CP violation and hints for new physics at the B factories

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Abstract
We report the latest results on CP violation measurements and the tantalizing hints of potential new physics effects obtained at the B factories.

1 Introduction

In the standard model (SM) of particle physics, CP violation occurs due to an irreducible phase appearing in the quark-flavor mixing matrix, called the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which relates the weak interaction eigenstates to that of mass. The study of B meson decays allows us to carry out a multitude of measurements involving the angles and sides of the so-called unitarity triangle (UT), a graphical sketch of the unitarity of the CKM matrix in the complex plane. The raison d’être of the two B-factory experiments – Belle at KEK, Japan and BaBar at SLAC, USA – was to precisely measure various UT parameters. By doing so, they were designed to verify the CP violation mechanism within the SM, as suggested by Kobayashi and Maskawa [1], and to set constraints on potential new physics contributions in the flavor sector.

In these proceedings, we summarize recent results on CP violation, involving three angles of the unitarity triangle, and describe a number of hints for new physics observed with the B-factory experiments.

2 Angles of the unitarity triangle

The UT angles are determined through the measurement of the time dependent CP asymmetry, $A_{CP}(t)$, defined as

$$A_{CP}(t) = \frac{N[B^0(t) \rightarrow f_{CP}] - N[B^0(t) \rightarrow f_{CP}^*]}{N[B^0(t) \rightarrow f_{CP}] + N[B^0(t) \rightarrow f_{CP}^*]}$$

(1)
where \( N[\bar{B}^0/B^0(t) \to f_{CP}] \) is the number of \( \bar{B}^0/B^0 \)s that decay into a \( CP \) eigenstate \( f_{CP} \) after time \( t \). The asymmetry, in general, can be expressed in terms of two components:

\[
A_{CP}(t) = S_f \sin(\Delta m t) + A_f \cos(\Delta m t),
\]

where \( \Delta m \) is the difference in mass of \( B^0 \) mass eigenstates. The sine coefficient \( S_f \) is related to the UT angles, while the cosine coefficient \( A_f \) is a measure of direct \( CP \) violation. For the latter to have a nonzero value, we need at least two competing amplitudes with different weak and strong phase to contribute to the decay final state. As an example, for the decay \( B^0 \to J/\psi K^0_s \), where mostly one diagram contributes, the cosine term is expected to vanish and the sine term is proportional to the UT angle \( \phi_1 \).

The time-dependent \( CP \) asymmetry is, therefore, given as

\[
A_{CP}(t) = -\xi_f \sin(2\phi_1) \sin(\Delta m t),
\]

where \( \xi_f \) is the \( CP \) eigenvalue of the final state. In the case of \( B \) factories, the measurement of \( A_{CP}(t) \) utilizes decays of the \( \Upsilon(4S) \) into two neutral \( B \) mesons, of which one can be completely reconstructed into a \( CP \) eigenstate, while the decay products of the other (called the tag \( B \)) identify its flavor at decay time. The time difference \( t \) between the two \( B \) decays is determined by reconstructing their decay vertices. Finally the \( CP \) asymmetry amplitudes, proportional to the UT angles, are obtained from an unbinned maximum likelihood fit to the proper time distributions separately for events tagged as \( \bar{B}^0 \) and \( B^0 \).

### 2.1 The angle \( \phi_1 \)

The most precise measurement of the angle \( \phi_1 \) is obtained from a study of the decays \( B^0 \to \text{charmonium} + K^{(*)0} \). These decays, known as “golden modes”, mainly proceed via the CKM-favored tree diagram \( b \to c\bar{c}s \) with an internal \( W \) boson emission. The subleading penguin (loop) contribution to the final state, that has a different weak phase compared to the tree diagram, is suppressed by almost two orders of magnitude. This makes \( A_f = 0 \) in Eq. 2 to a very good approximation. Besides the theoretical simplicity, these channels also offer experimental advantages because of the relatively large branching fractions \((\sim 10^{-3})\) and the presence of narrow resonances in the final state, which provides a powerful rejection against combinatorial

\(^1\)An alternative notation of \( \beta, \alpha \) and \( \gamma \), that correspond to \( \phi_1, \phi_2 \) and \( \phi_3 \), respectively, is equally abundant in the literature.
The \( CP \) eigenstates considered for this analysis include \( J/\psi K_S^0, \psi(2S) K_S^0, \chi_{c0} K_S^0, \eta_c K_S^0 \) and \( J/\psi K_L^0 \). The measured world-average value of \( \sin(2\phi_1) \) is \( 0.67 \pm 0.02 \). Figure 1 shows the impact of this measurement by Belle and BaBar, that eventually led to half of the 2008 physics Nobel prize \[2\] being awarded to Kobayashi and Maskawa, when compared to other experiments.

\[
\sin(2\beta) \equiv \sin(2\phi_1)
\]

| Experiment            | Year  | Value   |
|-----------------------|-------|---------|
| BaBar                 | 2009  | 0.69    |
| BaBar \( \chi_{c0} K_S \) | 2009  | 0.69    |
| BaBar \( J/\psi \) (hadronic) \( K_S \) | 2004  | 0.156   |
| Belle \( J/\psi \) \( K^0 \) | 2007  | 0.064   |
| Belle \( \psi(2S) \) \( K \) | 2008  | 0.72    |
| ALEPH \( \rho \rho \) | 2000  | 0.84    |
| OPAL \( \rho \pi \) | 1998  | 3.20    |
| CDF \( \pi \pi \) | 2000  | 0.79    |
| Average \( HFAG \) |       | 0.67    |

Figure 1: Average of \( \sin(2\phi_1) \) from all experiments, as compiled by the HFAG \[3\].

