Towards α (ϕ_2) and γ (ϕ_3) at the B factories

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Abstract. The main aim of the BaBar and Belle experiments is to test the Standard Model explanation of CP violation in the B system through measurements of the angles of the Unitarity Triangle. One angle (β/ϕ_1 is already well measured by the two collaborations. This paper describes some of the recent results from the two experiments from channels which are sensitive to the remaining angles.

INTRODUCTION

The primary objectives of the BaBar and Belle experiments is to test whether the Standard Model's single source of CP violation, the single non-trivial phase of the CKM matrix, can provide a full description of CP violation in B meson decays. This proposition is to be tested by over-constraining the so-called "Unitarity Triangle", through making multiple measurements of all three of its angles and requiring both that measurements made using different processes are consistent with each other and that the three angles sum to 180°.

The two collaborations use different naming conventions for these angles. The angles BaBar call α, β and γ are respectively called ϕ_2, ϕ_1 and ϕ_3 by Belle. In this paper the author will use the BaBar convention.

Indirect constraints on the Unitarity Triangle may be obtained from measurements of B_d and B_s mixing, $|V_{ub}/V_{cb}|$, and CP violation in K^0 decays. A global fit to these results [1] produces a single solution and the 95% confidence limits [2]:

$$\begin{array}{rcccl} 15.5^\circ & < & \beta & < & 26.4^\circ \\ 77^\circ & < & \alpha & < & 120^\circ \\ 39^\circ & < & \gamma & < & 80^\circ \end{array}$$

The angle β has been well measured by both collaborations, with an average value of $\sin(2\beta) = 0.734 \pm 0.055$ [3] in good agreement with the Standard Model fit. The remaining angles pose much greater experimental challenges. In this paper we describe the status of some of the measurements which may be used to constrain these angles.

THE EXPERIMENTS

The BaBar [4] and Belle [5] detectors both have tracking systems comprising silicon vertex trackers and drift chambers within a 1.5 T solenoidal field. Also within their superconducting coils are particle identification systems and electromagnetic calorimeters comprised of CsI(Tl) crystals, while outside the coils the return yokes of both experiments are instrumented to detect muons and neutral hadrons. For the analyses described here the particle identification systems are particularly important. Both experiments use energy loss (dE/dx) within the tracking detectors. Surrounding the BaBar drift chamber is an internally reflecting ring-imaging Cerenkov detector, while Belle use an array of aerogel threshold Cerenkov detectors and a barrel-like arrangement of time-of-flight scintillators. Both systems are capable of providing 2.5 σ separation between pions and kaons up to the maximim momentum of charged hadrons from 2-body B decays (around 4 GeV).

The BaBar and Belle experiments are sited at the PEP-II [6] and KEK-B [7] asymmetric e^+e^- colliders. In these machines the inequality in the energies of the e^- beams and the e^+ beams (9 GeV vs 3.1 GeV in PEP-II, 8 GeV vs 3.5 GeV in KEK-B) provides a boost to the $\Upsilon(4S)$ meson which allows the decay time difference between the two B mesons to be measured. Measurements of CP-violating asymmetries in neutral B decays are made as a function of the decay time difference between the decay of interest and the other B decay, whose characteristics (charge vs momentum of tracks, presence of high-momentum charged kaons or leptons) are used to identify the charge of the b quark or antiquark at the time of its decay ("tagging"), and hence the type ($B^0/\bar{B}^0$) of the CP-measuring B at that time.

MEASUREMENT OF α/ϕ_2

Principles

The CP angle α can in principle be measured from decays $b \to u\bar{u}d$, such as $B^0 \to \pi^+\pi^-$. In the absence of Penguin contributions, interference between the direct decay and mixing followed by decay to the same final state will produce a time-dependent asymmetry:

$$A_{\pi\pi}(B^0/\bar{B}^0) = S_{\pi\pi}\sin(\Delta m_d \Delta t) - C_{\pi\pi}\cos(\Delta m_d \Delta t) \quad (1)$$

where Δm_d is the mass difference between the two B^0 mass eigenstates and Δt the time difference between the $\bar{B}^0$ and B^0 decays. The coefficients of the sine and cosine terms are given by:

$$S_{\pi\pi} = \frac{2\mathrm{Im}\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2} \quad \text{and} \quad C_{\pi\pi} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2} \quad (2)$$

If only the $b \to u\bar{u}d$ amplitude contributes to this decay $|\lambda| = 1$, giving $C_{\pi\pi} = 0$ and $S_{\pi\pi} = \sin(2\alpha)$. In the presence of other amplitudes (i.e. penguins), $C_{\pi\pi}$ will in general differ from 0 (direct CP violation), while $S_{\pi\pi}$ will no longer measure $\sin(2\alpha)$ but rather and "effective alpha" (α_{eff}) which differs from the true α by an unknown amount $\Delta\alpha$. Information from other B decay modes is then needed in order to constrain or measure the penguin-induced shift $\Delta\alpha$.

