Recent Developments in Theory of CP Violation

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Abstract

Four topics in theory of CP violation are reviewed. (a) CP violation in $B$ decays: We describe a new clean way of constraining the angle $\gamma$ of the unitarity triangle and how new CP violation in decay amplitudes can signal new physics. (b) CP violation in $K$ decays: We explain the special features of the decay $K_L \to \pi^0 \nu \bar{\nu}$ both as a measurement of Standard Model CP violating parameters and as a probe of new physics. (c) CP violation in $D$ decays: We describe the consequences of CP violation from new physics in $D - \bar{D}$ mixing. (d) CP violation in Supersymmetry: We explain how a combination of measurements of CP violating processes will give insight into the flavor and CP structure of supersymmetry.

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1 Introduction

It is often said that the subject of CP symmetry and its violation is one of the least understood in particle physics. A better statement would be to say that it is experimentally one of the least constrained. CP violation is an expected consequence of the Standard Model with three quark generations, but is one of the least tested aspects of this model. The only part of CP violation that, at present, is considered puzzling by theorists is the lack of CP violation in strong interactions, that is the strong CP problem. The CP violation that shows up in a small fraction of weak decays is accommodated simply in the three-generation Standard Model Lagrangian. All it requires is that we do not impose CP as a symmetry.

However, while we know that CP violation occurs, because it has been observed in $K$ decays, we do not yet know whether the pattern of CP violation predicted by the minimal Standard Model is the one found in nature. The $K$-decay observations, together with other measurements, place constraints on the parameters of the Standard Model mixing matrix (the CKM matrix \cite{2,3}) but do not yet provide any test. A multitude of large CP-violating effects are expected in various $B$ decays and in $K \to \pi \nu \bar{\nu}$ decays, some of which are very cleanly predicted by the Standard Model. If we can make enough such independent observations then it will be possible to test the Standard Model predictions for CP violation. Either we will see that the relationships between various measurements are consistent with the Standard Model predictions and fully determine the CKM parameters or we will find that there is no single choice of CKM parameters that is consistent with all measurements.

This latter case, of course, would be much more interesting. It would
indicate that there is a contribution of physics beyond the Standard Model. There may be enough information in the pattern of the inconsistencies to tell us something about the nature of the new physics contributions. Thus the aim of the game is to measure enough quantities to impose redundant constraints on Standard Model parameters, including particularly the convention independent combinations of CP-violating phases of CKM matrix elements.

There are also many CP violating observables where the Standard Model contributions are too tiny to be observed. Most noticeable among these are the electric dipole moments of the neutron and the electron, CP violation in top production and decay, CP violation in $D - \bar{D}$ mixing, and transverse lepton polarization in meson decays. If experiments find a signal then, again, this will indicate new physics. The pattern of CP violation is likely to provide useful information on the details of the relevant new physics.

One may well ask, after the many successes of the Standard Model, why we would expect violations to show up in such a low-energy regime. The best answer is simply that it has not yet been tested. Theorists will give a variety of further reasons. Many extensions of the Standard Model have additional sources of CP violating effects, or effects which change the relationship of the measurable quantities to the CP-violating parameters of the Standard Model.

In addition there is one great puzzle in cosmology that relates to CP violation, and that is the disappearance of the antimatter. In grand unified theories, or even in the Standard Model at sufficiently high temperatures, there are baryon number violating processes. If such processes are active then thermal equilibrium produces equal populations of particles and antiparticles. Thus in modern theories of cosmology the net baryon number of the universe is zero in the early high temperature epochs. Today it is clearly not zero, at least in our local region. We will not here give a full discussion of the cosmological arguments. It suffices to remark that there is a large class of theories in which the baryon number asymmetry is generated at the weak phase transition. Such theories, however, must include CP violation from sources beyond the minimal Standard Model. Calculations made in that model show that it does not generate a large enough matter-antimatter imbalance to produce the baryon number to entropy ratio observed in the universe today. This is a hint that CP violation from beyond Standard Model sources is worth looking for. It is by no means a rigorous argument. There are theories in which baryon number is generated at a much higher temperature and then protected from thermalization to zero by $B - L$ (baryon number minus lepton number) symmetry. Such theories do not in general require any new low energy CP violation mechanism. Neither do they forbid it.

More generally, since we know there is CP violation in part of the theory,
any extension of the Standard Model cannot be required to be CP symmetric. Any additional fields in the theory bring possible additional CP violating couplings. Even assumptions such as soft or spontaneous CP symmetry breaking leave a wide range of possibilities. Further experimental constraints, from experiments such as the $B$ factory, are needed.

In this talk, we will focus on four aspects of CP violation:

(i) **CP violation in $B$ decays.** Within the Standard Model framework, we describe a new method to constrain the angle $\gamma$ of the unitarity triangle that is theoretically clean and experimentally feasible. Beyond the Standard Model, we explain how CP violation in the decay amplitudes can be useful for discovering new physics.

(ii) **CP violation in $D$ decays.** We study the neutral $D$ decays into final $K^\pm \pi^\mp$. We explain how CP violation from New Physics can affect the search for mixing through this decay.

(iii) **CP violation in $K$ decays.** We focus on the $K_L \to \pi^0 \nu \bar{\nu}$ decay. Within the Standard Model, it gives a clean measurement of the CP violating parameter $\eta$. Beyond the Standard Model, it probes new CP violating phases in the $s \to d \nu \bar{\nu}$ decay.

(iv) **CP violation as a probe of Supersymmetry.** We describe the various developments in understanding the flavor and CP problems in Supersymmetry. We explain how measurements of CP violation could distinguish among the various solutions to these problems.

