New Physics in CP Violating B Decays

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We discuss the sensitivity of the CP violating measurements at the upcoming B factories to the presence of physics beyond the Standard Model. We review the three manifestations of CP violation possible in the B meson system. We give examples of decay modes for each of these which are sensitive to new physics, are experimentally feasible, and theoretically clean. Finally, we present techniques to extract Standard Model parameters in the presence of new physics.

I. INTRODUCTION

CP violation has so far only been observed in the decays of neutral K mesons. It is one of the goals of the proposed B factories to find and study CP violation in the decays of B mesons, and thus elucidate the mechanisms by which CP violation manifests itself in the low energy world. There is a commonly accepted Standard Model of CP violation, namely that it is a result of the one physical phase in the 3×3 Cabbibo Kobayashi Maskawa (CKM) matrix [1]. If, however, there is physics beyond the Standard Model, we would expect to see its effects in CP violating B decays.

An important task when trying to detect new physics is to identify decay modes where one could find large deviations from the Standard Model expectations. Thus, one needs to find processes that are not only sensitive to new physics, but also experimentally accessible and for which there exist well defined Standard Model expectations. Moreover, if the presence of new physics is detected, it is then important to try and disentangle the new physics contributions to the CP violation from the Standard Model contribution.

CP violation can manifest itself in B decays due to three distinct mechanisms. "Indirect CP violation" which is caused by a phase in the $B^0 - \bar{B}^0$ mixing amplitude. "Direct CP violation" which is caused by interfering decay amplitudes. And finally, "mixed CP violation" is caused due to interference between the $B^0 - \bar{B}^0$ mixing amplitude and the B decay amplitudes. In this talk we give examples of CP violating B decays for each of these three possible manifestations of CP violation, and which could allow an early detection of new physics. These examples were chosen because they are both experimentally and theoretically "clean". Finally, we discuss a technique based on measuring the CP violation in semi-leptonic B decays that could help separate the Standard Model parameters from the new physics ones.

II. CP VIOLATION IN B DECAYS.

In this section we review the three sources of CP violation in B decays, and give examples for each of these where new physics could affect the Standard Model predictions in an observable way.

A. Indirect CP Violation

This arises due to a phase between Γ_{12} and M_{12}, the absorbtive and dispersive parts of the $B^0 - \bar{B}^0$ mixing amplitude respectively.

It measures the asymmetry in the process

$$B^0 \to \bar{B}^0 \qquad \text{vs.} \qquad \bar{B}^0 \to B^0 \tag{1}$$

and is experimentally measured as

$$a_{SL} \equiv \frac{\Gamma(\bar{B}^0 \to l^+ X) - \Gamma(B^0 \to l^- X)}{\Gamma(\bar{B}^0 \to l^+ X) + \Gamma(B^0 \to l^- X)}, \tag{2}$$

the CP violation in inclusive semi-leptonic B decays. The Standard Model expectation for

$$a_{SL} = \mathrm{Im}(\frac{\Gamma_{12}}{M_{12}}) = \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\phi_{12}, \tag{3}$$

(where ϕ_{12} is the phase between Γ_{12} and M_{12}) calculated using local quark-hadron duality, is $a_{SL}^{SM} < 10^{-3}$ [2] which is unobservably small. Thus, an observation of CP violation in this mode would signal the presence of physics beyond the Standard Model. The smallness of the Standard Model expectation is due to the fact that $|\Gamma_{12}/M_{12}| \sim 10^{-2}$ and because the GIM mechanism results in $\sin\phi_{12} \sim m_c^2/m_b^2 \sim 10^{-1}$. Thus, new physics can enhance a_{SL} by increasing $|\Gamma_{12}/M_{12}|$ and/or $\sin\phi_{12}$.

Most models of new physics introduce new heavy particles that contribute to M_{12} but not Γ_{12}. This could lead to enhancements of $\sin\phi_{12}$, thus allowing $a_{SL} \sim 0.01$ [3], which would be observable in about one year of running at the B factories. In order for new physics to significantly affect Γ_{12}, one would need either large new decay amplitudes into known states that are common to both B^0 and $\bar{B}^0$, or to introduce additional, exotic common final states. Such a scenario could enhance both the factors mentioned above, and could lead to $a_{SL} \sim 0.1$ [4]. This would be detected in the very early stages of data taking at the asymmetric B factories, with only about 10^6 $B^0 - \bar{B}^0$ pairs.