$B \to \pi\pi$ decays

Both collaborations study branching fractions and asymmetries using similar sized data samples: 81 fb^{-1} for BaBar and 78 fb^{-1} for Belle. Larger data samples of 113 fb^{-1} and 140 fb^{-1} respectively are used to search for $B^0/\bar{B}^0 \to \pi^0\pi^0$.

The main background to charmless B decay measurements comes from combinatorics in light-flavoured (u,d,s,c) events, which make up the majority of hadronic events even at the $\Upsilon(4s)$ resonance. To suppress these, both collaborations use similar methods. Two discriminating variables are used to select candidates with the CMS energy and momentum expected for B mesons. The first, $\Delta E = E^*_{beam} - E^*_B$ compares the expected and measured CMS energies for the B candidate, and should peak at zero. The position of the peak is shifted if the wrong mass hypothesis is assumed for any of the particles (e.g. if a kaon is treated as a pion), and so it can discriminate between $\pi\pi$ and πK final states. The second, $m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_B}$, should peak at the B mass, but is sensitive only to the measured momenta. Light flavour continuum events give smooth distributions in both variables with no peaking in the signal region. In addition, event shape variables are used to discriminate between the “spherical" $B\bar{B}$ events and the more “jet-like" continuum.

TABLE 1. Measured $B \to \pi\pi$ branching fractions, $\times 10^{-6}$

Mode	BaBar	Belle	Average
$\pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$	$4.4 \pm 0.6 \pm 0.3$	4.6 ± 0.4
$\pi^\pm\pi^0$	$5.5\ ^{+1.0}_{-0.9} \pm 0.6$	$5.0 \pm 1.2 \pm 0.5$	5.3 ± 0.6
$\pi^0\pi^0$	$2.1 \pm 0.6 \pm 0.3$	$1.7 \pm 0.6 \pm 0.3$	1.9 ± 0.5

TABLE 2. Results of time-dependent $B^0 \to \pi^+\pi^-$ asymmetry fits

	$C_{\pi\pi}$	$S_{\pi\pi}$
BaBar	$-0.19 \pm 0.19 \pm 0.05$	$-0.40 \pm 0.22 \pm 0.03$
Belle	$-0.77 \pm 0.27 \pm 0.08$	$-1.23 \pm 0.41\ ^{+0.08}_{-0.07}$
Average*	-0.38 ± 0.16	-0.58 ± 0.20

* Heavy Flavour Averaging Group [14]. The averaging has a confidence level of only 0.047

The precise methods do differ between the collaborations. BaBar make loose cuts on these variables to produce a signal-enhanced sample, then perform a multivariant fit to m_{ES}, ΔE and the event shape variables to estimate the signal yield. The Cerenkov angle θ_c is included in the fit, so that yeilds for $B \to \pi\pi$ and $B \to K\pi$ are estimated simultaneously. Belle instead make tighter cuts on event shape, m_{ES} and particle identification likelihoods to obtain a higher purity sample of a single final state, then fit the ΔE distribution to estimate signal yield. The branching fractions measured by the two collaborations are summarised in table 1 [8, 9, 10, 11].

The CP asymmetry amplitudes are estimated by unbinned maximum likelihood fits to the Δt distributions for the B^0- and $\bar{B}^0$-tagged events, as well as to m_{ES}, ΔE and, in BaBar's analysis, event shape and θ_c distributions. Extensive Monte Carlo tests were performed to validate the fitting procedures. The results are summarised in table 2 [12, 13]. In addition both experiments have found charge asymmetries in $B^\pm \to \pi^\pm\pi^0$ decays to be consistent with zero.

Interpreting the observed asymmetries is more challenging. Grossman and Quinn [15] proposed a simple limit on the magnitude of the effect may be determined from the branching fraction ratio

$$\sin^2(\alpha_{eff} - \alpha) < \frac{\mathrm{BF}(B^0/\bar{B}^0 \to \pi^0\pi^0)}{\mathrm{BF}(B^\pm \to \pi^\pm\pi^0)} \quad (3)$$

Unfortunately the relatively large branching fraction for $B \to \pi^0\pi^0$ means that this only yeilds $|\Delta\alpha| < 48°$ at