Unfortunately, due to lack of time and space, we have to leave out many other topics where there have been recent interesting developments, e.g. CP violation in top and Higgs physics, CP violation in neutrino oscillations, baryogenesis, and various others.

\section{2 CP Violation in Meson Decays}

\subsection{2.1 Formalism}

To establish our notations and to understand similarities and differences between $K$, $D$ and $B$ decays, we here briefly review the formalism of CP violation in meson decays.

We define decay amplitudes $A_f$ and $\bar{A}_f$ through

$$A_f = \langle f | H | B^0 \rangle, \quad A_f = \langle f | H | \bar{B}^0 \rangle. \quad (1)$$

We denote by $p$ and $q$ the components of the interaction eigenstates in the neutral meson mass eigenstates:

$$|B_{1,2}\rangle = p |B^0\rangle \pm q |\bar{B}^0\rangle. \quad (2)$$
Finally, the complex quantity $\lambda_f$ is defined by

$$\lambda_f = \frac{q}{p} \tilde{A}_f. \quad (3)$$

The possible manifestations of $CP$ violation can be classified in a model independent way:

(i) CP violation in decay, which occurs in both charged and neutral decays, when the amplitude for a decay and its $CP$-conjugate process have different magnitudes:

$$|\tilde{A}_f/A_f| \neq 1. \quad (4)$$

($\bar{f}$ denotes the CP-conjugate of the state $f$.)

(ii) CP violation in mixing, which occurs when the two neutral mass eigenstate admixtures cannot be chosen to be $CP$-eigenstates:

$$|q/p| \neq 1. \quad (5)$$

(iii) CP violation in the interference between decays with and without mixing, which occurs in decays into final states that are common to $B^0$ and $\bar{B}^0$. It often occurs in combination with the other two types but there are cases when, to an excellent approximation, it is the only effect, namely

$$\text{Im}\lambda_f \neq 0 \quad (|\lambda_f| \approx 1). \quad (6)$$

2.2 The CKM Constraints

To understand the Standard Model predictions for CP asymmetries in various neutral meson decays, we study the constraints on the CKM parameters from $|V_{cb}|$, $|V_{ub}/V_{cb}|$, $\Delta m_{B_d}$, $\varepsilon_K$ and $\Delta m_{B_s}$. We use a new method of statistically combining the many measurements involving CKM parameters\cite{60} This method was adopted by the BaBar collaboration\cite{61} and is described in detail in\cite{62}.

There are two types of errors which enter the determination of the CKM parameters: experimental errors and uncertainties due to theoretical model dependence. These two types of errors will be treated differently. Experimental errors are generally assumed to be Gaussianly distributed and can then enter a $\chi^2$ test. For the quantities with Gaussian errors, we use\cite{63,64}

$$|V_{cb}| = 0.039 \pm 0.004,$$

$$|V_{ub}/V_{cb}|_{\text{exp}} = |V_{ub}/V_{cb}|_{T} \pm 0.05,$$

$$\Delta m_{B_d} = 0.463 \pm 0.018 \text{ ps}^{-1},$$

$$|\varepsilon_K| = (2.258 \pm 0.018) \times 10^{-3}. \quad (7)$$
(The subscript $T$ implies that we here refer to the hadronic model dependent range for $|V_{ub}/V_{cb}|$ to which an experimental error should be added to give the full uncertainty.) A large part of the uncertainty in translating the experimental observables to the CKM parameters comes, however, from errors related to the use of hadronic models. At present, one cannot assume any shape for the probability density of these quantities (certainly not Gaussian) and include it in the fit. We thus do not assume any shape for these distributions but use a whole set of ‘reasonable’ values for the parameters. Specifically, we scan the ranges

$$
0.06 \leq |V_{ub}/V_{cb}|_T \leq 0.10,
160 \leq f_{B_d} \sqrt{B_{B_d}} \leq 240 \text{ MeV},
0.6 \leq B_K \leq 1.0.
$$

The mass difference in the $B_s$ system has not been measured and only 95% CL limits have been obtained:

$$
\Delta m_{B_s} \geq 10.0 \text{ ps}^{-1}.
$$

Such a limit is only a small part of the information and it cannot be included directly in the $\chi^2$ minimization. In our analysis, we include the full information from the amplitude method that is now being used by the LEP $\Delta m_{B_s}$ averaging Working Group. We also use

$$
\frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2} = 1.30 \pm 0.18.
$$

The present allowed region at 95% CL in the $\rho - \eta$ plane is presented in Fig. 1(a). Another useful presentation is in the $\sin 2\alpha - \sin 2\beta$ plane. The present allowed region at 95% CL is shown in Fig. 1(b).

Examining the figures, we find that, if the theoretical parameters are within the range (8), the following ranges for the various angles of the unitarity triangle are allowed at the 95% CL:

$$
0.28 \leq \sin 2\beta \leq 0.88,
-1.0 \leq \sin 2\alpha \leq 1.0,
0.23 \leq \sin^2 \gamma \leq 1.0.
$$

3 $B$ Physics

A huge amount of work has been devoted to CP violation in $B$ decays. This is no doubt a result of the forthcoming $B$-factories, BaBar and Belle.
Figure 1: The present allowed range (a) in the $\rho - \eta$ plane and (b) in the $\sin 2\alpha - \sin 2\beta$ plane using constraints from $|V_{cb}|$, $|V_{ub}/V_{cb}|$, $\Delta m_{B_d}$, $\varepsilon_K$ and $\Delta m_{B_s}$. For the methods used in this analysis, see refs. (160,161,162).
effort goes in two main directions: how to determine best the values of the CP violating angles of the unitarity triangle and how to find New Physics. Instead of trying to review all the work that has been done in this field, I will give two examples of recent attractive developments. In the direction of measuring CKM phases, I will describe a new method to constrain $\gamma$. In the direction of exploring new physics, I will describe a method that uses possible new phases in the decay amplitudes (rather than in the mixing).