B. Direct CP Violation

This form of CP violation arises from the interference between two or more decay amplitudes for the B mesons to decay to a particular final state. It could arise in the decays of charged as well as neutral B mesons, and measures the asymmetry between the rates for

$$B \to f \qquad \text{vs.} \qquad \bar{B} \to \bar{f} \tag{4}$$

where f is some final state, and $\bar{f}$ is its CP conjugate.

The Standard Model expectations for this kind of CP asymmetry in exclusive modes is hard to calculate. This is because in addition to the well defined CP violating phase between the amplitudes (arising from the CKM matrix) one also needs to compute the CP conserving strong interaction phases between these amplitudes. These can be estimated using any of a number of hadron models, but the uncertainties are large and essentially incalculable. Thus, one is led to consider inclusive modes, where one can use the notion of global quark-hadron duality to produce reliable Standard Model predictions. One such inclusive asymmetry is

$$a_{b \to s\gamma} \equiv \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}, \tag{5}$$

the CP asymmetry in the $b \to s\gamma$ decay.

The Standard Model expectation is $a_{b\to s\gamma} < 0.015$ [5], which is unobservably small for this mode. The presence of new physics could significantly enhance this asymmetry, leading to $a_{b\to s\gamma} \sim 0.1$ [5] which should be observable in the first year at the B factories. Detection of a CP asymmetry at this level would be a clear signal of new physics. Note, that the observed $\mathrm{BR}(b \to s\gamma) = (3.15 \pm 0.54) \times 10^{-4}$ [6] is in good agreement with the Standard Model expectation $\mathrm{BR}(b \to s\gamma) = (3.29 \pm 0.33) \times 10^{-4}$ [7]. Thus, one has to ensure that the proposed new physics effects that contribute to the CP asymmetry in this mode interfere destructively in their contribution to the total decay width for it.

C. Mixed CP Violation

This is caused due to interference between the amplitude for a B to decay into some final state f with the amplitude for a B to first oscillate into a $\bar{B}$ which subsequently decays to the same final state f. It measures the asymmetry in the process

$$B^0 \to \bar{B}^0 \to f \qquad \text{vs.} \qquad \bar{B}^0 \to B^0 \to \bar{f} \tag{6}$$

The theoretical predictions are particularly clean when the final state is a CP eigen state, and there is only one decay amplitude to that state [8]. This is the case for

$$a_{\psi K_S} \equiv \frac{\Gamma(B^0 \to \psi K_S) - \Gamma(\bar{B}^0 \to \psi K_S)}{\Gamma(B^0 \to \psi K_S) + \Gamma(\bar{B}^0 \to \psi K_S)}, \tag{7}$$

the CP asymmetry in $B \to \psi K_S$ which measures $\sin 2\beta$ in the Standard Model. Interestingly, within the Standard Model,

$$a_{\phi K_S} \equiv \frac{\Gamma(B^0 \to \phi K_S) - \Gamma(\bar{B}^0 \to \phi K_S)}{\Gamma(B^0 \to \phi K_S) + \Gamma(\bar{B}^0 \to \phi K_S)}, \tag{8}$$

the CP asymmetry in $B \to \phi K_S$ also measures $\sin 2\beta$ to a high degree of accuracy [9,10]. Since $B_d \to \phi K_S$ is a loop mediated process within the Standard Model, it is not unlikely that new physics could have a significant effect on it [11]. The expected branching ratio and the high identification efficiency for this decay suggests that $a_{\phi K_S}$ is experimentally accessible at the early stages of the asymmetric B factories. Thus, the search for a difference between $a_{\psi K_S}$ and $a_{\phi K_S}$ is a promising way to look for physics beyond the Standard Model [11,12]. A difference $|a_{\psi K_S} - a_{\phi K_S}| > 5\%$ would be an indication of new physics. A similar analysis can be carried out for $a_{\eta' K_S}$, the CP asymmetry in $B \to \eta' K_S$ [13].

