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NEW DEVELOPMENTS IN MEASUREMENTS OF CP VIOLATION

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We present several alternative techniques used by the *BABAR* Collaboration in order to measure the Unitarity Triangle angle γ. We also present the results of two searches designed to improve the measurements of $\sin(2\beta)$ using penguin B decay modes by reducing the hadronic corrections uncertainties.

1 Introduction

With the discovery of CP violation in the decays of neutral B mesons [1] and the precise measurement [2] of the angle β of the Cabibbo-Kobayashi-Maskawa (CKM) Unitarity Triangle [3], the experimental focus at the B factories has shifted towards over-constraining the unitarity triangle through precise measurements of $|V_{ub}|$ and the angles α and γ, and towards measurements of CP asymmetry in the charmless modes, that are sensitive to contributions from new physics. The angle γ is $\arg(-V^*_{ub}V_{ud}/V^*_{cb}V_{cd})$ where V_{ij} are CKM matrix elements. Several methods have been suggested and used to measure γ [4], but they all require large samples of B mesons not yet available in order to reduce uncertainties. Here we present the latest alternative methods explored by the *BABAR* experiment to measure the Unitarity Triangle (UT) angle γ.

The measurement of $\sin(2\beta)$ using penguin modes, while expected to yield values consistent with the most precise charmonium measurements, showed a small discrepancy in the recent past. In order to estimate if this deviation is due to new physics effects, the hadronic corrections uncertainties (Standard Model pollution) need to be reduced. We present an analysis aimed at reducing such uncertainties and the analysis of a new channel, free of Standard Model (SM) pollution.

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Figure 1: Feynman diagrams for the Cabibbo favored decay $B^0 \rightarrow D^{(*)-}\pi^+$ (left), corresponding to the decay amplitude A_c, and the Cabibbo suppressed decay $\overline{B}^0 \rightarrow D^{(*)-}\pi^+$ (right), whose amplitude is A_u.

2 Alternative methods to measure the Unitarity Triangle angle γ

A comprehensive review of γ measurements with the standard methods currently used was presented by A. Bondar (see his contribution to these Proceedings). In this section we will report the alternative methods explored by the *BABAR* collaboration and the latest results. In general, all measurements of the angle γ exploit the quantum interference between $b \rightarrow u$ and $b \rightarrow c$ transitions that starting from the same initial state lead to a common final state. The $b \rightarrow u$ transition, that is sensitive to the weak phase γ, is Cabibbo suppressed with respect to the $b \rightarrow c$ transition. As a consequence the ratio of the amplitudes of these transitions is generally small, leading to a difficult measurement. While for charged B decays [5,7] the time independent asymmetry measurement is sensitive to the weak phase γ directly, in the case of neutral B decays [8], since $B^0\overline{B}^0$ mixing is involved, the relevant weak phase is $2\beta+\gamma$. We will first consider the time dependent analyses of neutral B decays, then we will look into the time independent analyses of charged B decays.