3.1 Constraining $\gamma$

Of the three angles of the unitarity triangle, $\gamma$ is the most difficult one to measure in a $B$-factory. Many clever methods were suggested, but most of them either suffer from rather large hadronic uncertainties or are very difficult, not to say impossible, to carry out in a $B$-factory. Two methods, however, are theoretically rather clean. One is a proposal by Atwood, Dunietz and Soni based on an idea by Gronau and Wyler using triangle relations in $B \to D^0 K$ decays. The other, which is described in detail below, was proposed by Fleischer and Mannel using the branching ratios of four $B \to \pi K$ decay modes, it is possible to derive a bound on the angle $\gamma$ of the unitarity triangle which, under certain circumstances, is free of hadronic uncertainties.

The amplitudes for the relevant $B \to \pi K$ decays can be written as follows:

\begin{align*}
A(B^0 \to \pi^- K^+) &= A_0^0 - A_0^0 e^{i\gamma} e^{i\delta}, \\
A(\bar{B}^0 \to \pi^+ K^-) &= A_0^0 - A_0^0 e^{-i\gamma} e^{i\delta}, \\
A(B^+ \to \pi^+ K^0) &= A_0^+ - A_u^+ e^{i\gamma} e^{i\delta'}, \\
A(B^- \to \pi^- \bar{K}^0) &= A_0^- - A_u^- e^{-i\gamma} e^{i\delta'}. 
\end{align*}

(12)

The following two assumptions are very likely to hold with regard to these four channels:

1. The contributions to $A_u$ that do not come from tree amplitudes can be neglected. The reason is that the penguin amplitudes contributions to $A_u$ are suppressed compared to their contributions to $A_c$ by $O(|V_{ub}V_{us}|/|V_{tb}V_{ts}|) \sim 0.02$. Then in the charged $B$ decays, which require a $b \to d \bar{s}s$ transition, we can neglect $A_u$ while in the neutral $B$ decays, which can also be mediated by a $b \to u \bar{u}s$ transition, we take into account only the tree amplitude $A_T$:

\begin{equation}
A_u^+ = 0, \quad A_u^0 = A_T.
\end{equation}

(13)

2. The contributions from electroweak penguins can be neglected. Indeed these contributions can be reliably estimated and they are expected to be $O(0.01)$ of the leading contributions. Then $A_c$ comes purely from QCD penguin
amplitudes $A_P$ which, as a result of the $SU(2)$ isospin symmetry of the strong interactions, contribute equally to the charged and neutral $B$ decays:
\[
A_0^c = A_+^c = A_P.
\] (14)

We define
\[
\Gamma(B_d \to \pi^\pm K^\pm) \equiv \Gamma(B^0 \to \pi^- K^+) + \Gamma(\bar{B}^0 \to \pi^+ K^-)
\] and
\[
\Gamma(B^\pm \to \pi^\pm K) \equiv \frac{\Gamma(B^+ \to \pi^+ K^0) + \Gamma(B^- \to \pi^- K^0)}{2},
\]
\[
R \equiv \frac{\Gamma(B_d \to \pi^\pm K^\pm)}{\Gamma(B^\pm \to \pi^\pm K)}.
\] (15)

With the two approximations (13) and (14) one gets
\[
R = 1 - 2r \cos \gamma \cos \delta + r^2. \tag{16}
\]

In general, constraints on $\gamma$ from eq. (16) depend on hadronic physics. In particular, while $R$ is a measurable quantity, $r$ and $\cos \delta$ are hadronic, presently unknown parameters. (We treat $r$ as a free parameter. Estimates based on factorization and on $SU(3)$ relations prefer $r < \sim 0.5$.5.) Fortunately, one can find an inequality that is independent of $r$ and $\cos \delta$:
\[
\sin^2 \gamma \leq R. \tag{17}
\]

Clearly, the bound (17) is significant only for $R < 1$. Recent CLEO results\cite{14} give $R = 0.65 \pm 0.40$. Thus, we may be fortunate and indeed have $R < 1$. As soon as an upper bound on $R$ below unity is obtained, the limit (17) will give, within the Standard Model, useful constraints in the $\rho - \eta$ (fig. 2(a)) and $\sin 2\alpha - \sin 2\beta$ (fig. 2(b)) planes. It can also probe new physics.\cite{14}

3.2 New CP Violation in Decay Amplitudes

Grossman and Woral\cite{24} have argued that new CP violating effects in $\Delta B = 1$ processes can be cleanly signalled in experiment even if the effects are smaller than the widely discussed new CP violation in $\Delta B = 2$ processes. The reason is that to see the decay effects, one compares two experimentally measured quantities, and does not need to know the theoretically allowed range for either of them.
Figure 2: The effect of the FM bound with $R = 0.65 \pm 0.08$ on the constraints (a) in the $\rho - \eta$ plane and (b) in the $\sin 2\alpha - \sin 2\beta$ plane. The central value for $R$ is taken from the present CLEO measurement (ref. (169)) while the error is our estimate for the accuracy that can be obtained with about 80 fb$^{-1}$ in $B$-factories. For all other constraints, we use present data.
To explain the main points, we take the explicit example of the CP asymmetries in $B \to \psi K_S$ and $B \to \phi K_S$, which we denote by $a_{\psi K_S}$ and $a_{\phi K_S}$, respectively. Within the Standard Model, each of these is dominated by a single CKM phase. Consequently, to a very good approximation, the source of the CP asymmetries is CP violation in the interference of decays with and without mixing, namely $\text{Im}\lambda \neq 0$. Furthermore, the asymmetries can be calculated in a theoretically clean way, giving

