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

$$A_{CP}(t) = \frac{N[\overline{B}^0(t) \to f_{CP}] - N[B^0(t) \to f_{CP}]}{N[\overline{B}^0(t) \to f_{CP}] + N[B^0(t) \to f_{CP}]}, \tag{1}$$

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

$$A_{CP}(t) = S_f \sin(\Delta m t) + A_f \cos(\Delta m t), \quad (2)$$

where Δm 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 ϕ_1[1]. The time-dependent *CP* asymmetry is, therefore, given as

$$A_{CP}(t) = -\xi_f \sin(2\phi_1) \sin(\Delta m t), \quad (3)$$

where ξ_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 $\overline{B}^0$ and B^0.

2.1 The angle ϕ_1

The most precise measurement of the angle ϕ_1 is obtained from a study of the decays $B^0 \to$ 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 β, α and γ, that correspond to ϕ_1, ϕ_2 and ϕ_3, respectively, is equally abundant in the literature.

background. 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 ± 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.

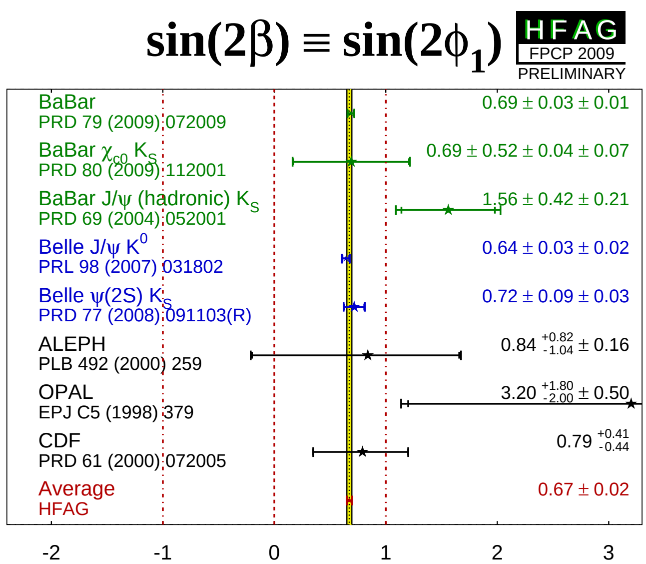

Figure 1: Average of $\sin(2\phi_1)$ from all experiments, as compiled by the HFAG [3].

2.2 The angle ϕ_2

Decays of B mesons to the final states hh ($h = \rho$ or π), dominated by the CKM-suppressed $b \to u$ transition, are sensitive to the UT angle ϕ_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 ϕ_2 alone, rather an effective value $\phi_2^{\rm eff} = \phi_2 + \delta\phi_2$. (Note that the same prescription *vis-a-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 $\phi_2 = \left(89.0^{+4.4}_{-4.2}\right)^\circ$ [4].

2.3 The angle ϕ_3

The angle ϕ_3 is measured by exploiting the interference between the decays $B^- \to D^{(*)0}K^{(*)-}$ and $B^- \to \overline{D}^{(*)0}K^{(*)-}$, 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 $D \to K_S^0\pi^+\pi^-$ decays [7]. Currently, the last method provides the strongest constraint on ϕ_3. Combining all related measurements from Belle and BaBar, the world-average value is found to be $\phi_3 = \left(73^{+19}_{-24}\right)^\circ$ [4].

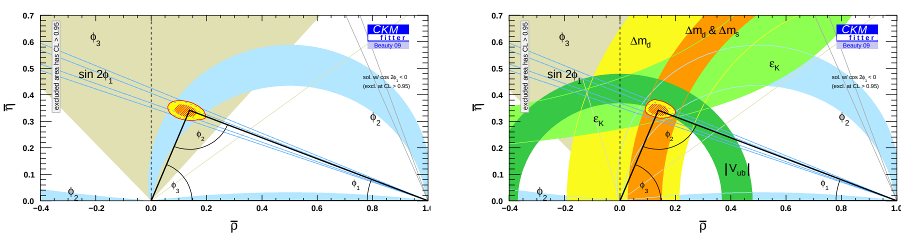

Figure 2: Constraints on the UT coming from the measurements of angles only (left) and using all relevant experimental inputs (right).

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 ϕ_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 $\sin(2\phi_1^{\rm eff})$ 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 $\sin(2\phi_1^{\rm eff})$. If these SM corrections, $\Delta_{\rm SM}$, are well known then any residual difference $\Delta S = \sin(2\phi_1^{\rm eff}) - \sin(2\phi_1) - \Delta_{\rm SM}$ 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 $\sin(2\phi_1^{\rm eff})$ with the predictions of SM-based constraints for the same observable. Figure 3 summarizes the different constraints on $\sin(2\phi_1^{\rm eff})$, where the maximum difference between the measured and indirect values has a significance above 2 standard deviations.

