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Review of ϕ_3 measurements at Belle

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Abstract. One of the main goals of the Belle experiment (and the upcoming Belle II experiment) is to measure parameters of electro-weak CP violation (CPV). A useful way to parametrize CPV is through the use of unitarity triangles. A brief introduction to unitarity triangle measurements of CP violation is presented, followed by a summary of recent results from the Belle experiment concerning measurements of the least well constrained angle of the standard unitarity triangle — ϕ_3/γ.

1 Unitarity Triangle

Charge-parity (CP) symmetry in weak interactions is broken by a single irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1], [2]. This matrix is embedded in the charged current Lagrangian

$$\mathcal{L}_{\mathrm{CC}} = \frac{g}{2\sqrt{2}}(\bar{u}\ \bar{c}\ \bar{t})\gamma^{\mu}(1-\gamma_5)\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix} W^{+}_{\mu} + \text{h.c.}\,. \tag{1}$$

It is useful to introduce unitarity triangles in order to parametrize the CKM matrix. The matrix is unitary, which can be written down in the following way,

$$\begin{pmatrix} V^*_{ud} & V^*_{cd} & V^*_{td} \\ V^*_{us} & V^*_{cs} & V^*_{ts} \\ \mathbf{V^*_{ub}} & \mathbf{V^*_{cb}} & \mathbf{V^*_{tb}} \end{pmatrix}\begin{pmatrix} \mathbf{V_{ud}} & V_{us} & V_{ub} \\ \mathbf{V_{cd}} & V_{cs} & V_{cb} \\ \mathbf{V_{td}} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \mathbf{0} & 0 & 1 \end{pmatrix}. \tag{2}$$

Eq. 2 is equivalent to 9 complex scalar equations. Let us focus on the ones that are equal to 0. Out of these, only 3 are independent. We can write down, e.g., the equation comprised of the terms marked in bold.

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0\,. \tag{3}$$

This is a sum of 3 complex numbers that is equal to 0 — any such equation represents a triangle in the complex plane (however, the triangle might be degenerate — have no area).

The triangle we picked is the standard choice, as it has the benefit of its angles being of the same order. This in turn means, they can be measured independently with reasonable relative errors. Furthermore, the triangle is usually rotated so one of its sides lies on the real axis and it is normalized to a unit length, as can be seen in Fig. 1.

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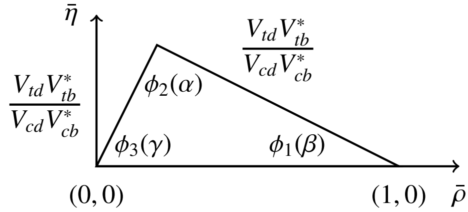

Figure 1. The standard unitarity triangle (Belle angle naming convention first, BaBar convention in parentheses).

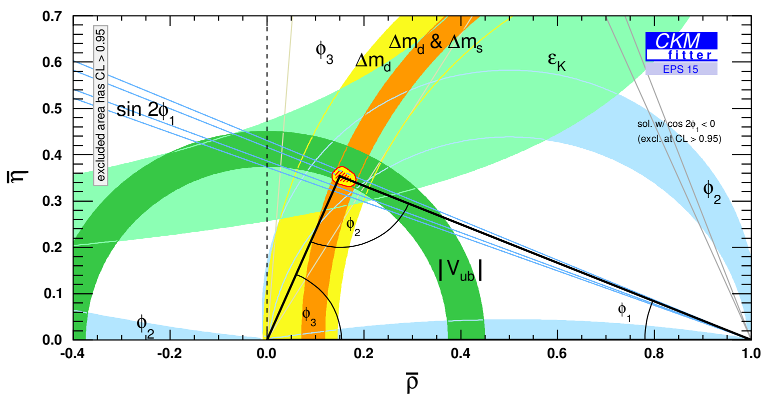

Figure 2. CKMfitter group's global unitarity triangle fit.