$$a_{\psi K_S} = \sin 2\beta, \quad a_{\phi K_S} = \sin 2\beta,$$

so that the present accuracy of the Standard Model prediction for these asymmetries is given by (see fig. 2):

$$0.3 \lesssim \sin 2\beta \lesssim 0.9 \quad (95\% \text{ CL}).$$

The Standard Model relation for $a_{\psi K_S}$ is extremely clean. For $a_{\phi K_S}$, effects of $O(|V_{ub}/V_{us}|/|V_{tb}/V_{ts}|) \lesssim 0.03$ are neglected. We thus learn that the Standard Model predicts $a_{\psi K_S} = a_{\phi K_S}$ to within 6%.

Most studies of new physics effects on CP asymmetries in neutral $B$ decays have focussed on new CP violation in $B - \bar{B}$ mixing. (For recent, model independent studies of this case, see [16, 22, 38].) The strong suppression of the Standard model box diagrams by the fourth order of the weak coupling and small CKM angles indeed allows for competing, maybe even dominant contributions from new physics. In this case, one can parameterize the new physics effects by two new parameters, $r_d$ and $\theta_d$, defined by

$$\frac{\langle B^0|H_{\text{full}}|\bar{B}^0 \rangle}{\langle B^0|H_{\text{SM}}|\bar{B}^0 \rangle} = (r_d e^{i\theta_d})^2.$$  \hfill (21)

The important features in this framework are that large effects on CP asymmetries in $B^0$ decays are possible and that the asymmetries are shifted universally. The shift depends on the new CP violating phase $\theta_d$ only. In particular:

$$a_{\psi K_S} = \sin 2(\beta + \theta_d), \quad a_{\phi K_S} = \sin 2(\beta + \theta_d),$$

and the equality between the asymmetries is maintained. The angle $\theta_d$ is generally unconstrained. If indeed $\sin 2\beta \sim 0.6$, then a rather large $\theta_d$ is required in order that the deviation from the Standard Model range will be manifest.
As for the decay amplitudes, the $B \rightarrow \psi K_S$ decay goes through the quark $\bar{b} \rightarrow \bar{s}c\bar{c}$ transition which gets contributions from Standard Model tree diagrams with only mild CKM suppression. It is then very unlikely that new physics could affect this decay in a significant way. On the other hand, the $B \rightarrow \phi K_S$ decay goes through the quark $\bar{b} \rightarrow \bar{s}s\bar{s}$ transition. This is a FCNC process to which the leading Standard Model contributions are QCD penguin amplitudes with an extra suppression by $\alpha_s$ and a loop factor. Here one could easily think of reasonable extensions of the Standard Model where there are significant new, possibly CP violating contributions. (For specific examples, see 33, 36, 37, 40.) Assuming that these new contributions do not induce CP violation in decay, namely that $|A_{\phi K_s}/A_{\phi K_S}| = 1$ is maintained, the new effects can be parameterized by

$$\left(\frac{A_{\phi K_S}/A_{\phi K_S}}{A_{\phi K_S}/A_{\phi K_S}}\right)^{\text{full}} = e^{2i\theta_A}.$$ (23)

The result of such New Physics is that the asymmetries are now modified as follows:

$$a_{\psi K_S} = \sin 2(\beta + \theta_d), \quad a_{\phi K_S} = \sin 2(\beta + \theta_d + \theta_A).$$ (24)

Again, to test each of these predictions against the Standard Model range (19) requires modifications of order 50%. The big advantage of having $\Delta B = 1$ effects is that (20) is modified:

$$a_{\psi K_S} \neq a_{\phi K_S},$$ (25)

and that relatively small effects, of order 10%, can lead to an observable failure of (20). Therefore, measurements of CP asymmetries in decays of $B^0$ that are suppressed by either being FCNC processes or by small CKM angles, while experimentally challenging, might provide exceptionally sensitive probes of New Physics.

4 $D$ Physics: CP Violation in $D - \bar{D}$ Mixing

The best bound on $D-\bar{D}$ mixing comes from measurements of $D^0 \rightarrow K^+\pi^-$. 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. For example, new CP violating phases are expected in various supersymmetric models.

The only type of CP violation that is likely to be relevant in the experimental search for $D-\bar{D}$ mixing is in the interference between decays with and without mixing:
(i) The decay $D^0 \to K^+\pi^-$ proceeds via the quark subprocess $c \to d\bar{s}u$. Within the SM, this process is dominated by doubly Cabibbo suppressed (DCS) tree amplitudes. It is very difficult, if not impossible, for diagrams involving new physics to contribute to this decay comparably to the $W$-mediated diagram. Consequently, $D^0 \to K^+\pi^-$ is dominated by a single weak phase, $\text{arg}(V_{cd}V_{us}^*)$, and it is safe to neglect CP violation in decay.

(ii) If $\Delta m_D$ is close to present bounds, then it is clearly dominated by new physics, $M_{12} \gg M_{12}^{SM}$. On the other hand, there is no reasonable type of new physics that could enhance $\Gamma_{12}$ by orders of magnitude, so that very likely $\Gamma_{12} \sim \Gamma_{12}^{SM}$. Therefore, if $\Delta m_D$ is close to present bounds, it is safe to assume that $\text{Im}(\Gamma_{12}/M_{12}) \ll 1$ and neglect CP violation in mixing.