III. SEPARATING THE NEW PHYSICS FROM THE STANDARD MODEL

Most models of physics beyond the Standard Model only affect the $B^0 - \bar{B}^0$ mixing amplitude M_{12} without significantly affecting the B decay amplitudes. In that case, one can couple the already measured values of $|V_{ub}|$ and Δm_B with the measurements of $a_{\psi K_S}$ and $a_{\pi\pi}$, the CP violating asymmetries in the decays $B \to \psi K_S$ and $B \to \pi\pi$ respectively, to disentangle the new physics contributions to $B^0 - \bar{B}^0$ mixing from the Standard Model ones [14]. A shortcoming of this approach is that discrete ambiguities in relating $a_{\psi K_S}$ and $a_{\pi\pi}$ to CKM phases leads to multiple solutions for the Standard Model and new physics parameters [14,15]. Thus, one needs additional information to try to resolve these.

Here we use a graphical representation of the data in the M_{12} plane [16] to highlight the information that can be obtained from a measurement of a_{SL}, the CP violation in semi-leptonic B decays. The sensitivity of a_{SL} to new physics has already been discussed in the previous section. We show, in addition, how one can use constraints on, or the observation of, a_{SL} to restrict allowed regions in the Standard Model parameter space [17].

A. The complex M_{12} plane

Under the assumption that the B decay amplitudes are not affected, all the new physics effects can be expressed in terms of one complex number: the new contribution to the dispersive part of the $B^0 - \bar{B}^0$ mixing amplitude, M_{12}. Explicitly, we write

$$M_{12} = r^2 e^{i2\theta} M_{12}^0 \tag{9}$$

where M_{12}^0 represents the Standard Model contribution. We will work in the convention where the phase of M_{12}^0 is 2β, thus that of M_{12} is $2(\beta+\theta) \equiv 2\tilde{\beta}$. (Note, that these phases are measured relative to that of the $b \to c\bar{c}d$ decay amplitude).

The magnitude of M_{12} is well determined:

$$|M_{12}| = \Delta m_B/2 \tag{10}$$

where $\Delta m_B = 0.470 \pm 0.019$ ps^{-1} $=3.09 \times 10^{-13}$ GeV [18]. We can use this to represent the actual value of M_{12} as lying somewhere on the unit circle centered at the origin of the complex M_{12} plane (where all data are rescaled by the experimentally determined central value of $\Delta m_B/2$). The phase of M_{12}, $2\tilde{\beta}$, will be obtained from the CP asymmetry in $B \to \psi K_S$:

$$a_{\psi K_S} = \sin 2\tilde{\beta}. \tag{11}$$

We can plot the allowed Standard Model region in this plane using [19]

$$M_{12}^0 = \frac{\Delta m_B}{2} \left|\frac{V_{tb}V_{td}^*}{0.0086}\right|^2 \left(\frac{\sqrt{B_B} f_B}{200 \text{ MeV}}\right)^2 e^{2i\beta} \tag{12}$$

In the absence of new physics, $M_{12}^0 = M_{12}$ and one can directly use Δm_B to infer a value for $|V_{tb}V_{td}^*|$. Although this is not possible if new physics is present, we can still use the unitarity of the CKM matrix to plot an allowed region for the Standard Model, and thus constrain $|V_{tb}V_{td}^*|$. Using $V_{ub}/V_{cb} = ae^{-i\gamma}$ with $0.06 \le a \le 0.10$ and considering $V_{ud} = 0.975$, $V_{cd} = -0.220$, and $V_{cb} = 0.0395$ [18] as well determined relative to the other uncertainties in the problem, we obtain $|V_{tb}V_{td}^*|e^{-i\beta} = -0.0395(-0.220 + 0.975ae^{-i\gamma})$. Using this relation in Eq. (12), we find that as a covers the stated range and γ varies over 0 to 2π, M_{12}^0 covers a region of the complex M_{12} plane as shown in Fig. 1. M_{12}, the full $B^0 - \bar{B}^0$ mixing amplitude can lie anywhere on the solid circle, and M_{12}^0, the Standard Model contribution lies somewhere in the region between the two dashed curves. If there were no new physics, M_{12} would have to lie on the solid circle in one of the two regions where it intersects with the allowed Standard Model area.

