STATUS OF CKM ANGLE MEASUREMENTS, A REPORT FROM BABAR AND BELLE

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I will review the latest developments in determining the CP-violating phases of the CKM matrix elements from measurements by the BaBar and BELLE experiments at the high-luminosity B factories (PEP-II and KEKB). The emphasis will be on the angle γ/ϕ_3 of the Unitarity Triangle, which is the relative phase $\arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$, or the CP-violating phase of the $b \to u$ transition in the commonly used Wolfenstein convention.

1 Introduction

Only 8 years after the experimental discovery of CP violation [1], Kobayashi and Maskawa noted in a seminal paper [2] that extending the quark sector to 3 generations would naturally introduce a CP violating phase in weak interactions. The BaBar and BELLE experiments and the high-luminosity B factories (PEP-II and KEKB) at the SLAC National Accelerator Laboratory and KEK were designed and built with the primary goal of performing the first precision tests of the Kobayashi-Maskawa theory using CP asymmetry measurements in B decays. The unitarity constraint involving the 1st and 3rd columns of the CKM quark mixing matrix $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ is often visualized as a triangle ("The Unitarity Triangle") in the complex plane. The CP asymmetry measurements from BaBar and BELLE can be directly related to the interior angles of the Unitarity Triangle with little theoretical uncertainty [3].

The current experimental constraints on the Wolfenstein parameters $\bar{\rho}$ and $\bar{\eta}$, which give the coordinates of the tip of the rescaled Unitarity Triangle in the complex plane, are shown in Figure 1. The analysis was done by two independent groups using different statistical approaches (frequentist for CKMfitter [4] and Bayesian for UTfit [5]). However, the conclusions are the same – the CP violation parameters of the CKM matrix are overconstrained and the Kobayashi-Maskawa theory has been experimentally confirmed. Kobayashi and Maskawa were awarded half of the 2008 Nobel Prize in physics.

The constraint on the angle β (or ϕ_1), from the amplitude of the proper-time-dependent CP asymmetry of $B^0 \to J/\psi K_S^0$ and other $b \to c\bar{c}s$ decays, is the strongest, with a one standard deviation uncertainty of less than one degree. The most difficult angle to measure is γ (or ϕ_3). Recent progress has been made over the past year in improving our measurements of γ and I will focus on this for the rest of this writeup.
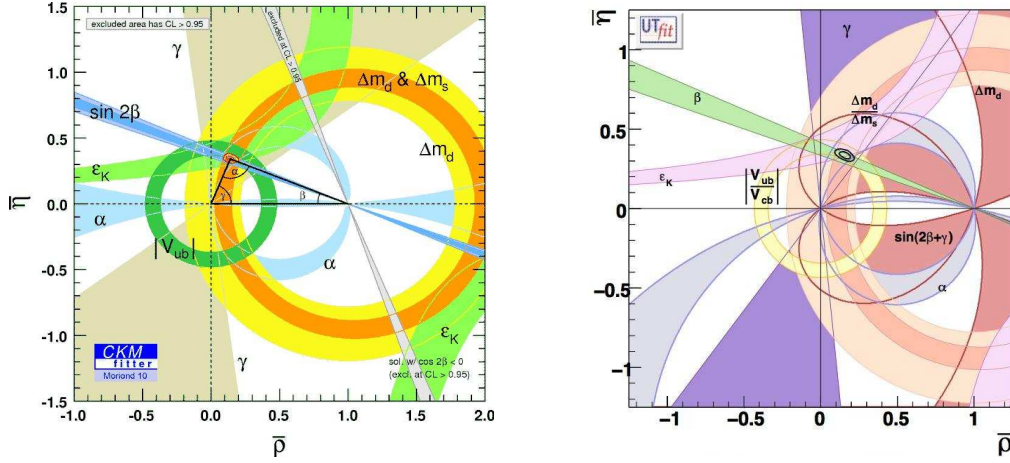
Figure 1: Experimental constraints on the Wolfenstein parameters $\bar{\rho}$ and $\bar{\eta}$. The CKMfitter group (left) uses a frequentist statistical approach, while the UTfit group (right) uses a Bayesian statistical approach.