(iii) Within the Standard Model, both the mixing amplitude for neutral $D$ mesons and the decay amplitude for $D \to K\pi$ occur through processes that involve, to a very good approximation, quarks of the first two generations only. Therefore, the relative weak phase between the mixing and decay amplitudes is extremely small. However, most if not all extensions of the Standard Model that allow $\Delta m_D$ close to the limit involve new CP violating phases. In these models, the relative phase between the mixing amplitude and the decay amplitude is usually unconstrained and would naturally be expected to be of $\mathcal{O}(1)$. CP violation in the interference between decays with and without mixing could then be a large effect.

To understand the consequences of this situation, we introduce the two quantities

$$\lambda_{K^+\pi^-} = \left(\frac{q}{p}\right)_{D} \frac{\bar{A}_{K^+\pi^-}}{A_{K^+\pi^-}}, \quad \lambda_{K^-\pi^+} = \left(\frac{q}{p}\right)_{D} \frac{\bar{A}_{K^-\pi^+}}{A_{K^-\pi^+}}$$

(26)

Our discussion above of CP violation has the following implications: Since CP violation in decay is negligible, $|A_{K^+\pi^-}/\bar{A}_{K^-\pi^+}| = |\bar{A}_{K^+\pi^-}/A_{K^-\pi^+}| = 1$. Since CP violation in mixing is negligible, $|(q/p)_D| = 1$. Then

$$|\lambda_{K^+\pi^-}| = |\lambda_{K^-\pi^+}| \equiv |\lambda|.$$  \hspace{1cm} (27)

Furthermore, since it experimentally known that $\Delta m_D \ll \Gamma_D$ and $\Delta \Gamma_D \ll \Gamma_D$, we have $|\lambda_{K^-\pi^+}| \ll 1$. If $\Delta m_D$ is close to the bound then $\Delta \Gamma_D \ll \Delta m_D$.

The result of this discussion is the following form for the (time dependent) ratio between the DCS and Cabibbo-allowed decay rates:

$$\frac{\Gamma[D^0(t) \to K^+\pi^-]}{\Gamma[D^0(t) \to K^-\pi^+]} = |\lambda|^2 + \frac{(\Delta m_D)^2}{4} t^2 + \text{Im}(\lambda_{K^+\pi^-}^{-1})t,$$
\[
\frac{\Gamma[D^0(t) \to K^-\pi^+)]}{\Gamma[D^0(t) \to K^+\pi^-]} = |\lambda|^2 + \frac{(\Delta m_D)^2}{4}t^2 + \text{Im}(\lambda_{K-\pi^+})t. \quad (28)
\]

This form is valid for time \( t \) not much larger than \( \frac{1}{\Gamma_D} \). As concerns the linear term, there are four possible situations:

1. \( \text{Im}(\lambda_{K^-\pi^+}) = \text{Im}(\lambda_{K-\pi^+}) = 0 \): both strong and weak phases play no role in these processes.

2. \( \text{Im}(\lambda_{K^-\pi^+}) = \text{Im}(\lambda_{K-\pi^+}) \neq 0 \): weak phases play no role in these processes. There is a different strong phase shift in \( D^0 \to K^+\pi^- \) and \( D^0 \to K^-\pi^+ \). (The strong phase shifts were calculated within two hadronic models and found to be small.)

3. \( \text{Im}(\lambda_{K^-\pi^+}) = -\text{Im}(\lambda_{K-\pi^+}) \neq 0 \): strong phases play no role in these processes. CP violating phases affect the mixing amplitude.

4. \( |\text{Im}(\lambda_{K^-\pi^+})| \neq |\text{Im}(\lambda_{K-\pi^+})| \): both strong and weak phases play a role in these processes.

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. 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.

5. \( K \) Physics: \( K_L \to \pi^0\nu\bar{\nu} \)

\( K_L \to \pi^0\nu\bar{\nu} \) is a very useful probe of CP violation:

(i) It is dominated by short distance contributions. There is a hard GIM suppression of \( \mathcal{O}(\Lambda_{QCD}^2/m_c^2) \) between the long distance contribution and the charm mediated short distance one (which by itself is small). It makes long distance contributions negligibly small. QCD corrections are known to NLO and electroweak corrections were calculated to two loops in the large \( m_t \) limit.

(ii) \( (\pi)(\bar{s}d)_{V-A}[K] \) is known. This matrix element is a current operator that is much simpler than the four quark operators that are relevant to other rare processes such as \( \Delta m_K \) and \( \varepsilon_K \). Moreover, it is related by isospin symmetry to \( (\pi)(\bar{s}u)_{V-A}[K] \) which is measured in \( K^+ \to \pi^0\nu^+\nu \) decay. The isospin breaking corrections were calculated.

(iii) The decay is purely CP violating. In general, three body final states are not CP eigenstates. However, in this case, if neutrinos are purely left-handed, the final state is almost purely CP-even, with only \( \mathcal{O}(m_K^2/m_{\pi}^2) \) CP-odd component. Thus, the decay violates CP. (An exception to this statement...
arises in models with lepton-number violating $K$ decays, where final states $\pi^0\nu_i\bar{\nu}_j$, $i \neq j$, could dominate \cite{69}.