2.2 The angle \( \phi_2 \)

Decays of \( B \) mesons to the final states \( hh \) (\( h = \rho \) or \( \pi \)), dominated by the CKM-suppressed \( b \to u \) transition, are sensitive to the UT angle \( \phi_2 \). The presence of \( b \to d \) penguin diagrams, however, complicates the situation by introducing additional phases such that the measured parameter is no more \( \phi_2 \) alone, rather an effective value \( \phi_2^{\text{eff}} = \phi_2 + \delta\phi_2 \). (Note that the same prescription \( \text{vis-\text{a}-\text{vis}} \) penguin pollution also applies to other UT angles, wherever appropriate.) At present, the most precise measurement of this angle is obtained in the analysis of the decays \( B \to \rho \rho \). Combining with additional constraints coming from \( B \to \rho \pi \) and \( B \to \pi \pi \), we measure \( \phi_2 = (89.0^{+14.4}_{-12.2})^\circ \) \[4\].
2.3 The angle $\phi_3$

The angle $\phi_3$ is measured by exploiting the interference between the decays $B^- \to D^{(*)0}K^{(*)-}$ and $B^- \to D^{(*)0}\overline{K}^{(*)-}$, where both $D^0$ and $\overline{D}^0$ decay to a common final state. This measurement can be performed in three different ways: utilizing decays of $D$ mesons to CP eigenstates [5], making use of doubly Cabibbo-suppressed decays of the $D$ meson [6], and exploiting the interference pattern in the Dalitz plot of $D \to K^0_S\pi^+\pi^-$ decays [7]. Currently, the last method provides the strongest constraint on $\phi_3$. Combining all related measurements from Belle and BaBar, the world-average value is found to be $\phi_3 = (73^{+19}_{-24})^\circ [4]$.

![Figure 2: Constraints on the UT coming from the measurements of angles only (left) and using all relevant experimental inputs (right).](image)

In Fig. 2 we summarize the constraints on the UT coming from the measurements of angles only, as well as after including other experimental inputs. To a very good approximation, the Kobayashi-Maskawa formalism is found to be the right description of CP violation in the SM. Needless to say that we still need to improve the precision on the third angle $\phi_3$ – one has just made a head-start! Similarly, we expect the errors on other two angles to shrink further, e.g., once Belle analyzes its full $\Upsilon(4S)$ dataset.

3 Search for physics beyond the SM

In this section we attempt to enumerate various hints for, or constraints on, potential new physics contributions, as observed with the $B$ factories.

3.1 Measured $\sin(2\phi_1)$ with the penguins

As $\sin(2\phi_1)$ is the most precisely measured observable concerning CP violation in $B$ decays, we can use it as a “Standard Candle” to set constraints on new physics by looking for possible deviations from this value in a number
of ways. One such is the comparison of the values of $\sin(2\phi_1^{\text{eff}})$ measured in penguin dominated decays with the world-average value of $\sin(2\phi_1)$, coming from decays involving charmonium final states. The caveat to making such a comparison is that the penguin modes may have additional topologies that could lead to a difference between $\sin(2\phi_1)$ and $\sin(2\phi_1^{\text{eff}})$. If these SM corrections, $\Delta_{\text{SM}}$, are well known then any residual difference $\Delta S = \sin(2\phi_1^{\text{eff}}) - \sin(2\phi_1) - \Delta_{\text{SM}}$ would be from new physics. It has been recently pointed out [8] that by comparing the penguin to tree channels one remains insensitive to possible new physics contribution common to both. Therefore, it is important to compare the directly measured values of $\sin(2\phi_1^{\text{eff}})$ with the predictions of SM-based constraints for the same observable. Figure 3 summarizes the different constraints on $\sin(2\phi_1^{\text{eff}})$, where the maximum difference between the measured and indirect values has a significance above 2 standard deviations.