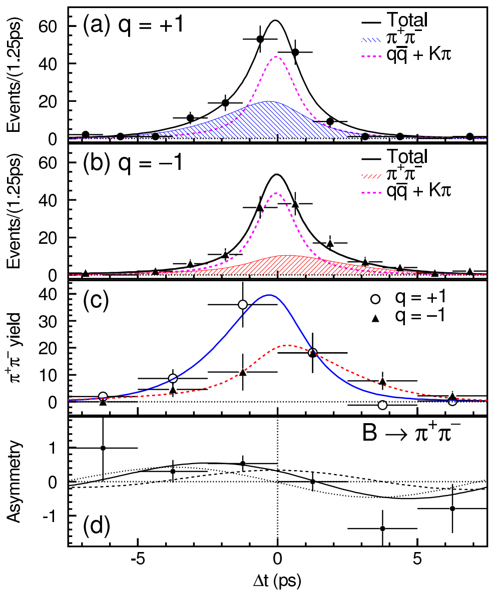

FIGURE 1. Belle's decay-time distribtions for B^0 and $\bar{B}^0$ decays to $\pi^+\pi^-$ and the resulting charge asymmetry

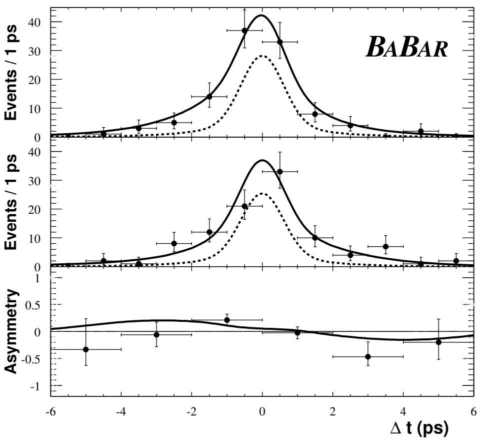

FIGURE 2. BaBar's decay-time distribtions for B^0 (top) and $\bar{B}^0$ (middle) decays to $\pi^+\pi^-$ and the resulting charge asymmetry

90% CL. Isospin analysis [16] as yet yields no significant constraints, and will require O(ab^{-1}) of data to achieve a precision which would test our theoretical understanding. More significant constraints on α are obtained by the Heavy Flavour Averaging Group [14], by identifying the penguin contribution to $\pi^+\pi^-$ with the enhanced penguins of $K^+\pi^-$ or with $B^+ \to K^0\pi^+$. Tighter constraints yet are obtained if QCD factorisation estimates of the penguin-to-tree amplitude ratio are used. The constraints are summarised in figure 3.

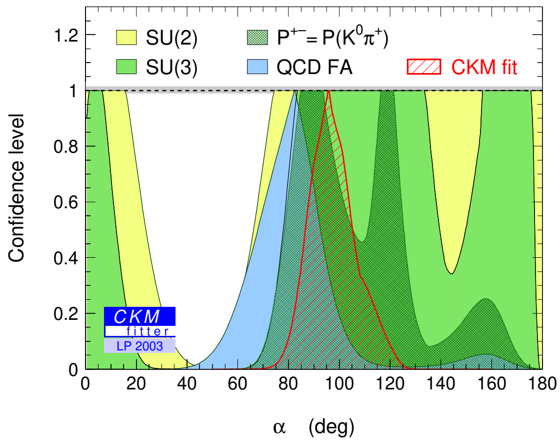

FIGURE 3. Constraints on α from $B \to \pi\pi$ results, with additional information and assumptions as described in the text, compared with the expectation from the CKM fit

$B \to \rho\pi$ decays

$B \to \rho\pi$ is more complex, because the final state is not a CP eigenstate. In the long term it offers the promise that a time-dependent Dalitz plot analysis, including interference between the different ρ bands, should allow the tree and penguin amplitudes to be measured and α to be determined unambiguously. However, with the present statistics only a quasi-two-body analysis is possible.

The decay probabilities for B^0 and $\bar{B}^0$ to $\rho^\pm\pi^\mp$ are given by:

$$f_{B^0}^{\rho^\pm h^\mp}(\Delta t) = (1 \pm A_{CP}(\rho h))e^{-|\Delta t|/\tau} \times$$
$$[1 + (S_{\rho h} \pm \Delta S_{\rho h})\sin(\Delta m \Delta t) - (C_{\rho h} \pm \Delta C_{\rho h})\cos(\Delta m \Delta t)]$$

$$f_{\bar{B}^0}^{\rho^\pm h^\mp}(\Delta t) = (1 \pm A_{CP}(\rho h))e^{-|\Delta t|/\tau} \times$$
$$[1 - (S_{\rho h} \pm \Delta S_{\rho h})\sin(\Delta m \Delta t) + (C_{\rho h} \pm \Delta C_{\rho h})\cos(\Delta m \Delta t)]$$

where the C and S terms are analogous to those in $\pi\pi$ decays, A_{CP} is the overall charge asymmetry between $B^0/\bar{B}^0 \to \rho^+\pi^-$ and $B^0/\bar{B}^0 \to \rho^-\pi^+$ (an example of direct CP violation), while ΔS and ΔC are CP-conserving dilution factors due respectively to strong phase differences between the amplitudes contributing to these decays and to any asymmetry between $\Gamma(B^0 \to \rho^+\pi^-) + \Gamma(\bar{B}^0 \to \rho^-\pi^+)$ and $\Gamma(B^0 \to \rho^-\pi^+) + \Gamma(\bar{B}^0 \to \rho^+\pi^-)$.