2 Methods for measuring γ (or ϕ_3)

The angle $\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ can be measured from direct CP violation in B decays where both $b \to c$ and $b \to u$ decay amplitudes contribute to the same final state and interfere with each other. The methods[6,7,8] that currently give the strongest constraints on γ use decays of the type $B^- \to D^0 K^-$ (from a $b \to c\bar{u}s$ decay) with $B^- \to \bar{D}^0 K^-$ (from a $b \to u\bar{c}s$ decay) where the D decays to a final state that is accessible from both the D^0 and the $\bar{D}^0$. These are both tree level b decays, so the interpretation of the measurements in terms of γ is theoretically extremely clean. However, the ratio of the hadronic B decay amplitudes $r_b \equiv |A(b \to u)/A(b \to c)|$ and the CP-conserving (strong) phase difference δ_b between $A(b \to u)$ and $A(b \to c)$ can not be calculated with precision and must be experimentally determined. In addition to γ, all of the various $B \to DK$ methods share the same hadronic parameters (r_b and δ_b). Decays of the type $B \to D^*K$ and $B \to DK^*$ may also be used with each distinct B decay having its own r_b and δ_b.

The precision of the current γ measurements is limited due to two factors. First, the signal samples of $B \to DK$ are relatively small (at most 100's of events) due to CKM suppression of the decay amplitudes. The second factor is that r_b is relatively small (about 0.10 due to CKM and color suppression) which limits the size of the interference that we are trying to measure.

3 The $B \to DK$, D decay Dalitz approach

The best individual measurements of γ come from using a 3-body D decay (either $K_S^0\pi^+\pi^-$ or $K_S^0K^+K^-$) in the $B \to DK$ method. The amplitude ($\mathcal{A}_D$) and CP-conserving phase of the $D \to K_S^0h^+h^-$ decay varies accross the D decay Dalitz plot, which is the decay intensity in the plane of $s^+ = m^2(Kh^+)$ vs $s^- = m^2(Kh^-)$. Assuming no CP violation in D decays, the $\bar{D}^0$ Dalitz plot is the same as the the D^0 Dalitz plot after reflection through the $s^+ = s^-$ diagonal, i.e. $\mathcal{A}_{\bar{D}}(s^+, s^-) = \mathcal{A}_D(s^-, s^+)$. The parameters of a D decay Dalitz amplitude model are determined from the data by fitting a very clean, high statistics sample of flavor-tagged D^0 mesons from $D^{*+} \to D^0\pi^+$ decays produced in $e^+e^- \to c\bar{c}$ events. The overall amplitudes for the processes $B^\pm \to DK^\pm$; $D \to K_S^0h^+h^-$ are given by

$$A(B^+; s^+, s^-) \quad \propto \quad \mathcal{A}_D(s^-, s^+) \; + \; r_b\, e^{+i\gamma+i\delta_b} \, \mathcal{A}_D(s^+, s^-) \qquad (1)$$

$$A(B^-; s^+, s^-) \quad \propto \quad \mathcal{A}_D(s^+, s^-) \; + \; r_b\, e^{-i\gamma+i\delta_b} \, \mathcal{A}_D(s^-, s^+) \qquad (2)$$

B decay mode	BELLE ($K_S^0 \pi^+ \pi^-$) 657 M $B\bar{B}$	BaBar ($K_S^0 \pi^+ \pi^-$) 468 M $B\bar{B}$	BaBar ($K_S^0 K^+ K^-$) 468 M $B\bar{B}$
$B^\pm \to DK^\pm$	757 ± 30	920 ± 35	142 ± 14
$B^\pm \to D^*(D\pi^0)K^\pm$	168 ± 15	246 ± 22	53 ± 11
$B^\pm \to D^*(D\gamma)K^\pm$	83 ± 10	191 ± 19	31 ± 7
$B^\pm \to DK^{*\pm}$		163 ± 17	28 ± 6

Table 1: Signal yields for the samples used in the final fits for the CP parameters. These results are preliminary.

where the first term is from the $b \to c$ transition and the second is from the $b \to u$ transition. The relative weight of the two terms, both in magnitude and CP-conserving phase, is known from $\mathcal{A}_D(s^+, s^-)$, apart from an overall factor of $r_b\, e^{\pm i\gamma + i\delta_b}$ that is experimentally determined in the data analysis.