2.1 Time dependent CP asymmetries in $B^0 \rightarrow D^{(*)\pm}\pi^\mp$ and $B^0 \rightarrow D^\pm\rho^\mp$ decays

The time dependent CP asymmetry in the decay modes $B^0 \rightarrow D^{(*)\pm}\pi^\mp$ has been extensively studied by *BABAR* [9,10] and BELLE [11]. In these modes the CP asymmetry arises from the phase difference between two amplitudes (see for example Fig. 1): one, involving $B^0\overline{B}^0$ mixing, that is Cabibbo suppressed by the product of two small CKM elements (V_{ub} and V_{cd}), the other one is favored (proportional to V_{cb}). Since the parameter $r_B^{(*)}$ for these decays is close to 0.02, the resulting interference between the two amplitudes, proportional to $r_B \sin 2\beta + \gamma \pm \delta$ is very small. The data sample currently available is not large enough to determine the parameter $r_B^{(*)}$, but assuming the validity of $SU(3)$ symmetry, factorization and excluding W exchange diagrams, it could be extracted from the measurement of the branching fraction $\mathcal{B}(B^0 \rightarrow D_s^{(*)\pm}\pi^\mp)$ [12]. For the first time in this analysis the new decay mode $B^0 \rightarrow D^\pm\rho^\mp$, with the same diagram, has been studied. With a time dependent maximum likelihood fit the following results [13] are obtained for the parameters related to the CP violation angle $2\beta+\gamma$: $a^{D\pi} = -0.010 \pm 0.023 \pm 0.007$, $c_{\rm lep}^{D\pi} = -0.033 \pm 0.042 \pm 0.012$, $a^{D^*\pi} = -0.040 \pm 0.023 \pm 0.010$, $c_{\rm lep}^{D^*\pi} = 0.049 \pm 0.042 \pm 0.015$, $a^{D\rho} = -0.024 \pm 0.031 \pm 0.009$, $c_{\rm lep}^{D\rho} = -0.098 \pm 0.055 \pm 0.018$. Combining these results with the partial reconstruction $B^0 \rightarrow D^{*\pm}\pi^\mp$ ones [10] the following limits are extracted: $|\sin(2\beta+\gamma)| > 0.64$ (0.40) at 68% (90%) C.L. [13]

2.2 Exploring $B^0 \rightarrow D^{(*)+}a_{0(2)}^-$ decays

Since the main difficulty with the $\sin(2\beta+\gamma)$ measurement is the small value of $r_B^{(*)}$, new decay modes have been proposed [14] to use other two-body final states. The basic idea is that decay amplitudes with light scalar or tensor mesons, such as a_0^+ or a_2^+, emitted from weak currents, are suppressed due to the small coupling constants $f_{a_{0(2)}}$. This means that the Cabibbo favored process ($b \rightarrow c$ transition) is expected to be suppressed, and can be comparable with the Cabibbo suppressed one, resulting in a potentially large CP asymmetry. Assuming $SU(3)$

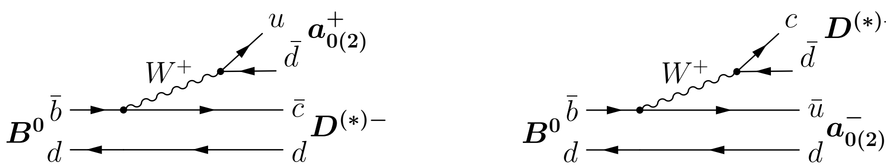

Figure 2: Tree diagrams contributing to the decay amplitude of $B^0 \to D^{(*)-}a^+_{0(2)}$

symmetry and factorization one can relate these decays to $B^0 \to D_s^{(*)+}a^-_{0(2)}$ decays, where the D is substituted by a D_s, and the branching fractions of these are Cabibbo enhanced. A search for $B^0 \to D_s^{(*)+}a^-_{0(2)}$ has been performed [15] using about 230 million $\Upsilon(4S)$ decays into $B^0\overline{B}^0$. No evidence of these decays has been observed and 90% C.L. upper limits on the branching fractions have been set: $\mathcal{B}(B^0 \to D_s^+a_0^-) < 1.9\times10^{-5}$, $\mathcal{B}(B^0 \to D_s^{*+}a_0^-) < 3.6\times10^{-5}$, $\mathcal{B}(B^0 \to D_s^+a_2^-) < 1.9\times10^{-4}$, and $\mathcal{B}(B^0 \to D_s^{*+}a_2^-) < 2.0\times10^{-4}$. The upper limit value for $B^0 \to D_s^+a_0^-$ is lower than the theoretical expectation, which might indicate the need to revisit the $B \to a_0X$ transition form factor estimate. It might also imply the limited applicability of the factorization approach for this decay mode. The upper limits suggest that the branching ratios of $B^0 \to D^{(*)+}a^-_{0(2)}$ are too small for CP asymmetry measurements given the present statistics of the B factories.