Both collaborations see clear signals for $B \to \rho^\pm\pi^\mp$ [17, 18], $\rho^0\pi^\pm$ [19, 20], and BaBar also measure branching fractions and asymmetries for $\rho^\pm\pi^0$, where there are 2 π^0s in the final state. There is some disagreement between the two experiments' measurements of $B \to \rho^0\pi^0$, where Belle [18] measure a branching fraction more than twice BaBar's limit. However, the difference in the cen-

TABLE 3. Measured $B \to \rho\pi$ branching fractions, $\times 10^{-6}$

Mode	BaBar	Belle
$\rho^{\pm}\pi^{\mp}$	$22.6 \pm 1.8 \pm 2.2$	$29.1\ ^{+5.0}_{-4.9} \pm 4.0$
$\rho \pm \pi^{0}$	$11.0 \pm 1.9 \pm 1.9$	
$\rho^{0}\pi^{\pm}$	$9.3 \pm 1.0 \pm 0.8$	$8.0\ ^{+2.3}_{-2.0} \pm 0.7$
$\rho^{0}\pi^{0}$	< 2.5 @ 90% CL $(0.9 \pm 0.7 \pm 0.4)$	$6.0\ ^{+2.9}_{-2.3} \pm 1.2$

TABLE 4. Asymmetry parameters and dilution factors from $B \to \rho^{p}m\pi^{\mp}$ analyses

Parameter	Value
$A_{CP}^{\rho\pi}$ (Belle)	$-0.38\ ^{+0.19}_{-0.21}\ ^{+0.04}_{-0.05}$
$A_{CP}^{\rho\pi}$ (BaBar)	$-0.114 \pm 0.062 \pm 0.027$
$A_{CP}^{\rho K}$	$-0.18 \pm 0.12 \pm 0.08$
$S_{\rho\pi}$	$-0.13 \pm 0.18 \pm 0.04$
$C_{\rho\pi}$	$+0.35 \pm 0.13 \pm 0.03$
$\Delta S_{\rho\pi}$	$+0.33 \pm 0.18 \pm 0.03$
$\Delta C_{\rho\pi}$	$+0.20 \pm 0.13 \pm 0.05$

tral values measured by the two experiments has a statistical significance only slightly $> 2\sigma$. The branching fractions are summarised in table 3.

BaBar have fitted the Δt distributions for B^0 and $\bar{B}^0$ tagged $\rho^{\pm}\pi^{\mp}$ candidates to extract the 5 parameters described above, and also the charge asymmetry for $B \to \rho^{\pm}K^{\mp}$ events. Belle have directly measured the A_{CP} parameter by counting unambiguous $\rho^{+}\pi^{-}$ and $\rho^{-}\pi^{+}$ events. These results are summarised in table 4. Measurements of the charge asymmetries for $\rho^{\pm}\pi^{0}$ and $rho^{0}\pi^{\pm}$ by BaBar were both consistent with 0 at the level of 1.5σ.

At present no significant constraints on α have been made from these results. BaBar have re-expressed their measurements in terms of the charge asymmetries for the two pairs of CP-conjugate decays $\bar{B}^0 \to \rho^{+}\pi^{-}$, $B^0 \to \rho^{-}\pi^{+}$ and $\bar{B}^0 \to \rho^{-}\pi^{+}$, $B^0 \to \rho^{+}\pi^{-}$. They find:

$$A_{+-} = \frac{N(\bar{B}^0 \to \rho^{+}\pi^{-}) - N(B^0 \to \rho^{-}\pi^{+})}{N(\bar{B}^0 \to \rho^{+}\pi^{-}) + N(B^0 \to \rho^{-}\pi^{+})} = -0.52\ ^{+0.17}_{-0.19} \pm 0.07$$

$$A_{-+} = \frac{N(\bar{B}^0 \to \rho^{-}\pi^{+}) - N(B^0 \to \rho^{+}\pi^{-})}{N(\bar{B}^0 \to \rho^{-}\pi^{+}) + N(B^0 \to \rho^{+}\pi^{-})} = -0.18 \pm 0.13 \pm 0.05$$

These results provide evidence for direct CP violation in $B \to \rho^{\pm}\pi^{\mp}$ decays, with the confidence level for $A_{+-} = A_{-+} = 0$ being only 1.5%.