The fact, that there is a non-trivial, non-degenerate unitarity triangle implies CP violation. Moreover, careful measurement of the triangle can reveal beyond Standard Model (BSM) physics. Telltale BSM signs would be if the triangle is actually not a triangle (its sides don't close), or if there is a discrepancy between measurements from tree-dominated processes and loop-dominated processes.

The various CKM measurements are combined into a single plot by the CKMfitter group [3], shown in Fig. 2. It's also worth noting that ϕ_3 is the least well constrained angle of the unitarity triangle.

2 Methods for Measuring ϕ_3

The most powerful and theoretically clean way of measuring ϕ_3 is based on the interference between $b \to \bar{u}cs$ and $b \to u\bar{c}s$ tree level amplitudes [4]. What we mean by saying theoretically clean is that there is no penguin graph contribution to these processes and consequently no theoretical uncertainty connected to the hadronic parameters, as they can be obtained from experiment. It is worth noting that ϕ_3 is the only parameter of CP violation that can be measured solely from tree-level processes. However, ϕ_3 measurement precision is limited by small branching fractions of the involved processes.

An example of the mentioned type of processes is $B^\pm \to D^{(*)}K^\pm$ followed by $D \to f$, and $B^\pm \to \bar{D}^{(*)}K^\pm$ followed by $\bar{D} \to f$, where f is a *common final state*. Interference between these two paths gives rise to direct CP violation. Diagrams of the relevant decays are depicted in Fig. 3.

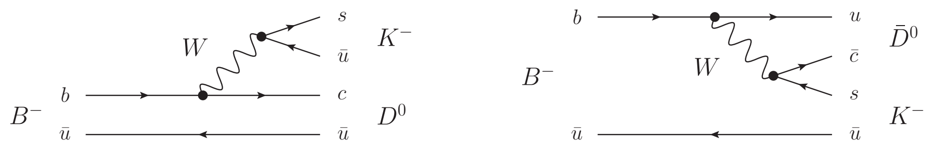

Figure 3. Diagrams of the two tree-level $B^- \to DK^-$ decays.

Most analyses neglect the effects of neutral D meson mixing and CP violation as these are expected to be small [5]. However, D mixing and CP violation can be included at no cost to the uncertainty by using measured values from other studies [6].

2.1 GLW Method

The method was first proposed by Gronau, London and Wyler [4], [7]. Their idea was that a B meson can decay weakly to a state with a D^0 or $\bar{D}^0$. But if we reconstruct the neutral D meson from a final state that is a CP-eigenstate, we actually select a superposition $(D^0 \pm \bar{D}^0)/\sqrt{2}$. We label these states D_{CP^+} and D_{CP^-} for the CP-even and CP-odd states respectively. We can then construct 4 observables that encode the CP violation parameters,

$$\mathcal{R}_{CP^\pm} = 2\frac{\Gamma(B^- \to D_{CP^\pm}K^-) + \Gamma(B^+ \to D_{CP^\pm}K^+)}{\Gamma(B^- \to D_{fav}K^-) + \Gamma(B^+ \to D_{fav}K^+)} = 1 + r_B^2 \pm 2r_B\cos(\delta_B)\cos(\phi_3), \tag{4}$$

$$\mathcal{A}_{CP^\pm} = \frac{\Gamma(B^- \to D_{CP^\pm}K^-) - \Gamma(B^+ \to D_{CP^\pm}K^+)}{\Gamma(B^- \to D_{CP^\pm}K^-) + \Gamma(B^+ \to D_{CP^\pm}K^+)} = \pm r_B\sin(\delta_B)\sin(\phi_3)/R_{CP^\pm}, \tag{5}$$

where D_{fav} signifies that the D meson is reconstructed in a favored hadronic mode such as $D^0 \to K^-\pi^+$, r_B is the magnitude of the ratio of $B \to \bar{D}^0K^-$ and $B \to D^0K^-$ amplitudes and δ_B is the strong phase difference between them. $\mathcal{A}_{CP^\pm}$ different from 0 means CP is violated in these processes.