3.1 The $B \to DK$, D decay Dalitz data samples

Both BaBar and BELLE have shown updates to their γ measurements using the D decay Dalitz technique in the past year. The BaBar collaboration has analyzed their full dataset, which contains 468 million $B\bar{B}$ events [9], while the Belle collaboration has shown results using 657 million $B\bar{B}$ events [10]. The BaBar results with their full dataset were shown for the first time in this talk. Both the BaBar and BELLE analyses have been submitted for publication and are still preliminary. Both experiments have done the analysis for the following three B decays: $B^\pm \to DK^\pm$, $B^\pm \to D^*(D^0\pi^0, D^0\gamma)K^\pm$, and $B^\pm \to DK^{*\pm}(K_S^0\pi^\pm)$ using the $D \to K_S^0\pi^+\pi^-$ decay mode. The BaBar analysis also includes results using $D \to K_S^0 K^+ K^-$.

The signal is separated from combinatoric background using two standard reconstruction variables in the center of mass frame: $m_{\text{ES}} = \sqrt{E_{\text{beam}}^2 - p_B^2}$ and $\Delta E = E_B - E_{\text{beam}}$. Continuum ($e^+e^- \to q\bar{q}$) background is rejected using event shape variables that are combined in an optimal linear combination (Fisher discriminant). These shape variables take advantage of the fact that the decay products in $B\bar{B}$ events are fairly isotropic, while continuum events have a preferred direction along the $q\bar{q}$ axis. Large $B^+ \to D^{(*)}\pi^+$ data control samples, where the $b \to u$ amplitude is more suppressed with respect to the $b \to c$ transition ($r_b \approx 0.01$), are used to calibrate and validate the analysis methods.

The Dalitz model parameters are determined from large, clean, flavor-tagged charm samples from continuum production. The $D^0 \to K_S^0\pi^+\pi^-$ Dalitz models in the BaBar and BELLE analyses are not the same. The main differences are in the treatment of the S-wave components. Babar uses a K-matrix formalism with the P-vector approximation and 5 poles for the $\pi\pi$ S-wave and a LASS model consisting of a $K_0^*(1430)^\mp$ resonance together with a coherent non-resonant contribution parameterized by a scattering length and an effective range for the $K\pi$ S-wave. BELLE includes σ_1 and σ_2 $\pi\pi$ scalar resonances and a $K_0^*(1430)$ for the $K\pi$ S-wave. Details of the Dalitz models can be found in the preprints [9,10] describing the measurements.

Table 1 gives the $B \to D^{(*)}K^{(*)}$ signal yield for the samples used in the final fits for the CP parameters (described below). The BaBar signal efficiencies have improved substantially (20% to 40% relative) with respect to the previous BaBar analysis, which used 383 million $B\bar{B}$ events [13], coming mainly from reprocessing the data with improved track reconstruction and particle identification.

3.2 The $B \to DK$, D decay Dalitz CP analysis

The CP parameters are determined using unbinned maximum likelihood fits. Probability density functions in the likelihood depend on ΔE, m_{ES}, continuum rejection variables, and the Dalitz

CP parameters for $B^+ \to DK^+$, $D \to K_S^0 \pi^+ \pi^-$		
Parameter	BaBar	BELLE
x_- (%)	$6.0 \pm 3.9 \pm 0.7 \pm 0.6$	$10.5 \pm 4.7 \pm 1.1$
y_- (%)	$6.2 \pm 4.5 \pm 0.4 \pm 0.6$	$17.7 \pm 6.0 \pm 1.8$
x_+ (%)	$-10.3 \pm 3.7 \pm 0.6 \pm 0.7$	$-10.7 \pm 4.3 \pm 1.1$
y_+ (%)	$-2.1 \pm 4.8 \pm 0.4 \pm 0.9$	$-6.7 \pm 5.9 \pm 1.8$

Table 2: Preliminary results of the CP fit for $B^+ \to DK^+$. The BELLE fit uses $D \to K_S^0 \pi^+ \pi^-$, while the BaBar fit uses both $D \to K_S^0 \pi^+ \pi^-$ and $D \to K_S^0 K^+ K^-$. The uncertainties from left to right are statistical, experimental systematic, and Dalitz model systematic. The BELLE analysis does not report Dalitz model uncertainties on $x_\pm$ and $y_\pm$.

plot position. The interference terms in the intensity are proportional to

$$x_\pm = r_b \cos(\delta_b \pm \gamma) \quad \text{and} \quad y_\pm = r_b \sin(\delta_b \pm \gamma). \quad (3)$$

The Cartesian parameters are free parameters in the fits. They are used rather than r_b, δ_b, and γ directly because they are uncorrelated with Gaussian uncertainties.