![Figure 3: Measured values of $\sin(2\phi_1)$ in (yellow/light-shaded) charmonium decays, (blue/dark-shaded) penguin decays, and (green/medium-shaded) inferred from indirect measurements [8].](image)

### 3.2 Direct CP violation in B decays

Both Belle and BaBar have carried out a number of sensitive CP violation measurements in various B decays. Most notable of them is the decay $B^0 \rightarrow K^+\pi^-$, where direct CP violation has been established beyond any doubt – the measured CP asymmetry is $(−9.8^{+1.2}_{−1.1})\%$. There are a number
of interesting evidences at the level of 3 standard deviations in the decays $B^0 \rightarrow \eta K^{*0}$, $B^- \rightarrow \eta K^-$, $B^- \rightarrow \rho^0 K^-$, $B^0 \rightarrow \rho^+ \pi^-$, and $B^- \rightarrow \overline{D}^{(*)0} K^-$. Another important result has come out from $B^- \rightarrow K^- \pi^0$, with the CP asymmetry $(+5.0 \pm 2.5)\%$. This in contrast to the result of $B^0 \rightarrow K^+ \pi^-$, where similar Feynman diagrams contribute at the tree level, tells us that it could be either due to a large contribution from the color-suppressed tree diagram, or from possible new physics contribution in the electroweak penguin, or from both. Before firmly concluding anything, it is suggested [10] to check the CP violation result from the decay $B^0 \rightarrow K^0 \pi^0$, with a larger dataset.

3.3 Polarization puzzle in $B \rightarrow VV$

For a $B$ meson decaying to two vector particles, $B \rightarrow VV$, theoretical models based on QCD factorization [11] or perturbative QCD [12] predict the fraction of longitudinal fraction $f_L$ to be approximately $1 - (m_V^2/m_B^2)$, where $m_{V(B)}$ is the mass of the vector ($B$) meson, for tree-dominated decays. As an example, in the case of $B \rightarrow \rho \rho$ the prediction for $f_L$ is close to 0.9, which matches well with the measurement [3]. For decays dominated by the penguin transition, however, there is a large discrepancy between predictions ($\sim 0.75$) and observations, that tend to cluster around 0.5. This unexpected result on polarization, mostly driven by the measurement of $B \rightarrow \phi K^*$, has motivated several further studies.

3.4 Constraints on the charged Higgs

The purely leptonic decay $B^- \rightarrow \tau^- \nu_\tau$ provides an excellent probe for the charged Higgs that could potentially appear in the annihilation of $b$ and $\bar{u}$ quarks similar to the SM diagram, where a $W^-$ boson is created in the annihilation process (see Fig. 4). For instance, if we take the prediction...
of the two-Higgs doublet model [13], the observed branching fraction could be enhanced or suppressed by a factor of $(1 - \frac{m_B^2 \tan^2 \beta}{m_H^2})^2$, where $m_H$ is the mass of the charged Higgs and $\tan \beta$ is the ratio of the two Higgs vacuum expectation values. On the experimental side, identifying the decay $B^- \rightarrow \tau^- \nu_\tau$, which involves at least two neutrinos in the final state, is a real challenge. Both Belle and BaBar have made the best use of their detector hermiticity and particle identification capability, and in doing so they obtain [14] a branching fraction world-average of $(1.73 \pm 0.35) \times 10^{-4}$ for the decay. The SM prediction is $(1.20 \pm 0.25) \times 10^{-4}$, where the dominant uncertainties come from the error in the CKM matrix element $V_{ub}$ and the $B$-meson decay constant. Comparing the SM expectation with the measurement, we derive a constraint on $m_H$ as a function of $\tan \beta$. This constraint is well complimented by the measurement of $B \rightarrow D^{(*)} \tau \nu_\tau$ [15] and the inclusive $b \rightarrow s \gamma$ measurement [16]. It is worth noting that the combined result [17], which excludes a charged Higgs up to a mass of 600 GeV/$c^2$ for $\tan \beta > 60$ and 300 GeV/$c^2$ for $\tan \beta > 30$, is already comparable to what is expected for a direct search [18] using a 30 fb$^{-1}$ data sample at the LHC.

### 3.5 $B \rightarrow K^{(*)} \ell^+ \ell^-$: Any smoking gun?

The decay channel $b \rightarrow s \ell^+ \ell^-$ is an experimenters delight, since it offers many interesting observables that can be measured in the decays of $B$ mesons to both inclusive and exclusive $s \ell^+ \ell^-$ final states, where $s$ denotes a strangeness-one meson. In particular, for the exclusive mode $K^{(*)} \ell^+ \ell^-$ the observables include $f_L$, the forward-backward asymmetry $A_{FB}$, the isospin asymmetry $A_I$, and the ratio of rates to $e^+e^-$ and $\mu^+\mu^-$ final states (lepton flavor ratio). Recent measurements at the $B$ factories [19, 20] show that the branching fraction and the lepton flavor ratio agree with SM expectations. However, a deviation from the SM is indicated in $A_{FB}$ (Fig. 5), albeit with large statistical uncertainty. We need more statistics than currently available, which would be possible with the future experiments [21], to either confirm or refute this tantalizing hint. If it is finally turned out to be real, it would be a clean signature of new physics [22, 23].

### 4 Conclusions

The two $B$-factory experiments have performed exceptionally well, each producing an average over 400 high-quality journal publications within only ten years of their inception. What we present here, is a small sampling of their recent highlighted results. It is fair to say that the SM continues to hold
its ground in the flavor sector, though there are some hints of new physics available, which should be investigated with more data.

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