely but also supported by experimental evidence: $\Delta M/\Gamma \sim 0.7$ ( $\gtrsim 6$) for $B_d$ ($B_s$), while branching ratios into states that contribute to $\Gamma_{12}$ are $\leq 10^{-3}$ (0.1).

(v) The relevant decay processes (for tree decays) are dominated by Standard Model diagrams. It is unlikely that new physics, which typically takes place at a high energy scale, would compete with weak tree decays. (On the other hand, for penguin dominated decays, there could be significant contributions from new physics.)

Within the Standard Model, both $B$ decays and $B - \bar{B}$ mixing are determined by combinations of CKM elements. The asymmetries then measure the relative phase between these combinations. Unitarity of the CKM matrix directly relates these phases (and consequently the measured asymmetries) to angles of the unitarity triangles. In models with new physics, unitarity of the three-generation charged-current mixing matrix may be lost and consequently the relation between the CKM phases and angles of the unitarity triangle violated. But this is not the main reason that the predictions for the asymmetries are modified. The reason is rather that if $B - \bar{B}$ mixing has significant contributions from new physics, the asymmetries measure different quantities: the relative phases between the CKM elements that determine $B$ decays and the elements of mixing matrices in sectors of new physics (squarks, multi-scalar, etc) that contribute to $B - \bar{B}$ mixing.
Thus, when studying CP asymmetries in models of new physics, we look for violation of the unitarity constraints and, more importantly, for contributions to $B - \bar{B}$ mixing that are different in phase and not much smaller in magnitude than the Standard Model contribution. In Supersymmetry, the aspect of new CP violating phases in $B - \bar{B}$ mixing is markedly different in the cases of universality and alignment. We explain this point in the next subsection.

5.2. Supersymmetry: Universality and Alignment

The constraints from $\Delta m_B$ analogous to (3.7) are [26]:

$$\Delta m_B \implies \sqrt{|\text{Re}(\delta^d_{LL})_{13}^2|} \lesssim 1 \times 10^{-1}, \quad \sqrt{|\text{Re}(\delta^d_{LL})_{13}(\delta^d_{RR})_{13}|} \lesssim 2 \times 10^{-2}. \quad (5.1)$$

In models of universality,

$$(K^d_L)_{33}(K^d_L)^* = V_{td}V_{tb}^*, \quad \frac{\tilde{m}_{dL3}^2 - \tilde{m}_{dL3}^2}{\tilde{m}^2} = O \left( \frac{\ln m_{Z'} m_{Z}^2}{16\pi^2 m_{Z}^2} \right) \implies (\delta^d_{LL})_{13} \sim 10^{-3}. \quad (5.2)$$

In models with alignment,

$$(K^d_L)_{33}(K^d_L)^* \sim V_{td}V_{tb}^* \implies (\delta^d_{LL})_{13} \sim 10^{-2}. \quad (5.3)$$

A supersymmetric contribution to $B - \bar{B}$ mixing of $O(0.1)$ is possible. The crucial difference between universality and alignment does not lie, however, in the magnitude of the contributions: these are too small to be clearly signalled in $\Delta m_B$ because of the hadronic uncertainties (most noticeably in $f_B$). The important difference lies in the fact the the supersymmetric contribution in the models of universality carries the same phase as the Standard Model box diagram, while in models of alignment the phase is unknown. Therefore, models of universality predict no effect on CP asymmetries in $B$ decays, while models of alignment allow reasonably large deviations from the Standard Model.

6. Conclusions

FCNC and CP violation in the $K$ system have played an extremely important role in shaping the way we think about supersymmetry. In particular, to solve the supersymmetric flavor problems, all models incorporate either universality or alignment. Future
measurements of mixing and CP violation should allow us to distinguish between the two possibilities:

a. Alignment predicts that $D - \bar{D}$ mixing is close to the present experimental bound. Universality predicts that it is well below the bound.

b. Alignment allows large CP violation in $D - \bar{D}$ mixing. Universality predicts that it is negligible.

c. Alignment allows shifts in CP asymmetries in neutral $B$ decays into final CP eigenstates (compared to the Standard Model contributions) of order 0.2. Universality does not modify the Standard Model values.

The combination of these measurements might then exclude or strongly support either of these supersymmetric frameworks.

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