(iv) The required CP violation is dominated by interference between decays with and without mixing. It is experimentally known that $|q/p| = 1 + \mathcal{O}(10^{-3})$. It is theoretically estimated that $|\bar{A}/A| = 1 + \mathcal{O}(10^{-5})$. In contrast, the effects of CP violation in the interference of decays with and without mixing ($\text{Im}\lambda \neq 0$) are expected to be of $\mathcal{O}(1)$.

As a result of these special features, the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay is theoretically clean to the level of $10^{-3}$. The theoretical cleanliness (features (i) and (ii) above) is also valid for the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay. This mode is, however, not CP violating. (Recently, the first experimental evidence for this decay has been announced by the E787 collaboration \cite{176}.) The combination of the two decay modes provide a very clean determination of the angle $\beta$ of the unitarity triangle. The cleanliness is comparable to that of the determination of $\beta$ from the CP asymmetry in $B \rightarrow \psi K_S$. The constraints on the CKM parameters are demonstrated in fig. 3.

Model independently, we get a clean determination of $\theta_K$, the relative phase between the $K^-\bar{K}$ mixing amplitude and the $s \rightarrow d\nu\bar{\nu}$ decay amplitude:

$$a_{\pi\nu\bar{\nu}} \equiv \frac{\Gamma(K_L \rightarrow \pi^0\nu\bar{\nu})}{\Gamma(K^+ \rightarrow \pi^+\nu\bar{\nu})} = \sin^2 \theta_K. \quad (29)$$

Eq. (29) together with the experimental upper bound \cite{177,176} $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) \leq 2.4 \times 10^{-9}$, give a model independent bound:

$$BR(K_L \rightarrow \pi^0\nu\bar{\nu}) \leq 1.1 \times 10^{-8}, \quad (30)$$

which is more than two orders of magnitude stronger than the new direct experimental bound from KTeV \cite{178}

$$BR(K_L \rightarrow \pi^0\nu\bar{\nu}) \leq 1.8 \times 10^{-6}. \quad (31)$$

The $K \rightarrow \pi\nu\bar{\nu}$ decays are useful in probing CP violation beyond the Standard Model. The bound (31) is still about three orders of magnitude above the Standard Model prediction $BR(K_L \rightarrow \pi^0\nu\bar{\nu}) = (2.8 \pm 1.7) \times 10^{-11}$, leaving plenty of room for new physics. The $\varepsilon_K$ constraints on CP violation in $K - \bar{K}$ mixing imply that such new physics can only appear in the decay amplitude. For example, significant new contributions to $s \rightarrow d\nu\bar{\nu}$ with new CP violating phases are possible in extensions of the quark sector \cite{69}.

Finally, we would like to clarify one further point. In certain superweak models, CP violation appears in processes that change flavor by two units only, i.e. in mixing but not in decay amplitudes. This leads to the prediction that...
Figure 3: The effect of the $K \rightarrow \pi \nu \bar{\nu}$ measurements on the constraints (a) in the $\rho - \eta$ plane and (b) in the $\sin 2\alpha - \sin 2\beta$ plane. We use $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.0 \pm 0.1) \times 10^{-10}$, $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.0 \pm 0.3) \times 10^{-11}$, and $|V_{cb}| = 0.039 \pm 0.02$. (These are the hypothetical ranges used in ref. (65).) For all other constraints we use present data.
the CP asymmetries in $K$ decays should be ‘universal’, namely independent of the final state. In particular, the CP asymmetry in $K \to \pi \pi$ has been measured (that is the $\varepsilon_K$ parameter) and is $O(10^{-3})$. We learn that if the ratio (29) is measured and found to be $\gg 10^{-3}$ (or, equivalently at present, if $BR(K_L \to \pi^0\nu\bar{\nu}) \sim 10^{-11}$, as predicted by the SM) then superweak CP violation will be excluded. This situation is sometimes described in the literature by the statement that $K_L \to \pi^0\nu\bar{\nu}$ will provide an unambiguous evidence for direct CP violation. A similar conclusion will follow if the asymmetries in, say, $B \to \psi K_S$ and $B \to \pi\pi$ are found to be unequal.

6 Supersymmetry

6.1 The Supersymmetric CP Problems

A generic supersymmetric extension of the Standard Model contains a host of new flavor and CP violating parameters. 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. A discussion of CP violation in this context can hardly avoid addressing the flavor problem itself. Indeed, many of the supersymmetric models that we analyze below were originally aimed at solving flavor problems.

As concerns CP violation, one can distinguish two classes of experimental constraints. First, bounds on nuclear and atomic electric dipole moments determine what is usually called the supersymmetric CP problem. It involves effects that are flavor preserving and consequently appears already in the minimal supersymmetric standard model (MSSM) with universal sfermion masses and with the trilinear SUSY-breaking scalar couplings proportional to the corresponding Yukawa couplings. In such a constrained framework, there are two new physical phases beyond the two phases of the Standard Model ($\delta_{\text{KM}}$ and $\theta_{\text{QCD}}$) usually denoted by $\phi_A$ and $\phi_B$. In the more general case of non-universal soft terms there is one independent phase $\phi_{Ai}$ for each quark and lepton flavor. Moreover, complex off-diagonal entries in the sfermion mass matrices may represent additional sources of CP violation.

The most significant effect of $\phi_A$ and $\phi_B$ is their contribution to electric dipole moments (EDMs). In particular, the present experimental bound, $d_N < 1.1 \times 10^{-25} \, e \, cm$ [6,8], implies

$$\left(\frac{100 \, GeV}{\tilde{m}}\right)^2 \sin \phi_{A,B} \lesssim 10^{-2} \frac{d_N}{10^{-25} \, e \, cm},$$

where $\tilde{m}$ represents the overall SUSY scale. Whether the phases are small or
squarks are heavy, a fine-tuning of order $10^{-2}$ seems to be required, in general, to avoid too large a $d_N$. This is the Supersymmetric CP Problem.