The full results of the fits can be found in the BaBar and BELLE preprints[9,10] and averages are available through HFAG[12]. Table 2 gives the $x_\pm$ and $y_\pm$ results for the $B^+ \to DK^+$ mode as an example to give you an idea of the measurement precision and the consistency of the two measurements. The BaBar and BELLE results are consistent with each other. The BaBar statistical errors are lower due to the higher signal statistics (see Table 1). The degree to which the $x_\pm$ and $y_\pm$ are inconsistent with zero is the significance of the $b \to u$ transition, while the degree to which $x_- \neq x_+$ and $y_- \neq y_+$ is the significance of the CP violation.

The interpretation of selected $x_\pm$ and $y_\pm$ measurements is given in Table 3. Each experiment independently finds a value of γ close to around 70°, which is consistent with indirect determinations of γ within the CKM framework (see Figure 1 and refs[4,5]). Each experiment rules out CP conservation with a significance of 3.5 standard deviations. The Belle experiment favors a larger $b \to u$ contribution to the decay (larger r_b), which leads to a smaller statistical uncertainty on γ, though the BELLE and BaBar r_b measurements are not incompatible. Both the BaBar and BELLE measurements are statistics limited.

One noteworthy difference between the BaBar and BELLE measurements is the uncertainty from the Dalitz model, which is 3° for BaBar and 8.9° for BELLE. The BaBar γ analysis[9] and D^0 mixing analysis[11] used the same Dalitz model and the same model variations in the evaluation of the systematic uncertainties. The Dalitz model systematic errors are not negligible in the D^0 mixing analysis, so the Dalitz model and model variations were refined and reconsidered, with respect to the initial BaBar D decay Dalitz γ analysis[13]. This Dalitz model work, motivated by the requirements of the D^0 mixing analysis, was propagated back into the γ analysis, which lead to the substantial improvement in the model systematic uncertainty on γ. In the future, LHCb and super B factories will have much larger datasets, making model independent approaches[8,14,15] feasible.

4   The "ADS" approach for γ

The so-called "ADS" method (for Atwood, Dunietz, and Soni[7]) for determining γ maximizes the size of the interference term with a clever choice of final state. The favored $b \to c$ transition from $B^- \to D^0 K^-$ is combined with the suppressed $c \to d$ transition from $D^0 \to K^+ \pi^-$. This interferes with the suppressed $b \to u$ transition from $B^- \to \bar{D}^0 K^-$ followed by the favored $\bar{c} \to \bar{s}$ transition from $\bar{D}^0 \to K^+ \pi^-$. Since both paths to the $[K^+ \pi^-]_D K^-$ final state involve a CKM favored transition combined with a CKM suppressed transition, the paths have roughly equal

Parameter	BaBar	BELLE
γ (°)	$68\,{}^{+15}_{-14}\,\{4,3\}$	$78.4\,{}^{+10.8}_{-11.6}\,\pm 3.6\,\pm 8.9$
r_b, DK (%)	$9.6 \pm 2.9\,\{0.5,0.4\}$	$16.0\,{}^{+4.0}_{-3.8}\,\pm 1.1\,{}^{+5.0}_{-1.0}$
r_b^*, D^*K (%)	$13.3\,{}^{+4.2}_{-3.9}\,\{1.3,0.3\}$	$19.6\,{}^{+7.2}_{-6.9}\,\pm 1.2\,{}^{+6.2}_{-1.2}$
δ_b, DK (°)	$119\,{}^{+19}_{-20}\,\{3,3\}$	$136.7\,{}^{+13.0}_{-15.8}\,\pm 4.0\,\pm 22.9$
δ_b^*, D^*K (°)	$-82 \pm 21\,\{5,3\}$	$341.9\,{}^{+18.0}_{-19.6}\,\pm 3.0\,\pm 22.9$

Table 3: Interpretation of selected $x_\pm$ and $y_\pm$ measurements. For the BaBar results, the first uncertainty gives the 68.3% confidence interval including all sources of uncertainty (stat., expt. syst., Dalitz model). The values inside the {} indicate the symmetric contributions to the total uncertainty coming from the experimental systematic and Dalitz amplitude model systematic uncertainties, respectively. For the BELLE results, the uncertainties from left to right are statistical, systematic, and Dalitz model systematic. All results are preliminary.

amplitudes. This means the direct CP asymmetry can be quite large (of order 1) but you pay a heavy price in signal statistics due to the CKM suppression. This method is quite sensitive to the amplitude ratio r_b, which is common with the other $B \to DK$ methods, such as the D decay Dalitz method above.