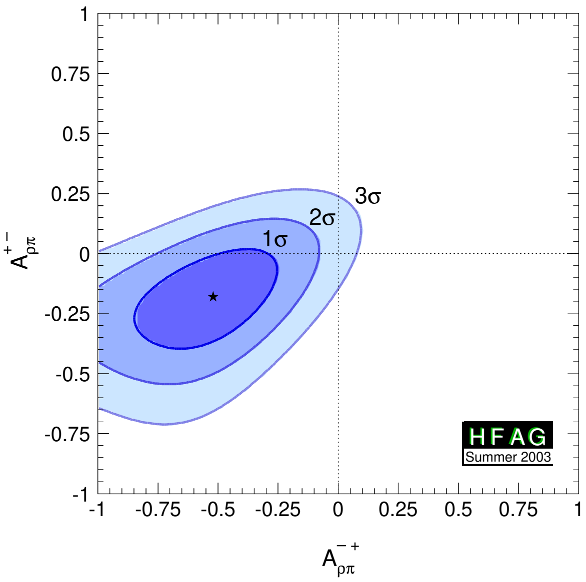

FIGURE 4. Probability contours for A_{+-} vs A_{-+} [21]

$B \to \rho\rho$ decays

The particular feature of $B \to \rho\rho$ is the polarisation of the two ρ mesons, which must be either both longitudinal or both transverse. The former will give CP-even eigenstates, while the latter will contain a mixture of CP-even and CP-odd terms. In general an angular analysis is needed to separate the two. However, the longitudinal term is expected to dominate, with

$$f_L = \frac{\Gamma_L}{\Gamma_L + \Gamma_T} \approx 1 - O(m_\rho^2/m_B^2) \qquad (4)$$

This considerably simplifies the CP analysis. Experimentally the longitudinal and transverse fractions are determined by fitting the angular distributions and correlations between the ρ decays. This is important for branching fraction measurements, since the reconstruction efficiencies depend on the π^0 momenta, and thus on the ρ decay angles and hence the longitudinal fraction.

Both experiments have observed and measured branching fractions and longitudinal polarisation fractions for $B^{\pm} \to \rho^{\pm}\rho^{0}$ [22, 23]. BaBar have also measured these for $B^0 \to \rho^{+}\rho^{-}$ [24]. In both channels the expectation of longitudinal dominance is verified. These results are summarised in table 5.

Belle measure the $B^{\pm} \to \rho^{\pm}\rho^{0}$ charge asymmetry directly by separately estimating signals for the two charge states. They find $N(\rho^{+}\rho^{0}) = 29.3 \pm 9.1$, and $N(\rho^{-}\rho^{0}) = 29.3 \pm 9.5$, giving a charge asymmetry $A_CP(\rho^{p}m\rho^{0}) = 0.00 \pm 0.22 \pm 0.03$.

BaBar fit the Δt distributions for longitudinally-polarised $\rho^{+}\rho^{-}$ events, using the form:

TABLE 5. Measured $B \to \rho\rho$ branching fractions ($\times 10^{-6}$) and longitudinal polarisation fractions

Mode	BF	f_L
$\rho^{\pm}\rho^{0}$ BaBar	$22.5 \pm 5.7 \pm 5.8$	$0.97\ ^{+0.03}_{-0.07} \pm 0.04$
$\rho^{\pm}\rho^{0}$ Belle	$31.7 \pm 7.1\ ^{+3.8}_{-6.7}$	$0.95 \pm 0.11 \pm 0.02$
$\rho^{+}\rho^{-}$ BaBar	$27\ ^{+7}_{-6}\ ^{+5}_{-7}$	$0.99\ ^{+0.01}_{-0.07} \pm 0.03$
$\rho^{0}\rho^{0}$ BaBar	< 2.1 (90% CL)	

$$f_{B/\bar{B}}(\Delta t) = \frac{1}{4\tau} e^{-|\Delta t|/\tau}[1 \pm S_L \sin(\Delta m \Delta t) \mp C_L \cos(\Delta m \Delta t)] \tag{5}$$

A simultaneous fit for yield, longitudinal fraction and CP asymmetries yields $f_L = 0.98 \pm 0.03$ and asymmetries $C_L = -0.21 \pm 0.25 \pm 0.11$ and $S_L = -0.37 \pm 0.36 \pm 0.17$, consistent with zero.