A second class of experimental constraints, involving the physics of neutral mesons and, most importantly, the small experimental value of $\varepsilon_K$, pose the supersymmetric $\varepsilon_K$ problem. The contribution to the CP violating $\varepsilon_K$ parameter in the neutral $K$ system is dominated by diagrams involving $Q$ and $\bar{d}$ squarks in the same loop. A typical bound on the supersymmetric parameters reads:

$$\left(\frac{300 \text{ GeV}}{m}\right)^2 \left|\frac{(\delta m_Q^2)_{12} (\delta m_D^2)_{12}}{m_Q^2}ight| \sin \phi \lesssim 0.5 \times 10^{-7},$$

where $\phi = \arg((\delta m_Q^2)_{12}(\delta m_D^2)_{12})$, and $(\delta m_Q^2,D)_{12}$ are the off diagonal entries in the squark mass matrices in a basis where the down quark mass matrix and the gluino couplings are diagonal. For dimensionless parameters assuming their natural values of $O(1)$, the constraint (33) is generically violated by about seven orders of magnitude. This is the supersymmetric $\varepsilon_K$ problem.

### 6.2 Classes of Supersymmetric Models

The supersymmetric flavor and CP problems have provided a very significant input to supersymmetry model builders. Two scales play an important role in supersymmetry: $\Lambda_S$, where the soft supersymmetry breaking terms are generated, and $\Lambda_F$, where flavor dynamics takes place.

Both supersymmetric CP problems are solved if, at the scale $\Lambda_S$, the soft supersymmetry breaking terms are universal and the genuine SUSY CP phases $\phi_{A,B}$ vanish. Then the Yukawa matrices represent the only source of flavor and CP violation which is relevant in low energy physics. This situation can naturally arise if $\Lambda_S \ll \Lambda_F$, as in models where supersymmetry breaking is mediated by the Standard Model gauge interactions. In the simplest scenarios, the $A$-terms and the gaugino masses are generated by the same SUSY and $U(1)_R$ breaking source, leading to $\phi_A = 0$. In specific models also $\phi_B = 0$ in a similar way.

The most important implication of this type of boundary conditions for soft terms, which we refer to as *exact universality*, is the existence of the SUSY analogue of the GIM mechanism which operates in the SM. The CP violating phase of the CKM matrix can feed into the soft terms via Renormalization Group (RG) evolution only with a strong suppression from light quark masses. The resulting phenomenology of CP violation is hardly distinguishable from the Standard Model.

When $\Lambda_F \lesssim \Lambda_S$, we do not expect, in general, that flavor and CP violation are limited to the Yukawa matrices. One way to suppress CP violation would
be to assume that CP is an approximate symmetry of the full theory. In such a case, we expect also the SM phase $\delta_{\text{KM}}$ to be $\ll 1$. Then the standard box diagrams cannot account for $\varepsilon_K$ which should arise from another source. In supersymmetry with non-universal soft terms, the source could be diagrams involving virtual superpartners, mainly squark-gluino box diagrams. Let us call $(M_{K12}^{\text{SUSY}})$ the supersymmetric contribution to the $K - \bar{K}$ mixing amplitude. Then the requirements $\text{Re}(M_{K12}^{\text{SUSY}}) \lesssim \Delta m_K$ and $\text{Im}(M_{K12}^{\text{SUSY}}) \sim \varepsilon_K \Delta m_K$ imply that the generic CP phases are $\geq \mathcal{O}(\varepsilon_K) \sim 10^{-3}$. Then, somewhat similar to the superweak scenario, all CP violating observables (when defined appropriately) are characterized by a similar small parameter. This situation implies many dramatic consequences, e.g. $d_N$ just below or barely compatible with the present experimental bound and, most striking, that CP asymmetries in $B$ meson decays are small, perhaps $\mathcal{O}(\varepsilon_K)$, rather than $\mathcal{O}(1)$ as expected in the SM.

Another option is to assume that, similarly to the Standard Model, CP violating phases are large, but their effects are screened, possibly by the same physics that explains the various flavor puzzles. This usually requires Abelian or non-Abelian horizontal symmetries. Two ingredients play a major role here: selection rules that come from the symmetry and holomorphy of Yukawa and $A$-terms that comes from the supersymmetry. With Abelian symmetries, the screening mechanism is provided by alignment, whereby the mixing matrices for gaugino couplings have very small mixing angles, particularly for the first two down squark generations. With non-Abelian symmetries, the screening mechanism is approximate universality, where quarks of the two light families fit into an irreducible doublet and are, therefore, approximately degenerate. An extension of these ideas, aimed at screening the CP phases in the $A$-terms, assumes that CP is a symmetry of the Lagrangian, spontaneously broken by the same fields that break the horizontal symmetry. In general, it can be shown that non-universality of $A$-terms and the requirement of $\mathcal{O}(1)$ CKM phase imply $\phi_A \gtrsim \sin^6 \theta_C$, leading to $d_N \gtrsim 10^{-28} \text{e} \text{cm}$. The minimal result can be reached only with almost triangular Yukawa matrices, which can be achieved with Abelian flavor symmetries. In models of non-Abelian symmetries, where the two light families are in irreducible doublets, one does not expect such a structure and typically the effective CP phases for light quarks are expected to be $\gtrsim \sin^4 \theta_C$.

