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Results on CP violation and CKM UT angles from Belle and BaBar

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We report recent results on CP violation measurements from the two B-factory experiments, Belle and BaBar.

1. INTRODUCTION

In the standard model (SM), CP violation occurs due to a single, irreducible phase appearing in the 3×3 quark-flavor mixing matrix, called the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1], which relates quark mass eigenstates to weak eigenstates. Unitarity of the CKM matrix yields a set of relations among its elements that can be depicted as triangles in the complex plane. In particular, the unitarity condition $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ gives rise to the so-called unitarity triangle (UT), whose sides and angles are related to the magnitudes and phases of the CKM matrix elements V_{id} and V_{ib}, where $i = u, c, t$. The main goal of the two B-factory experiments – Belle [2] at KEK, Japan and BaBar [3] at SLAC, USA – is to overconstrain the UT through precise measurements of its sides and angles. By doing so, they are designed to verify whether the CKM mechanism is the correct description of CP violation in the SM, and to set constraints on possible new physics effects that could lead to inconsistencies among these measurements.

In these proceedings, we summarize recent results on CP violation, involving three UT angles, from Belle and BaBar. After a decade of successful operation, during which many records are made and broken subsequently, these two B-factory experiments have together collected over 10^9 $B\overline{B}$ pairs at the $\Upsilon(4S)$ peak. The KEKB accelerator of the B factory in Japan holds the current world record with a peak luminosity $2.1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Results reported here comprise the full $\Upsilon(4S)$ data from BaBar ($\sim 465 \times 10^6$ $B\overline{B}$) and a large fraction of the $\Upsilon(4S)$ data available with Belle ($\sim 535 \times 10^6$ $B\overline{B}$).

2. ANGLES OF THE UNITARITY TRIANGLE

The UT angles are mostly determined through the measurement of the time-dependent CP asymmetry,

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

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

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

where Δm is the mass difference between the two B^0 mass eigenstates. (Note that BaBar uses a notation $C_f = -A_f$.) The sine coefficient S_f here 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, one needs at least two competing amplitudes with different weak and strong phases to contribute to the decay final state. As an example, for the decay $B^0 \to J/\psi K_S^0$, where mostly one diagram contributes, the cosine term is expected to vanish and the sine term is proportional to the UT angle ϕ_1[2]. The time-dependent CP asymmetry is,

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[2]An alternative notation of β, α, and γ corresponding to ϕ_1, ϕ_2, and ϕ_3, respectively, is adopted by BaBar.

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therefore, given as

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

where ξ_f is the CP eigenvalue of the final state f_{CP}. 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 fully reconstructed into a CP eigenstate, while decay products of the other (called the tag B) identify its flavor at the 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 a 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, having 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 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 the combinatorial background. The CP eigenstates considered for this analysis include $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c0}K^0_S$, $\eta_c K^0_S$, and $J/\psi K^0_L$.

BaBar has updated the $\sin(2\phi_1)$ measurement with its full $\Upsilon(4S)$ data sample [4]. The result is $\sin(2\phi_1) = 0.687 \pm 0.028(\text{stat}) \pm 0.012(\text{syst})$. Combined with Belle's result based on 535×10^6 $B\overline{B}$ pairs [5], $\sin(2\phi_1) = 0.642 \pm 0.031(\text{stat}) \pm 0.017(\text{syst})$, the world-average value is $\sin(2\phi_1) = 0.672 \pm 0.023$ [6]. The result, having a precision of 3%, serves as a firm reference point for the SM. The world-average value of A_f is 0.004 ± 0.019 [6], which is consistent with zero as expected. This major accomplishment of the B factories has been cited [7] as leading to half of the 2008 physics Nobel prize being awarded to Kobayashi and Maskawa. Figure 1 compares the impact of measurements from Belle and BaBar with those from the other experiments.

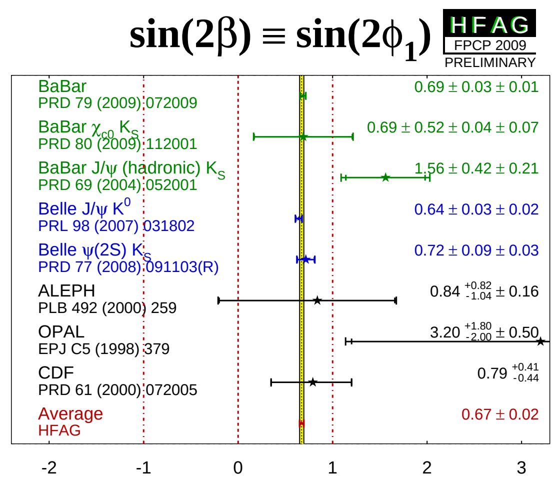

Figure 1. Average of $\sin(2\phi_1)$ from all experiments, as compiled by the HFAG.

