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Progress toward measuring the unitarity angle γ

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Abstract. Measuring the angle γ of the unitarity triangle is an important part of over-constraining the standard model's explanation of CP violation and testing for new physics contributions to CP violation. Although there are many ways to measure γ, all of them have significant experimental or theoretical challenges. This talk presents progress at the BABAR experiment toward measuring γ using B meson decays.

Keywords. γ; CP violation; BABAR.

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1. Introduction

Recent measurements of the CP violation parameter $\sin 2\beta$ have shown good agreement with Standard Model predictions. As this becomes a precision measurement the experimental challenge is to make numerous measurements of CP violating parameters in order to over-constrain the Standard Model and test its explanation of CP violation.

A complimentary measurement to $\sin 2\beta$ is the measurement of the unitarity angle $\gamma = \arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$, where V_{xy} are elements of the CKM matrix. In the standard phase convention [1] most of these elements are approximately real and $\gamma \sim -\arg(V_{ub})$. Thus measurements of γ typically use B decays with a $b \to u$ quark transition. Since $|V_{ub}| \sim 0.004$, these decays have small branching fractions and are experimentally challenging.

Fortunately there are many ways to measure γ, which have various trade-offs in the theoretical interpretation and experimental difficulty. This talk focuses on three methods which the BABAR Collaboration is using to measure γ: $B^\pm \to D^0_{\mathrm{CP}}K^\pm$, $B^0 \to D^{(*)\mp}\pi^\pm$, and $B \to \pi\pi, K\pi, KK$. The work presented here uses $\sim$88 million $B\bar{B}$ pairs produced at the $\Upsilon(4S)$ resonance by the PEP-II asymmetric e^+e^- accelerator and measured with the BABAR detector [2].

2. $B^\pm \to D^0_{\mathrm{CP}}K^\pm$

One method to measure γ uses $B^\pm \to DK^\pm$ decays, where D is either a D^0, $\bar{D}^0$, or a CP eigenstate $D^0_{\mathrm{CP}} = (D^0 \pm \bar{D}^0)/\sqrt{2}$.

The amplitudes $A(B^+ \to \bar{D}^0 K^+) = A(B^- \to D^0 K^-)$ have been measured using $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K^-\pi^+\pi^0$, and the charge conjugate decays for $\bar{D}^0$. A maximum likelihood analysis using kinematic information and K/π particle identification measures the ratio of branching ratios:

$$\frac{\mathrm{BF}(B^- \to D^0 K^-)}{\mathrm{BF}(B^- \to D^0 \pi^-)} = (8.31 \pm 0.35 \pm 0.20)\%. \tag{1}$$

The modes with D^0_{CP} have been measured using $D^0_{\mathrm{CP}} \to K^+K^-$ with $36.8 \pm 8.4 \pm 4.0$ signal events. The direct CP asymmetry has been measured:

$$A_{\mathrm{CP}} = \frac{\mathrm{BF}(B^- \to D^0_{\mathrm{CP}} K^-) - \mathrm{BF}(B^+ \to D^0_{\mathrm{CP}} K^+)}{\mathrm{BF}(B^- \to D^0_{\mathrm{CP}} K^-) + \mathrm{BF}(B^+ \to D^0_{\mathrm{CP}} K^+)} \tag{2}$$

$$= 0.17 \pm 0.23^{+0.09}_{-0.07}. \tag{3}$$

Future measurements will include $D^0_{\mathrm{CP}} \to \pi^+\pi^-$ decays.

The amplitudes $A(B^+ \to D^0 K^+) = A(B^- \to \bar{D}^0 K^-)$ are difficult to measure since doubly Cabibbo suppressed D^0 decays obscure the difference between $B^- \to D^0_{K^+\pi^-} K^-$ and $B^- \to \bar{D}^0_{K^+\pi^-} K^-$. Measurements with multiple D^0_{CP} eigenstates may help to measure γ with this method even with these uncertainties.

Reference [3] provides the details of this analysis.

3. $\sin(2\beta + \gamma)$ with $B^0 \to D^{(*)\mp}\pi^\pm, \rho^\pm, a_1^\pm$

Interference between $B^0 \to D^{(*)\mp}\pi^\pm$ and $\bar{B}^0 \to D^{(*)\mp}\pi^\pm$ gives rise to CP violation proportional to $\sin(2\beta + \gamma)$. The interfering decays have very different branching fractions, which cause the CP violating effects to be small. An advantage of this method, however, is that it can be done with several different decay modes: D or D^*; and π, ρ, or a_1. Each different mode measures the same weak phase $2\beta + \gamma$ with a different strong phase. The results can be combined to eliminate the strong phases and measure the weak phase.