2.3 Another idea: $\overline{B}^0 \to D^{(*)0}\overline{K}^{(*)0}$ decays

The decay modes $\overline{B}^0 \to D^{(*)0}\overline{K}^0$ offer a new approach for the determination of $\sin(2\beta+\gamma)$ from the measurement of time-dependent CP asymmetries in these decays [5]. The CP asymmetry appears as a result of the interference between two diagrams leading to the same final state $D^{(*)0}K^0_S$ (Figure 3). A $\overline{B}^0$ meson can either decay via a $b \to c$ quark transition to the $D^{(*)0}\overline{K}^0$ ($\overline{K}^0 \to K^0_S$) final state, or oscillate into a B^0 which then decays via a $\bar{b} \to \bar{u}$ transition to the $D^{(*)0}K^0$ ($K^0 \to K^0_S$) final state (reference to the charge conjugate state is implied). The $\overline{B}^0B^0$ oscillation provides the weak phase 2β and the relative weak phase between the two decay diagrams is γ.

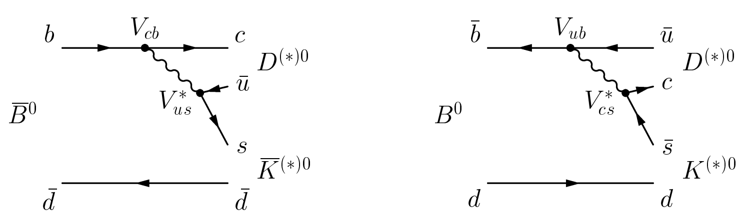

Figure 3: The decay diagrams for the $b \to c$ transition $\overline{B}^0 \to D^{(*)0}\overline{K}^0$ and the $\bar{b} \to \bar{u}$ transition $B^0 \to D^{(*)0}K^0$.

Both diagrams are color suppressed, this means that the parameter r_B could be large (expected to be close to 0.4), so the CP asymmetry is expected to be large. In order to get insight into the Cabibbo suppressed diagram in $B^0 \to D^{(*)0}\overline{K}^0$, the self-tagging $B^0 \to D^{(*)0}\overline{K}^{*0}$ with $\overline{K}^{*0} \to K^-\pi^+$. Using a sample of 226 million $B^0\overline{B}^0$ decays, the Cabibbo favored processes have been observed [16]. The ΔE distributions of candidates for the sums of the reconstructed D^0 decay modes are illustrated in Figure 4 and no evidence of the Cabibbo suppressed mode $B^0 \to \overline{D}^0\overline{K}^{*0}$ was observed. The following branching fractions are obtained: $\mathcal{B}(\tilde{B}^0 \to D^{*0}\tilde{K}^0) = (3.6 \pm 1.2 \pm 0.3) \times 10^{-5}$, $\mathcal{B}(\tilde{B}^0 \to D^0\tilde{K}^0) = (5.3 \pm 0.7 \pm 0.3) \times 10^{-5}$, and $\mathcal{B}(\overline{B}^0 \to D^0\overline{K}^{*0}) = (4.0 \pm 0.7 \pm 0.3) \times 10^{-5}$. A 90% confidence level upper limit is set on