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 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 $\phi_2^{\text{eff}} = \phi_2 + \delta\phi_2$. Through an isospin analysis [8] one can isolate the tree contribution, and hence the ϕ_2 value. 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 $\phi_2 = \left(89.0^{+4.4}_{-4.2}\right)^\circ$ [9].

2.3. The angle ϕ_3

The angle ϕ_3 cannot be extracted using time-dependent CP violation study in a similar fash-

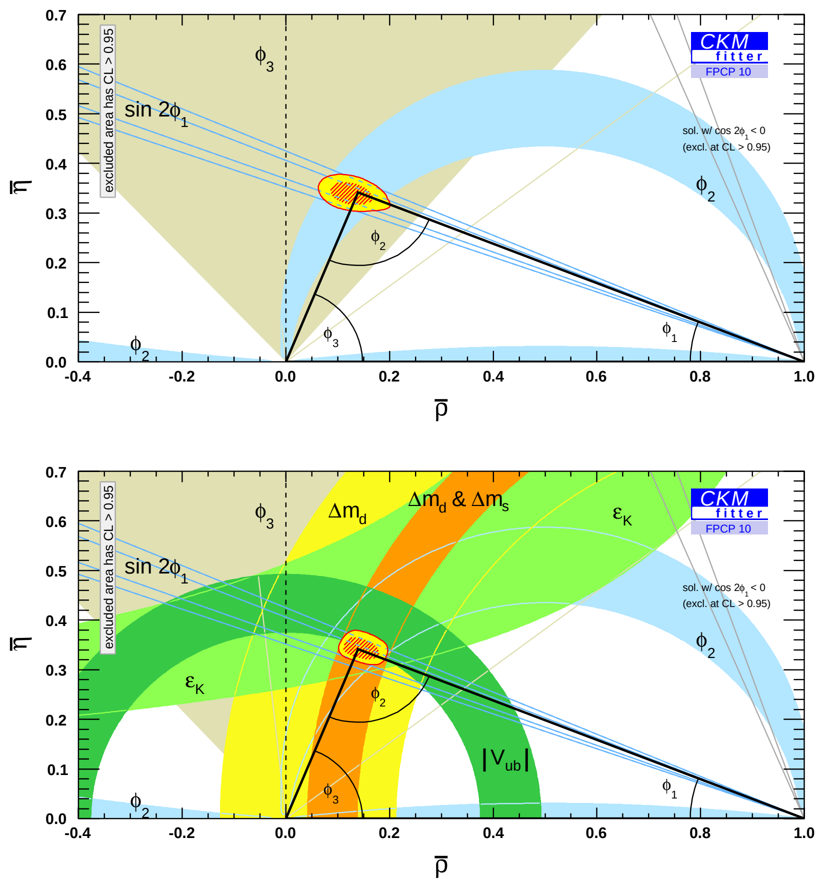

Figure 2. Constraints on the UT [9] coming from the measurements of angles only (above) and using all relevant experimental inputs (below).

ion as was done for other two angles. It is rather measured by exploiting the interference between $B^- \to D^{(*)0}K^{(*)-}$ (dominated by the $b \to c$ tree diagram with an external W emission) and $B^- \to \overline{D}^{(*)0}K^{(*)-}$ (dominated by the color-suppressed $b \to u$ tree diagram with an internal W emission). Here, both D^0 and $\overline{D}^0$ decay to a common final state. This measurement can be performed in three different ways: (a) by utilizing decays of D mesons to CP eigenstates, such as $\pi^+\pi^-$, K^+K^- (CP even) or $K^0_S\pi^0$, ϕK^0_S (CP odd) [10], (b) by making use of doubly Cabibbo suppressed decays of D mesons, *e.g.*, $D^0 \to K^+\pi^-$ [11], or (c) by exploiting the interference pattern in the Dalitz plot of the decays $D \to K^0_S\pi^+\pi^-$ [12]. The first two methods are theoretically clean but suffer from low statistics. On the other hand, the Dalitz method currently provides the strongest constraint on ϕ_3. Combining all recent measurements from Belle [13] and BaBar [14], the world-average value is found to be $\phi_3 = \left(70^{+14}_{-21}\right)^\circ$ [9].