Notice that the system is not over-constrained by the 4 observables even though there are 3 parametes, as $\mathcal{R}_{CP^+}\mathcal{A}_{CP^+} = -\mathcal{R}_{CP^-}\mathcal{A}_{CP^-}$.

2.2 ADS Method

Atwood, Dunietz and Soni [8] realized that CKM-suppressed decays can also be used to measure ϕ_3. Let us consider the process $B^- \to [K^+\pi^-]_DK^-$, where the parentheses represent a final state that was produced from an intermediate D resonance. The full final state can be reached in two ways — either CKM-favored $B^- \to D^0K^-$ followed by CKM-suppressed $D^0 \to K^+\pi^-$, or CKM-suppressed $B^- \to \bar{D}^0K^-$ followed by CKM-favoured $D^0 \to K^-\pi^+$.

In contrast to the GLW method, when the D meson decays to a non-CP-eigenstate, one has to factor in the magnitude of the ratio of the suppressed and favored D decays r_D as well as their relative strong phase δ_D, much like we did for the B decay. Fortunately, these hadronic parameters can be obtained from mixing measurements [9].

The ADS observables are similar to the GLW ones, however there are only 2 of them as they are charge-averaged,

$$\mathcal{R}_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^-\pi^+]_D K^-) + \Gamma(B^+ \to [K^+\pi^-]_D K^+)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\phi_3). \quad (6)$$

$$\mathcal{A}_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = 2r_B r_D \sin(\delta_B + \delta_D)\sin(\phi_3)/\mathcal{R}_{ADS}. \quad (7)$$

2.3 Dalitz Plot Method (GGSZ)

The Dalitz plot analysis method for ϕ_3 measurements was proposed by Giri, Grossman, Soffer and Zupan [10] and independently by Bondar [11]. The idea behind it is to use (usually self-conjugate) multi-body final states accessible to both D^0 and $\bar{D}^0$ mesons. One then measures relative phases and magnitudes of their amplitudes for D mesons coming from B decays such as $B^\pm \to DK^\pm$.

Let us consider a $B^\pm \to [K_S^0\pi^+\pi^-]_D K^\pm$ process. Its amplitude can be written down as

$$A_{B^+}(s_+, s_-) = \bar{A}_D(s_+, s_-) + r_B e^{i(\delta_B+\phi_3)} A_D(s_+, s_-), \quad (8)$$

$$A_{B^-}(s_+, s_-) = A_D(s_+, s_-) + r_B e^{i(\delta_B+\phi_3)} \bar{A}_D(s_+, s_-), \quad (9)$$

where we have introduced the Dalitz variables $s_\pm = m^2_{K_S^0\pi^\pm}$ and A_D is the amplitude of the D decay. The strong phase $\delta_B \equiv \delta_B(s_+, s_-)$ has to have a large variation over the Dalitz plot; if it were constant, there would be no ϕ_3 sensitivity.

Two approaches are possible — model independent, binned analysis (as proposed in the original paper) and model dependent, unbinned analysis. The former divides the Dalitz plot into bins across which there is a small strong phase variation. The events in one bin are then treated equally. Extra input in the form of strong phase measurements from charm factories are required for this method [12].

The second method employs a certain model of the strong phase distribution function across the Dalitz phase-space. While introducing an obvious model uncertainty, it has a higher statistical power, which can be very desirable in low yield analyses.

2.4 Continuum Suppression

A vital procedure in these measurements is called continuum suppression. It distinguishes B meson decay events from $e^+e^- \to q\bar{q}$ type events, where q stands for u, d, s or c type quarks. The name *continuum* comes from the fact, that these events hadn't gone through an intermediate $\Upsilon(4S)$ resonance, in contrast to the B meson decay events.

These backgrounds can be quite prominent, but have very different event shapes (solid angle distribution of decay particles); see Fig. 4. This allows us to exploit a variety of observables such as thrust, sphericity, Fox-Wolfram moments, Δz and flavor tag to discriminate against these backgrounds. Usually neural networks or boosted decision trees are used to combine many of the listed variables into a single one with high discriminating power.