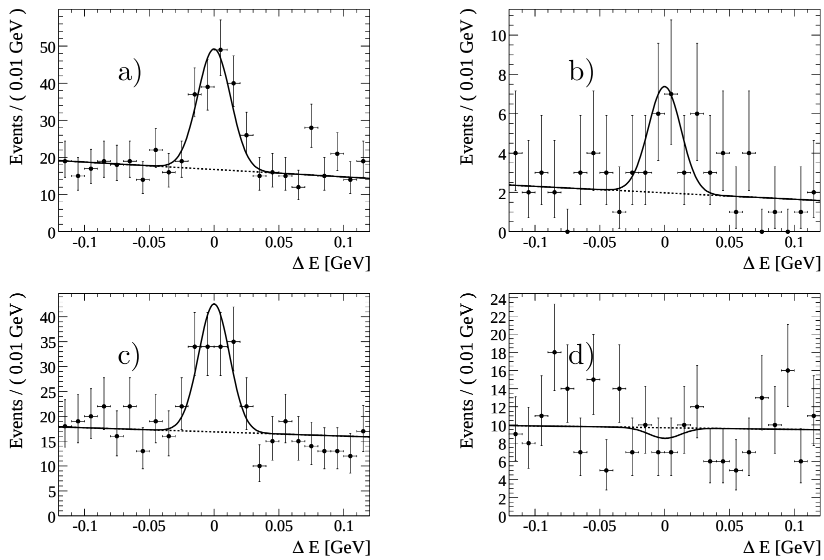

Figure 4: Distribution of ΔE for a) $\tilde{B}^0 \to D^0 \tilde{K}^0$, b) $\tilde{B}^0 \to D^{*0} \tilde{K}^0$, c) $\overline{B}^0 \to D^0 \overline{K}^{*0}$, and d) $\overline{B}^0 \to \overline{D}^0 \overline{K}^{*0}$ candidates with $|m_{\rm ES} - 5280\ \mathrm{MeV}/c^2| < 8\,\mathrm{MeV}/c^2$. The points are the data, the solid curve is the projection of the likelihood fit, and the dashed curve represents the background component.

$\mathcal{B}(\overline{B}^0 \to \overline{D}^0 \overline{K}^{*0}) < 1.1 \times 10^{-5}$. These limit can be translated into an upper limit for the decay amplitude ratio $r_B \equiv |\mathcal{A}(\overline{B}^0 \to \overline{D}^0 \overline{K}^{*0}) / \mathcal{A}(\overline{B}^0 \to D^0 \overline{K}^{*0})|$ to be less than 0.4 at the 90% confidence level, excluding the naive expected value for r_B.

2.4 Time independent CP asymmetries in $B^0 \to \overline{D}^0 K^+ \pi^-$ and $B^0 \to D^0 K^+ \pi^-$ decays

Even if these decays are from neutral B mesons, this analysis is time independent and it is sensitive directly to γ, not $2\beta + \gamma$. The principle is the same of all time independent charged B analyses: two diagrams (Cabibbo favored $b \to c$ and Cabibbo suppressed $b \to u$ transitions) interfering, one of which is color favored, the other color suppressed. The new idea behind this analysis is that in three body decays such as $B^0 \to \overline{D}^0 K^+ \pi^-$ and $B^0 \to D^0 K^+ \pi^-$, it is possible to get two extra $b \to c$ and $b \to u$ transitions, adding a color allowed $b \to u$ transition diagram[6,7]. This could lead to larger rates and potentially significant CP asymmetries. In addition, a Dalitz plot analysis of the $DK\pi$ final state can resolve the strong phase and reduce the ambiguity to two-fold, compared to the GLW standard method with the charged B. Using a sample of 226 million $B\overline{B}$ events, a branching fraction measurement of the Cabibbo favored decay has been performed[17]: $\mathcal{B}(B^0 \to \overline{D}^0 K^+ \pi^-) = (88 \pm 15 \pm 9) \times 10^{-6}$. Resonant contributions were observed but the search for the Cabibbo suppressed $B^0 \to D^0 K^+ \pi^-$ decays showed no evidence of signal. A 90% C.L. upper limit on the branching fraction was set: $\mathcal{B}(B^0 \to D^0 K^+ \pi^-) < 19 \times 10^{-6}$. The event yields in these modes are lower than expected, indicating that a larger data sample is required in order to constrain γ with this type of analysis.

3 New developments in the measurement of $\sin 2\beta$ using penguin modes

Measuring $\sin 2\beta$ with penguin modes opens the possibility of observing, or constraining new physics phenomena that could enter the loops. If the decay amplitude of these penguin modes is dominated, as naively expected, by the short distance penguin transition $b \to s\bar{s}s$, then the measured asymmetry in the tree level and penguin case should be consistent. Unfortunately, for many of these penguin modes there are other Standard Model diagrams that introduce the so-called SM pollution. Understanding the contribution from these hadronic corrections and reducing their uncertainties is thus necessary in order to evaluate any eventual contribution from new physics. To address this problem, several measurements have been proposed to estimate these corrections, and at the same time penguin modes that are theoretically free from SM pollution have been explored. Here we report the results of some branching fractions measurements needed to reduce the SM pollution uncertainties mentioned above, and the analysis of a new pollution-free penguin mode by the *BABAR* collaboration.