Although the current measurements do not yield very strong constraints on α, this channel does offer the prospect of a relatively straightforward measurement in the near future. As with $\pi^+\pi^-$ there is a simple relation between S_L and α_{eff}:

$$S_L = \sqrt{1 - C_L^2} \sin(\alpha_e ff) \tag{6}$$

As for $\pi\pi$, $|\alpha_{eff} - \alpha|$ may be constrained by a Grossman-Quinn bound:

$$\sin^2(\alpha_{eff} - \alpha) < \frac{BF(B^0/\bar{B}^0 \to \rho^0\rho^0)}{BF(B^{\pm} \to \rho^{\pm}\rho^0)} \tag{7}$$

Using BaBar's limit $BF(B^0 \to \rho^0\rho^0) < 2.1 \times 10^{-6}$, and conservatively taking this as the limit on the longitudinal decay mode, we find at 90% confidence level that $\sin^2(\alpha_{eff} - \alpha) < 19^{\circ}$. This is already more than a factor of two better than the corresponding limit for $\pi\pi$, and may improve with further statistics if the branching fraction is significantly lower than this limit. Thus this channel offers the possibility of a simple, reasonably-accurate measurement of α in the coming years.

MEASUREMENT OF γ/ϕ_3

Principles

The third angle of the Unitarity Triangle is that between $V_{cd}V_{cb}^*$ and $V_{ud}V_{ub}^*$. Constraints on it may therefore be obtained from channels where there is interference between $b \to c$ and $b \to u$ transitions. The resulting asymmetries are correspondingly small. On the positive side, in contrast to the α-sensitive channels described above, these measurements do not suffer from penguin pollution.

$B^{\pm} \to D^0 K^{\pm}$ decays

This method measures the weak phase difference between the Cabbibo-allowed decay $B^- \to D^0 K^-$ (a $b \to c\bar{u}s$ transition) and the suppressed decay $B^- \to \bar{D}^0 K^-$ (a $b \to u\bar{c}s$ transition), which is equal to γ. These two processes may interfere if the D^0 and $\bar{D}^0$ decay to the same final state.

One method is to study channels where the $D^0/barD^0$ decay to CP eigenstates, either even (e.g. $\pi\pi$, KK) or odd (e.g. $K_s\pi^0$, $K_s\phi$). Measurements of the rates and charge asymmetries in the even and odd decays should allow the extraction of γ. Both experiments are actively persuing such measurements, but at present statistics are too limited to constrain γ.

Belle [25] have recently presented results from another method, based on $D^0/\bar{D}^0$ decays to a common 3-body state $K_s\pi^+\pi^-$. Interference between the $b \to c$ and $b \to u$ channels may be observed by fitting the $K_s\pi\pi$ Dalitz plots from B^- and B^+ decays. The Dalitz plot amplitudes are given by:

$$A(B^- \to K_s\pi^+\pi^- K^-) = f(m_-^2, m_+^2) + re^{i(\delta-\gamma)} f(m_+^2, m_-^2) \tag{8}$$

$$A(B^+ \to K_s\pi^+\pi^- K^+) = f(m_+^2, m_-^2) + re^{i(\delta-\gamma)} f(m_-^2, m_+^2) \tag{9}$$

where $m_{\pm}^2$ is the mass-squared of the $K_s\pi^{\pm}$ combination, r is the ratio of the amplitudes for the Cabbibo-suppressed and Cabbibo-allowed decays and δ is the strong phase difference between the two. A simultaneous fit to both Dalitz plots allows the parameters r, γ and δ to be extracted.

With sufficient statistics a binned fit to the Dalitz plot would allow a model-independent measurement. At present, in order to maximise the statistical power of the method, a model is chosen for the Dalitz plot amplitude for $D^0 \to K_s\pi^+\pi^-$, $f(m^2(K_s\pi^-), m^2(K_s\pi^+))$. This model was obtained by fitting a set of resonant amplitudes, plus a non-resonant term, to 57,800 $D^*+ \to D^0\pi^+ \to (K_s\pi^+\pi^-)\pi^+$ events reconstructed in $78fb^{-1}$ of Belle data. Monte Carlo studies were used to estimate the effect of using different D^0 decays models on the measurement of γ, and a systematic uncertainty $\Delta\gamma = 10^{\circ}$ was assigned for the model-dependence.

$140fb^{-1}$ of data were used in the analysis, yielding 107 ± 12 signal events over a background of 33 ± 3. The fit yields 2 mirrored solutions for γ and δ, each 180° apart in both angles. Concentrating on the solution closest to the Standard Model fit result, Belle find $\gamma = 95^{\circ}\ ^{+25^{\circ}}_{-20^{\circ}} \pm 13^{\circ} \pm 10^{\circ}_{model}$. The 90% confidence limits obtained are $61^{\circ} < \gamma < 142^{\circ}$. The results are summarised in figure 5.