Both BaBar and BELLE have searched for $B^- \to [K^+\pi^-]_D K^-$. The BaBar collaboration recently released a preliminary version of their analysis using the full dataset of 468 million $B\bar{B}$ events. Unlike previous searches from both experiments, the new BaBar analysis sees the first signs of ADS signals in $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$. Figure 2 shows the $m_{\rm ES}$ distributions separately for $B^+ \to [K^-\pi^+]_D K^+$ and $B^- \to [K^+\pi^-]_D K^-$. Comparing the B^+ and B^- distributions, a large CP asymmetry is evident.

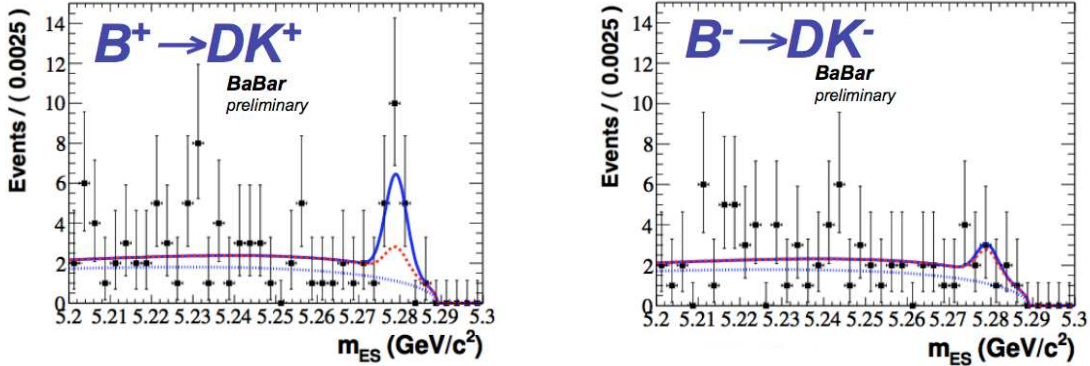Figure 2: Distributions of $m_{\rm ES}$ for $B^+ \to [K^-\pi^+]_D K^+$ (left) and $B^- \to [K^+\pi^-]_D K^-$ (right) for the preliminary BaBar analysis of 468 million $B\bar{B}$ events. The dotted blue curve is combinatoric background only, the dashed red curve is combinatoric plus peaking background, and the solid blue curve represents all components including the signal.

The interpretation of the ADS rate and CP asymmetry gives $r_b = (9.0^{+5.6}_{-5.1})\%$ and $r_b^* = (11.6^{+3.4}_{-5.0})\%$ for $B \to DK$ and $B \to D^*K$ respectively and constraints on γ, δ_b, and δ_b^* that are consistent with the D decay Dalitz measurements.

5 Summary and future prospects

The CKM parameters are now over constrained. All CP violation measurements made thus far are consistent with the Kobayashi-Maskawa mechanism of the Standard Model. The B factory

experiments, BaBar and BELLE, have made recent progress on the most difficult Unitarity Triangle angle to measure: γ or ϕ_3. Unlike other angle measurements, γ from $B \to DK$ involves only tree-level processes, which make the interpretation very clean theoretically, providing a solid Standard Model reference. However, our experimental constraints on γ from $B \to DK$ are still relatively weak and statistics limited. The analysis of all experimental constraints by the UTfit [5] and CKMfitter [4] collaborations gives $\gamma = (72 \pm 11)^\circ$ and $\gamma = \left(69\,{}^{+19}_{-21}\right)^\circ$, respectively.

Looking ahead, the LHCb experiment will make substantial progress on γ using $B \to DK$ decays, taking advantage of the huge $b\bar{b}$ production cross section in pp collisions to address the current limitation, which is signal statistics. The high statistics will make model-independent D decay Dalitz approaches viable, removing the dependence on the Dalitz amplitude model assumptions. A super B factory could also turn γ into a precision measurement.

Acknowledgments

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