As far as the third generation is concerned, the signatures of Abelian and non-Abelian models are similar. In particular, they allow observable deviations from the SM predictions for CP asymmetries in $B$ decays. In some cases, non-Abelian models give relations between CKM parameters and consequently predict strong constraints on these CP asymmetries. For the two light genera-
tions, only alignment allows interesting effects. In particular, it predicts large CP violating effects in $D - \bar{D}$ mixing.

Finally, it is possible that CP violating effects are suppressed because squarks are heavy. If the masses of the first and second generations squarks $m_i$ are larger than the other soft masses, $m_i^2 \sim 100 \tilde{m}^2$ then the Supersymmetric CP problem is solved and the $\epsilon_K$ problem is relaxed (but not eliminated). This does not necessarily lead to naturalness problems, since these two generations are almost decoupled from the Higgs sector.

Notice though that, with the possible exception of $m_{\tilde{b}_R}^2$, third family squark masses cannot naturally be much above $m_Z^2$. If the relevant phases are of $O(1)$, the main contribution to $d_N$ comes from the third family via the two-loop induced three-gluon operator and it is roughly at the present experimental bound when $m_{\tilde{t}_{L,R}} \sim 100 \text{ GeV}$.

Models with the first two squark generations heavy have their own signatures of CP violation in neutral meson mixing. The mixing angles relevant to $D - \bar{D}$ mixing are similar, in general, to those of models of alignment (if alignment is invoked to explain $\Delta m_K$ with $m_{Q,D}^2 \lesssim 20 \text{ TeV}$). However, as $\tilde{u}$ and $\tilde{c}$ squarks are heavy, the contribution to $D - \bar{D}$ mixing is only about one to two orders of magnitude below the experimental bound. This may lead to the interesting situation that $D - \bar{D}$ mixing will first be observed through its CP violating part.

In the neutral $B$ system, $O(1)$ shifts from the Standard Model predictions of CP asymmetries in the decays to final CP eigenstates are possible. This can occur even when the squarks masses of the third family are $\sim 1 \text{ TeV}$ since now mixing angles can naturally be larger than in the case of horizontal symmetries (alignment or approximate universality).

To summarize, measurements of CP violation will provide us with an excellent probe of the flavor and CP structure of supersymmetry. This is clearly demonstrated in Table (1).

7 Final Comments

The unique features of CP violation are well demonstrated by examining the CP asymmetry in $B \to \psi K_S$, $a_{\psi K_S}$, and CP violation in $K_L \to \pi^0 \nu\bar{\nu}$, $a_{\pi^0 \nu\bar{\nu}}$. Model independently, $a_{\psi K_S}$ measures the relative phase between the $B - \bar{B}$ mixing amplitude and the $b \to c\bar{c}d$ decay amplitude (more precisely, the $b \to c\bar{c}s$ decay amplitude times the $K - \bar{K}$ mixing amplitude), while $a_{\pi^0 \nu\bar{\nu}}$ measures the relative phase between the $K - \bar{K}$ mixing amplitude and the $s \to d\nu\bar{\nu}$ decay amplitude. We would like to emphasize the following three points:

(i) The two measurements are theoretically clean to better than $O(10^{-2})$. Thus they can provide the most accurate determination of CKM parameters.
Table 1: CP violating observables in various classes of Supersymmetric flavor models. $\theta_d$, $\theta_A$, $\lambda_{K-\pi^+}$ and $\theta_K$ are defined in eqs. (21), (23), (26) and (29), respectively.

| Model                  | $\frac{dN}{10^{-36}\text{ c cm}}$ | $\theta_d$ | $\theta_A$ | $\frac{\text{Im}(\lambda_{K-\pi^+})}{|\lambda_{K-\pi^+}|}$ | $\theta_K$ |
|------------------------|----------------------------------|------------|------------|----------------------------------------------------------|------------|
| Standard Model         | $\lesssim 10^{-6}$               | 0          | 0          | 0                                                        | $\mathcal{O}(1)$ |
| Exact Universality     | $\lesssim 10^{-6}$               | 0          | 0          | 0                                                        | $\neq \text{SM}$ |
| Approximate CP         | $\approx 10^{-1}$                | $-\beta$   | 0          | $\mathcal{O}(10^{-3})$                                  | $\mathcal{O}(10^{-3})$ |
| Alignment              | $\gtrsim 10^{-3}$                | $\mathcal{O}(0.2)$ | $\mathcal{O}(1)$ | $\mathcal{O}(1)$                                       | $\approx \text{SM}$ |
| Approx. Universality   | $\gtrsim 10^{-2}$                | $\mathcal{O}(0.2)$ | $\mathcal{O}(1)$ | 0                                                        | $\approx \text{SM}$ |
| Heavy Squarks          | $\lesssim 10^{-1}$               | $\mathcal{O}(1)$ | $\mathcal{O}(1)$ | $\mathcal{O}(10^{-2})$                                  | $\approx \text{SM}$ |

In particular, the theoretical accuracy will be better than in the determination of $\sin\theta_C$ from $K \to \pi\ell\nu$.

(ii) As concerns CP violation, the Standard Model is a uniquely predictive model. In particular, it predicts that the seemingly unrelated $a_{\psi K_S}$ and $a_{\pi\nu\bar{\nu}}$ measure the same parameter, that is the angle $\beta$ of the unitarity triangle.

(iii) In the presence of New Physics, there is in general no reason for a relation between $a_{\psi K_S}$ and $a_{\pi\nu\bar{\nu}}$. Therefore, a measurement of both will provide a sensitive probe of New Physics.

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