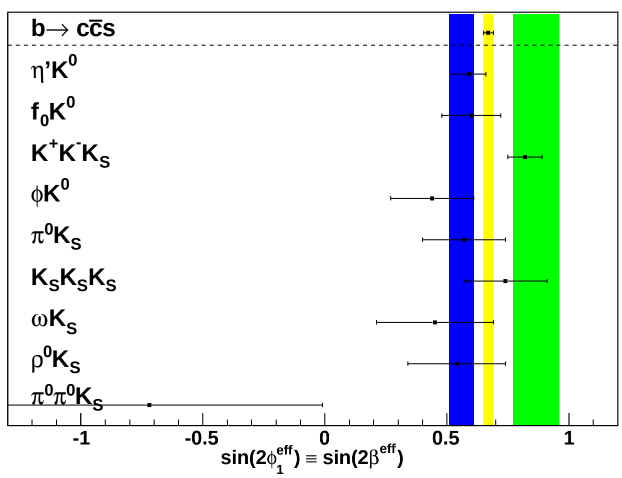

Figure 3: Measured values of $\sin(2\phi_1)$ in (yellow/light-shaded) charmonium decays, (blue/dark-shaded) penguin decays, and (green/medium-shaded) inferred from indirect measurements [8].

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 $B^0 \to K^+\pi^-$, 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 $B^0 \to \eta K^{*0}$, $B^- \to \eta K^-$, $B^- \to \rho^0 K^-$, $B^0 \to \rho^+\pi^-$ and $B^- \to \overline{D}^{(*)0} K^-$. Another important result has come out from $B^- \to K^-\pi^0$, with the *CP* asymmetry $(+5.0 \pm 2.5)\%$. This in contrast to the result of $B^0 \to K^+\pi^-$ [9], 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 $B^0 \to K^0\pi^0$, with a larger dataset.

3.3 Polarization puzzle in $B \to VV$

For a B meson decaying to two vector particles, $B \to VV$, 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 $B \to \rho\rho$ 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 (~ 0.75) and observations, that tend to cluster around 0.5. This unexpected result on polarization, mostly driven by the measurement of $B \to \phi K^*$, has motivated several further studies.

3.4 Constraints on the charged Higgs

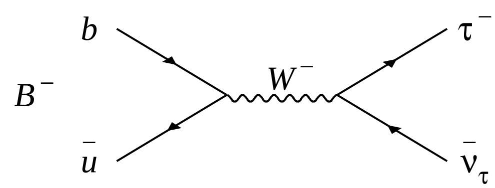

Figure 4: Purely leptonic B decays proceed via the annihilation of quark-antiquark into a W boson (or, potentially into a charged Higgs boson).

The purely leptonic decay $B^- \to \tau^-\overline{\nu}_\tau$ 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 $(1 - m_B^2 \tan^2\beta/m_H^2)^2$, 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 $B^- \to \tau^-\nu_\tau$, 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 $B \to D^{(*)}\tau\nu_\tau$ [15] and the inclusive $b \to s\gamma$ 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 $B \to K^{(*)}\ell^+\ell^-$: Any smoking gun?

The decay channel $b \to s\ell^+\ell^-$ 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

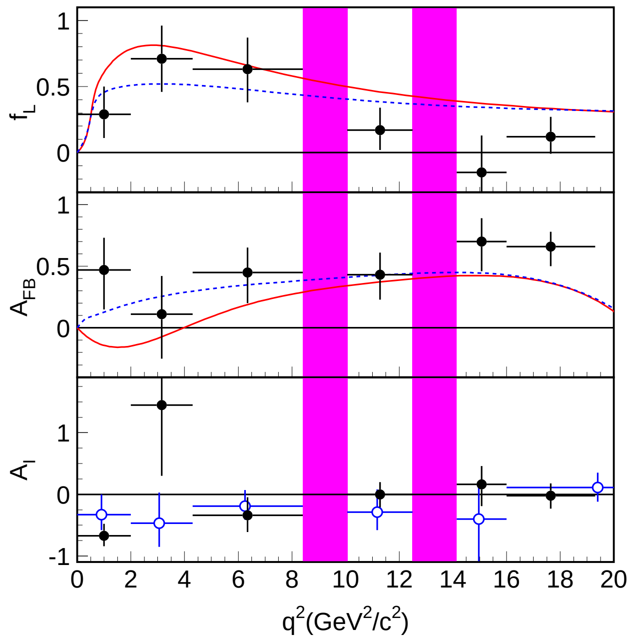

Figure 5: Results for (top) f_L and (middle) A_{FB} in $K^*\ell^+\ell^-$ as a function of q^2, together with the solid (dotted) curve representing the SM ($C_7^{\rm NP} = -C_7^{\rm SM}$) prediction. (Bottom) The plot of A_I *vs.* q^2 for the $K^*\ell^+\ell^-$ (filled circles) and $K\ell^+\ell^-$ (open circles) modes. The two shaded regions are veto windows to reject events containing a J/ψ or a $\psi(2S)$.

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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