It is estimated that this method could reach 10° statistical precision with 1 ab^{-1} of data.

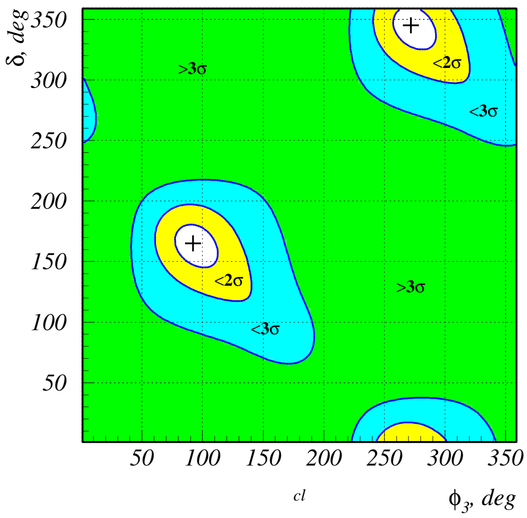

FIGURE 5. Confidence levels in $\phi_3(\gamma) - \delta$ plane from Dalitz plot analysis

$B^0 \to D^{(*)\pm}\pi^\mp$ decays

In this channel the interference between direct $B^0 \to D^{(*)-}\pi^+$ decay, via a $\bar{b} \to \bar{c}d\bar{u}$ transition, and mixing followed by the decay $\bar{B}^0 \to D^{(*)\pm}\pi^\mp$ via $b \to u\bar{c}d$ is sensitive to $\sin(2\beta+\gamma)$. However, although there is no penguin pollution, there is also an unknown strong phase difference between the 2 contributing amplitudes which must be measured. The time-evolution of the decay is described by:

$$P_{B^0}(D^\mp\pi^\pm) \propto e^{-\Gamma|\Delta t|}(1 \pm C\cos(\Delta m_d \Delta t) + S^\mp \sin(\Delta m_d \Delta t)) \quad (10)$$

$$P_{\bar{B}^0}(D^\mp\pi^\pm) \propto Ne^{-\Gamma|\Delta t|}(1 \mp C\cos(\Delta m_d \Delta t) - S^\mp \sin(\Delta m_d \Delta t)) \quad (11)$$

and similar equations for $D^*\pi$, where

$$C = \frac{1-r^2}{1+r^2} \approx \quad \text{and} \quad S^\mp = \frac{2r}{1+r^2}\sin(2\beta+\gamma\pm\delta) \quad (12)$$

and $r = |V_{ub}^* V_{cd}/V_{cb}V^*ud| \approx 0.02$. Thus by measuring the time-dependent asymmetries for both B and $\bar{B}$ tagged events it is possible to separate δ from $2\beta+\gamma$, allowing $2\beta+\gamma$ to be determined (with a 4-fold ambiguity).

Two analysis methods have been used, based on full and partial reconstruction. Both collaborations have presented analyses based on fully-reconstructed D and D^* decays [26, 27]. These methods provide high purity but relatively limited statistics. BaBar, analysing 81fb^{-1} of data, find 5207 ± 87 $D\pi$ candidates (85% purity) and 4746 ± 78 $D^*\pi$ (94% purity), while Belle in 140fb^{-1} find 8375 $D\pi$ (88% purity) and 7556 $D^*\pi$ (95% purity). Fits to the Δt distributions for different signal and tag charge combinations were then used to measure the CP asymmetries.

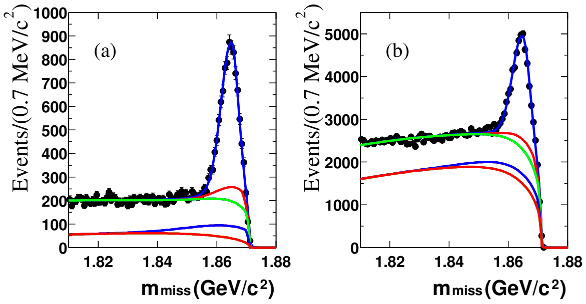

FIGURE 6. Missing mass signals from partially-reconstructed $D^*\pi$ decays, for lepton-tagged (left) and kaon-tagged (right) events

The results of the fit are summarised in table 6. Note that Belle present their results in a different form, as $2r\sin(2\beta+\gamma\pm\delta)$. For the purposes of comparison these have been transformed trignonmetrically to the same form used by BaBar.