2.4. Putting them together

In Fig. 2 we summarize constraints on the UT coming from the measurements of angles only, as well as after including other experimental inputs. To a good approximation, the CKM framework is found to be the right description of CP violation in the SM. Needless to say that the precision on the third angle ϕ_3 ought to be improved. Similarly, we expect errors on the other two angles to shrink further, *e.g.*, once Belle analyzes its full $\Upsilon(4S)$ dataset.

2.5. Probing new physics in *CP* violation

As $\sin(2\phi_1)$ is the most precisely measured observable concerning CP violation in B decays, one 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 results are summarized in Fig. 3, where the largest discrepancy is found to be at the level of 2 standard deviations. A caveat one should be aware of while 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. Nevertheless, looking at Fig. 3 it is fair to say that we need more data before drawing a firm conclusion whether the observed deviations are due to some new physics effects or a play of statistics.

3. DIRECT *CP* VIOLATION

Both Belle and BaBar have intensively searched for direct CP violation in several B decays. The most notable result comes from the decay $B^0 \to K^+\pi^-$, where direct CP violation has been established beyond any doubt: the measured CP asymmetry is $\left(-9.8^{+1.2}_{-1.1}\right)\%$. This is in contrast to the result from $B^- \to K^-\pi^0$ having a CP asymmetry $(+5.0 \pm 2.5)\%$. Since both the decays are expected to proceed via similar Feynman diagrams at the tree level, the discrepancy between the two measurements [15] 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 a mixture of both. Before concluding anything, it has been suggested [16] to improve the precision on CP violation results of the decay $B^0 \to K^0\pi^0$ [17] using more data. In addition to these results, there are also a number of interesting evidences for direct CP violation at a level of 3 standard deviations in the decays $B^0 \to \eta K^{*0}$, $B^- \to \eta K^-$, $B^- \to \rho^0 K^-$, $B^0 \to \rho^+\pi^-$, $B^- \to f_2(1270)K^-$ and $B^- \to \overline{D}^{(*)0}K^-$.

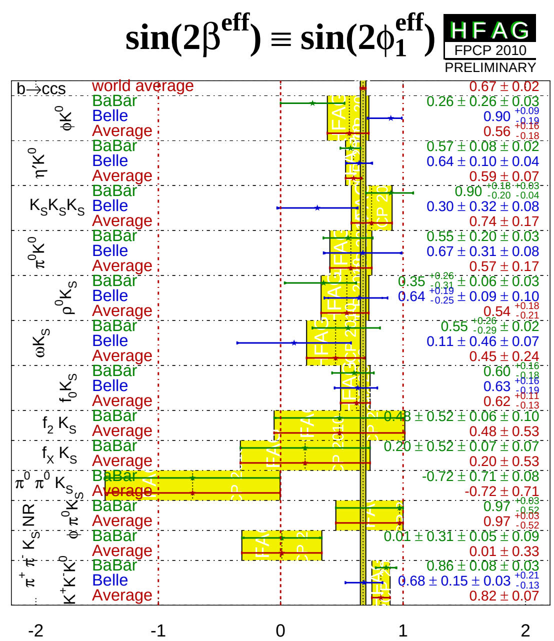

Figure 3. Time-dependent CP asymmetry measured in the $b \to s$ penguin decay channels [6].

4. SUMMARY

Thanks to the excellent performance of the two B factories, studies using a large sample of e^+e^- collision data at the $\Upsilon(4S)$ peak have now established the CKM framework as the only source of CP violation in the SM. There are a number of intriguing hints, such as time-dependent CP asymmetry in penguin dominated decays and direct

CP asymmetry difference in $B \to K\pi$, at various levels of significance. These results need to be clarified with much larger data samples. Towards this end, we are eagerly looking forward to final updates from Belle in several important channels, *e.g.* the angle ϕ_1 in the $B \to$ charmonium $+ K^{(*)0}$ decays, while warming up to the next generation of flavor experiments: LHCb and super flavor factories.

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