Measuring $a_{\pi\pi}$, the CP asymmetry in $B \to \pi\pi$, would give $\sin 2(\gamma + \tilde{\beta})$ (once the penguin effects are determined) Since, in principle, both $\tilde{\beta}$ and $\gamma + \tilde{\beta}$ are known, γ itself is known. Thus, in principle, the CP violating measurements $a_{\psi K_S}$ and $a_{\pi\pi}$ allow us to disentangle the Standard Model contribution to $B^0 - \bar{B}^0$ mixing from the new physics contribution.

Without additional inputs, however, the measurements of $a_{\psi K_S}$ and $a_{\pi\pi}$ only allow us to extract $2\tilde{\beta}$ up to a two-fold ambiguity, and γ up to an eight-fold ambiguity as shown in Fig. 1. The true value of the $B^0 - \bar{B}^0$ mixing amplitude, M_{12} could be either of the points labeled a or b. The Standard Model contribution to it, M_{12}^0 could lie on any one of the curves labeled γ_1 through γ_8. Although there exist techniques that allow a direct extraction of the angle γ, these are either experimentally difficult [20], or suffer from theoretical uncertainties and sensitivity to new physics [21]. We will now discuss how a measurement of, or constraints on a_{SL} restricts the allowed Standard Model parameter space and helps resolve some of these discrete ambiguities.

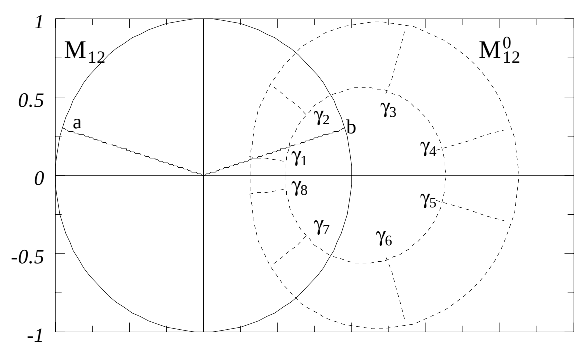

FIG. 1. The complex M_{12} plane in units of $\Delta m_B/2$. We show the two-fold discrete ambiguity in the value of $2\tilde{\beta}$ (the points a and b) and the eight-fold ambiguity in γ (the curves labeled $\gamma_1 ... \gamma_8$) resulting from the measurements $a_{\psi K_S} = 0.3$ and $a_{\pi\pi} =$ -0.7. We have used $\sqrt{B_B} f_B = 200$ MeV in obtaining the Standard Model region.

B. The role of a_{SL}

Within the Standard Model, at leading order we have [2]

$$\frac{\Gamma^0_{12}}{M^0_{12}} = -5.0 \times 10^{-3} \left(1.4\frac{B_S}{B_B} + 0.24 + 2.5\frac{m_c^2}{m_b^2}\frac{V_{cb}V^*_{cd}}{V_{tb}V^*_{td}}\right). \tag{13}$$

where B_S and B_B are the bag factors corresponding to the matrix elements of the operators $Q_S \equiv (\bar{b}d)_{S-P}(\bar{b}d)_{S-P}$ and $Q \equiv (\bar{b}d)_{V-A}(\bar{b}d)_{V-A}$. In the vacuum saturation approximation one has $B_S/B_B = 1$ at some typical hadronic scale, and this expectation is confirmed by a leading order lattice calculation [22]. From the measured value of $|V_{ub}/V_{cb}|$ and CKM unitarity we know that $|\sin\beta| < 0.35$. Then, using $m_c^2/m_b^2 = 0.085$ and $\text{Im}(V_{cb}V^*_{cd}/V_{tb}V^*_{td}) \sim \sin\beta$ leads to the limit $\text{Im}(\Gamma^0_{12}/\text{M}^0_{12}) = a^{SM}_{SL} < 10^{-3}$ which is unobservably small. To simplify matters, we will ignore this small phase in the Standard Model value of Γ_{12}/M_{12}. One can then write