BaBar [28] have also presented an analysis based on partial reconstruction of the decay $B^0 \to D^{*\mp}\pi^\pm$. This decay produces two distinctive pions, a "fast" π from the B decay and a "slow" π from the D^* decay. Beam constraints then allow the "missing mass" to be reconstructed, which is required to be consistent with the mass of the unreconstructed D^0. Combinatorial backgrounds are much higher in this method, and also depend on the flavour tag. High momentum leptons are a good signature of B decays, so lepton-tagged events have a much higher B purity than kaon tagged events, as can be seen in figure 6. In 81fb^{-1} BaBar reconstruct 6406 ± 129 lepton-tagged $D^*\pi$ and 25157 ± 323 kaon-tagged. A simultaneous time=dependent fit to the lepton- and kaon-tagged samples yields

$$2r\sin(2\beta+\gamma)\cos(\delta) = -0.063 \pm 0.024 \pm 0.014 \quad (13)$$

BaBar have interpreted their results in terms of $\sin(2\beta+\gamma)$ by minimising a χ^2 between the various measurements and the values of $\sin(2\beta+\gamma)$ and $\delta_{D\pi}/\delta_{D^*\pi}$, assuming values of r_D and r_{D^*} obtained from studies of $B^0 \to D_s^{(*)}\pi$, with an additional 30% theoretical uncertainty added. Table 7 summarises the limits obtained from the fully- and partially-reconstructed analyses and from combining the two analyses. The combination of the two analyses excludes $|\sin(2\beta+\gamma)| = 0$ with a confidence of 99.5%.

TABLE 6. CP asymmetry measurements from $B^0 \to D^{(*)}\pi$

	BaBar	Belle
$2r_{D^*\pi}\sin(2\beta+\gamma)\cos(\delta_{D^*\pi})$	$-0.068 \pm 0.038 \pm 0.021$	$0.063 \pm 0.041 \pm 0.016 \pm 0.036$
$2r_{D^*\pi}\sin(2\beta+\gamma)\sin(\delta_{D^*\pi})$	$0.031 \pm 0.070 \pm 0.035$	$0.030 \pm 0.041 \pm 0.016 \pm 0.036$
$2r_{D\pi}\sin(2\beta+\gamma)\cos(\delta_{D\pi})$	$-0.022 \pm 0.038 \pm 0.021$	$0.058 \pm 0.038 \pm 0.013 \pm 0.036$
$2r_{D\pi}\sin(2\beta+\gamma)\sin(\delta_{D\pi})$	$0.025 \pm 0.068 \pm 0.035$	$0.036 \pm 0.068 \pm 0.013 \pm 0.036$

TABLE 7. Limits on $|\sin(2\beta+\gamma)|$ from BaBar's $B^0 \to D^{(*)}\pi$ measurements

	68% CL	90% CL
Fully reconstructed	> 0.69	-
Partially reconstructed	> 0.88	> 0.75
Combined	> 0.89	> 0.76

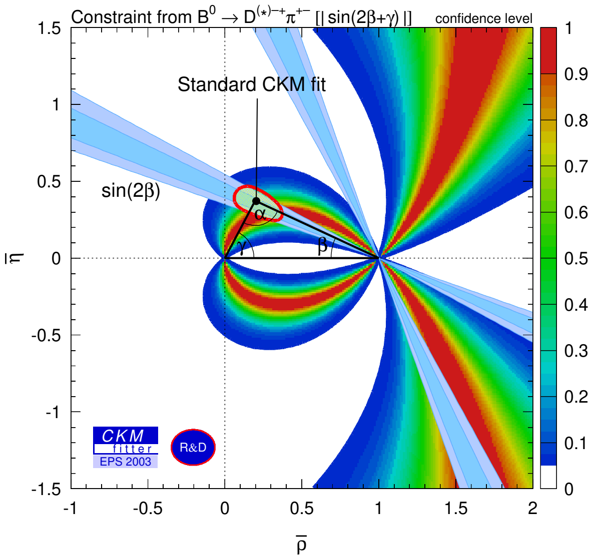

FIGURE 7. Probability contours in the $\rho - \eta$ plane from $D^{(*)}\pi$ constraints on $\sin(2\beta+\gamma)$

The results are in good agreement with the solution favoured by the Standard Model fit, as shown in Figure 7 [2].

SUMMARY AND PROSPECTS

The analyses described here are all in their early stages. Larger data samples in the coming years will increase the statistical significance of the measurements, allow better control of systematic uncertainties, and in permit more sophisticated analyses to be made. Other channels, not described here, may bring additional constraints. If the predictions of the QCD factorisation approach are validated it will be possible to extract stronger constraints from these measurements. At present such constraints as exist are all consistent with the Standard Model solution. However, the analyses described here will be statistically-limited for several years to come, and significant improvements in precision are to be expected in the future.

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