3 Measurements

All the listed analyses use the entire 711 fb^{-1} Belle data sample containing $772 \times 10^6 B\bar{B}$ events. Listed uncertainties are statistical first, systematic second.

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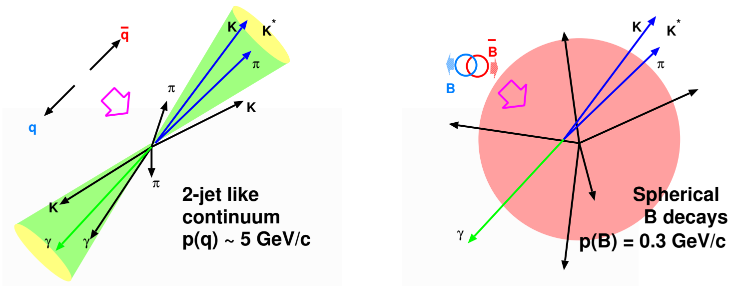

Figure 4. Event shapes for continuum (left) and B decay events (right) [13].

3.1 $B^- \to D^{*0}K^-, D^{*0} \to D^0\pi^0, D^0 \to K^0_S\pi^0, K^0_S\eta$ (GLW)

It is of note, that this measurement is a B-factory exclusive — it would be very difficult to study this channel on hadron machines, because of the multiple neutral final-state particles.

The analysis was carried out in both $D^{*0} \to D^0\pi^0$ and $D^{*0} \to D^0\gamma$ modes. Combining them with CP-even D^0 final-states $\pi^+\pi^-$ and K^+K^-, yields the following results [14],

$$R_{CP+} = +1.19 \pm 0.13 \pm 0.03, \quad (10)$$
$$R_{CP-} = +1.03 \pm 0.13 \pm 0.03, \quad (11)$$
$$A_{CP+} = -0.14 \pm 0.10 \pm 0.01, \quad (12)$$
$$A_{CP-} = +0.22 \pm 0.11 \pm 0.01. \quad (13)$$

The observables show clear hints of CP asymmetry.

3.2 $B^- \to D^0K^-, D^0 \to K^+\pi^-$ (ADS)

The authors updated this study with the full Belle dataset, adding 20% more data to the previous study [15]. They also incorporated several improvements such as a 2D fit for signal yield extraction and a neural network for background suppression. This resulted in a first observation of the suppressed mode, with a 4.1σ significance (including systematic uncertainties) [16],

$$R_{DK} = (1.63^{+0.44+0.07}_{-0.41-0.13}) \times 10^{-2}, \quad (14)$$
$$A_{DK} = -0.39^{+0.26+0.04}_{-0.28-0.13}. \quad (15)$$

3.3 $B^0 \to D^0K^{*0}, K^{*0} \to K^+\pi^-, D^0 \to K^-\pi^+$ (ADS)

A major advantage of this analysis is that it uses a self-tagging channel, because of the K^* decay. This in turn boosts efficiency. While the study uses the ADS method, the fact that K^* has a natural width larger than the experimental resolution, leads to some complications which require a modified definition of the ADS observables. Further details can be found in [17]. The obtained result is [18]

$$R_{DK^{*0}} = (4.1^{+5.6+2.8}_{-5.0-1.8}) \times 10^{-2}. \quad (16)$$

As the $R_{DK^{*0}}$ value is not significant, an upper limit was established

$$R_{DK^{*0}} < 0.16 \quad (95\% \text{ C.L.}). \quad (17)$$

3.4 $B^- \to D^0 K^-, D^0 \to K^+\pi^-\pi^0$ (ADS)

The fact that there is a 3-body final-state in this ADS analysis means that the strong phase difference between the interfering processes can vary over the phase-space. This can "dilute" direct CP violation effects. To quantify this dilution, correlated $D\bar{D}$ production is used [19], [20]. Fortunately, the effect is small in this channel and allows for a CP violation measurement [21]:

$$R_{DK} = (1.98 \pm 0.62 \pm 0.24) \times 10^{-2},$$
$$A_{DK} = 0.41 \pm 0.30 \pm 0.05.$$

This is a first evidence for the suppressed decay, with a 3.2σ significance.