$$\begin{aligned}\frac{\Gamma_{12}}{M_{12}} &= \frac{\Gamma_{12}}{M^0_{12}}\frac{M^0_{12}}{M_{12}} \\ &= -0.8 \times 10^{-2}\frac{e^{-i2\theta}}{r^2}\end{aligned} \tag{14}$$

where we have used Eq. (9) in Eq. (13). Thus, Eqs. (3) and (14) lead to

$$\begin{aligned}a_{SL} &= 0.8 \times 10^{-2}\text{Im}(\frac{M^0_{12}}{M_{12}}) \\ &= 0.8 \times 10^{-2}\frac{\sin 2\theta}{r^2}\end{aligned} \tag{15}$$

Combining Eqs. (9) and (15) one sees that M^0_{12} is given by a vector at an angle 2θ from M_{12} and whose tip is a perpendicular distance $a_{SL}/0.8 \times 10^{-2}$ from it. In Fig. 2 we demonstrate this relation between M_{12}, M^0_{12}, and a_{SL}.

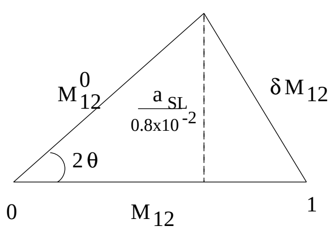

FIG. 2. The relationship between M_{12}, M^0_{12}, and a_{SL}. The perpendicular distance between M_{12} and the tip of the M^0_{12} vector is given by $a_{SL}/0.8 \times 10^{-2}$. Where 0.8×10^{-2} is the calculated central value of Γ^0_{12}/M^0_{12}.

In Fig. 3 we use a hypothetical scenario to highlight the effects of combining $a_{\psi K_S}$ and $a_{\pi\pi}$ with a_{SL} in constraining the allowed Standard Model parameter space. As before, we use $\sqrt{B_B}f_B = 200$ MeV and $0.06 \le a \le 0.10$ to construct the allowed Standard Model region, and assume that $a_{\psi K_S} = 0.3$, and $a_{\pi\pi} = -0.7$ have been measured. We then assume a measurement of $a_{SL} = (-5 \pm 1) \times 10^{-3}$. In this case the Standard Model point must lie in one of the two shaded bands parallel to the M_{12} vectors a and b respectively. For particular values of γ, this construction gives us both $\sin 2\theta$ and r^2, hence one has not only resolved the Standard Model parameters, but also the new physics ones. Note, however, that we have ignored the uncertainties in the calculation of Eq. (13). These uncertainties, and their effects on the analysis presented here are discussed in Ref. [17].

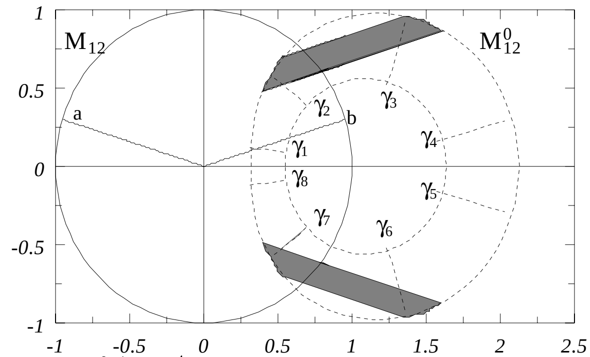

FIG. 3. The complex M_{12} plane in units of $\Delta m_B/2$. The points a and b and the curves $\gamma_1 ... \gamma_8$ result from the measurements $a_{\psi K_S}$= 0.3 and $a_{\pi\pi}$= -0.7. The shaded region corresponds to the allowed Standard Model parameter space coming from a measurement of $a_{SL} = (-5 \pm 1) \times 10^{-3}$. We have used $\sqrt{B_B} f_B = 200$ MeV in obtaining the Standard Model region.

IV. CONCLUSIONS

We have reviewed the three different ways that CP violation can manifest in the B meson system. We have given example of decay modes for each of these classes of CP violation that could allow an early detection of new physics effects. Finally, we have discussed a technique based on the CP violating asymmetry in semi-leptonic B decays that helps us in separating the Standard Model contributions from the new physics ones.

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