The branching fractions for the decays $B^0 \to D^{(*)+}\pi^-$ are too small to measure with the current BABAR dataset. These branching fractions can be estimated using $SU(3)$ symmetry and the decays $B^0 \to D_s^{(*)+}\pi^-$. BABAR measures [4]:

$$\mathrm{BF}(B^0 \to D_s^+ \pi^-) = (3.2 \pm 0.9 \pm 1.0) \times 10^{-5}, \tag{4}$$

$$\mathrm{BF}(B^0 \to D_s^{*+} \pi^-) < 4.1 \times 10^{-5} \quad (90\% \;\; \mathrm{CL}). \tag{5}$$

To measure $\sin(2\beta + \gamma)$, one analysis at BABAR uses fully reconstructed $B^0 \to D^{(*)-}\pi^+$ decays. This sample has thousands of events with almost no background. At the time of this conference the $\sin(2\beta + \gamma)$ fit results are not yet finalised.

Another related analysis uses partially reconstructed D^* decays. The low momentum pion from $D^* \to D\pi$ is found but D is not fully reconstructed. This sample has over 40,000 flavour tagged B decays with a signal to background ratio of approximately one. The reconstruction method has been validated with a B^0 lifetime measurement using a subset of the full data set [4]. It measures

Table 1. Branching fractions (BF) and CP asymmetries for $B \to \pi\pi$, $K\pi$, KK. All results are based upon 81 fb^{-1} of data except $K^+\bar{K}^0$ which uses 54 fb^{-1} of data.

Mode	BF $\times 10^{-6}$	CP asymmetry
$B^0 \to \pi^0\pi^0$	< 3.6 [90% CL]	
$B^0 \to \pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$	$S = 0.02 \pm 0.34$; $C = -0.30 \pm 0.25$
$B^0 \to K^0\pi^0$	$10.4 \pm 1.5 \pm 0.8$	$0.03 \pm 0.36 \pm 0.09$
$B^0 \to K^+\pi^-$	$17.9 \pm 0.9 \pm 0.7$	$-0.102 \pm 0.050 \pm 0.016$
$B^0 \to K^+K^-$	< 0.6 [90% CL]	
$B^+ \to \pi^+\pi^0$	$5.5^{+1.0}_{-0.9} \pm 0.6$	$-0.03^{+0.18}_{-0.17} \pm 0.02$
$B^+ \to K^+\pi^0$	$12.8^{+1.2}_{-1.1} \pm 1.0$	$-0.09 \pm 0.09 \pm 0.01$
$B^+ \to K^0\pi^+$	$17.5^{+1.8}_{-1.7} \pm 1.3$	$-0.17 \pm 0.10 \pm 0.02$
$B^+ \to K^+\bar{K}^0$	< 1.3 [90% CL]	

$\tau(B^0) = 1.510 \pm 0.040 \pm 0.041$ ps, in good agreement with the world average measurement [1]. This confirms the ability of the partial reconstruction method to correctly identify the position of the B^0 decay vertex, which is an important step in measuring $\sin(2\beta + \gamma)$ with this method. As with the fully reconstructed $D^{(*)}$ analysis, the $\sin(2\beta+\gamma)$ fit results are not yet available at the time of this conference.

4. $B \to \pi\pi, K\pi, KK$

Amplitude relationships with $B \to \pi\pi, K\pi, KK$ can also measure or constrain γ. The theoretical interpretation is complicated by penguin contributions, rescattering effects, and $SU(3)$ symmetry breaking. The measurements from BABAR in these decay modes are summarised in table 1 [5].

5. Conclusions

Now that CP violation with B mesons has been well-established with $\sin 2\beta$ measurements, the study of other CP violating parameters will play an important role in over-constraining the standard model's explanation of CP violation. Much progress has been made in the past year toward measuring the unitarity angle γ with a variety of methods at BABAR. This talk has reported progress in several of the classic methods for measuring γ. There are additional methods of measuring γ which have been suggested more recently which show promise for resolving some of the theoretical difficulty in interpreting experimental results related to γ.

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