3.5 $B^- \to D^0 K^-, D^0 \to K_S^0\pi^+\pi^-$ (Dalitz)

This analysis is the first model-independent measurement of ϕ_3 in the relevant channel. The authors report a result of [22]

$$\phi_3 = (77^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ, \tag{18}$$

where the third uncertainty comes from the precision of the strong-phase parameters obtained by CLEO, which are an external input to this analysis.

This uncertainty is comparable to the model uncertainties from the latest Belle and BaBar measurements: $3^\circ - 9^\circ$. For future experiments, the model uncertainty is expected to dominate as there will be more statistics and, possibly, better systematics control. On the other hand, the precision of the strong-phase parameters measurement will improve as BES-III results supersede CLEO's.

3.6 $B^0 \to D^0 K^{*0}, K^{*0} \to K^+\pi^-, D^0 \to K_S^0\pi^+\pi^-$ (Dalitz)

This analysis also uses the model-independent approach and resulted in establishing an upper limit on the suppressed vs. favored ratio $r_S < 0.87$ at the 68% confidence level [23]. This value is closely related to ϕ_3 sensitivity because the statistical uncertainty of ϕ_3 measurements is proportional to $1/r_S$.

The authors also report the "raw" observables $x_\pm$, $y_\pm$ which are defined as

$$x_\pm = r_S \cos(\delta_S \pm \phi_3),$$
$$y_\pm = r_S \sin(\delta_S \pm \phi_3)$$

and are measured to be

$$x_- = +0.4^{+1.0+0.0}_{-0.6-0.1} \pm 0.0,$$
$$y_- = -0.6^{+0.8+0.1}_{-1.0-0.0} \pm 0.1,$$
$$x_+ = +0.1^{+0.7+0.0}_{-0.4-0.1} \pm 0.1,$$
$$y_+ = +0.3^{+0.5+0.0}_{-0.8-0.1} \pm 0.1,$$

where the third uncertainty again comes from the precision of the strong-phase parameters, as in Sec. 3.5.

These observables have the benefit, that they can be readily merged with similar results from other studies for a combined measurement.

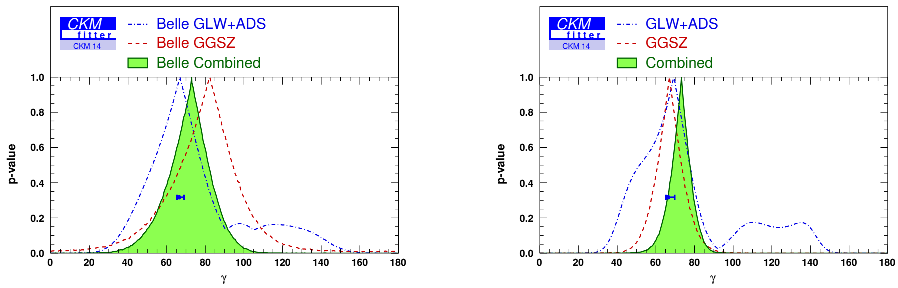

Figure 5. ϕ_3 combination fit; Belle (left) and world (right) [3].

4 Conclusion

Precision of the measurements of the ϕ_3 angle of the unitarity triangle is currently dominated by statistical uncertainty. The current Belle and world combination ϕ_3 fits can be seen in Fig. 5.

With the new generation of flavor experiments, Belle II and the LHCb upgrade, along with inputs from charm threshold provided by BES-III, the world combination of the least well-known parameter of the unitarity triangle — ϕ_3, could reach sub-degree precision. It is important we continue constraining the unitarity triangle as New Physics *could* very well be hiding there.

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