3.1 Branching Fraction Limits for B^0 Decays to $\eta'\eta$, $\eta'\pi^0$ and $\eta\pi^0$

The branching fraction measurement of these B^0 decays into two-body charmless final states has its own interest in comparing with the various theoretical predictions from QCD factorization [18], perturbative QCD (for $B^0 \to \eta^{(\prime)}\pi^0$) [19], soft collinear effective theory [20], and flavor-SU(3) symmetry [21]. The expectations lie in the approximate ranges 0.2–1.0×10^{-6} for $B^0 \to \eta^{(\prime)}\pi^0$, and 0.3–$2\times10^{-6}$ for $B^0 \to \eta'\eta$. These decays are also of interest in constraining the expected value of the time-dependent *CP*-violation asymmetry parameter S_f in the decay with $f = \eta' K^0_S$ [21,22]. The leading-order SM calculation gives the equality $S_{\eta' K^0_S} = S_{J/\psi K^0_S}$, where the latter has been precisely measured [2], and equals sin2β in the SM. The *CP* asymmetry in the charmless modes is sensitive to contributions from new physics, but also to contamination from sub-leading SM amplitudes. The most stringent constraint on such contamination in $S_{\eta' K^0_S}$ comes from the measured branching fractions of the three decay modes studied in this paper [21,22]. Recently it has also been suggested [23] that $B^0 \to \eta'\pi^0$ and $B^0 \to \eta\pi^0$ can be used to constrain the contribution from isospin-breaking effects on the value of sin2α in $B \to \pi^+\pi^-$ decays. No evidence of any of the signal signatures above was found in the 232 million $B\overline{B}$ pairs collected by *BABAR*. Combining the measurements we obtain the central values and 90% C.L. upper limits for the branching fractions: $\mathcal{B}(B^0 \to \eta'\eta) = (0.2^{+0.7}_{-0.5} \pm 0.4) \times 10^{-6}$ ($< 1.7 \times 10^{-6}$), $\mathcal{B}(B^0 \to \eta\pi^0) = (0.6^{+0.5}_{-0.4} \pm 0.1) \times 10^{-6}$ ($< 1.3 \times 10^{-6}$), and $\mathcal{B}(B^0 \to \eta'\pi^0) = (0.8^{+0.8}_{-0.6} \pm 0.1) \times 10^{-6}$ ($< 2.1 \times 10^{-6}$). These upper limits represent two to three-fold improvement over the previous measurements [25]. The range of sensitivity of these measurements is comparable to the range of the theoretical estimates. Using the method proposed by Gronau *et al.* [22], these results will provide approximately 20% improvement of the prediction for the contribution of the color suppressed tree amplitude in $B^0 \to \eta' K^0$ decays. This translates into a 20% reduction of this theoretical uncertainty in $S_{\eta' K^0_S}$. A similar improvement is found in the corresponding uncertainty of sin2α measured with $B \to \pi^+\pi^-$ decays [23].

3.2 Exploring $B^0 \to K^0_S K^0_S K^0_L$ penguin decays

As mentioned above, recent CP asymmetry measurements in $b \to s\bar{q}q$ penguin decays have suggested deviations from the SM expectations. The final state is a CP eigenstate, so there is no CP dilution effects, and it is also a pure $b \to s\bar{s}s$ penguin transition, so it is free from SM pollution [26]. This channel has been searched for the first time [27] and no evidence was found for this decay in 232 million $B\overline{B}$, so a branching fraction measurement and upper limit have been derived: $\mathcal{B}(K^0_S K^0_S K^0_L) = (2.4^{+2.7}_{-2.5} \pm 0.6) \times 10^{-6}$, $\mathcal{B}(K^0_S K^0_S K^0_L) < 6.4 \times 10^{-6}$ at 90% C.L.

4 Conclusion

The measurement of γ at the B factories is currently still limited by statistical uncertainties and a larger sample of B mesons is needed to improve the measurement. In the meanwhile a lot of effort has been spent in finding alternative paths to γ, all of which proved to lack statistical significance with the current data sample. Improvements in the estimate of hadronic corrections uncertainties has been made that will allow a more clear interpretation of some of the $\sin 2\beta$

penguin results. A new SM pollution free analysis has been performed but the channels proved to be suppressed beyond the initial theoretical predictions.

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