Measurements of Time-Dependent CP
Asymmetries in $b\rightarrow s$ Penguin Dominated
Hadronic $B$ Decays at $B_{\Lambda}B_{AR}$

Pietro Biassoni
(On behalf of the $B_{\Lambda}B_{AR}$ Collaboration)

Università degli Studi and INFN Milano, via Celoria 16, I-20133 Milano, Italy

Abstract. We report measurements of Time-Dependent CP asymmetries in several $b\rightarrow s$ penguin dominated hadronic $B$ decays, where New Physics contributions may appear. We find no significant discrepancies with respect to the Standard Model expectations.

Keywords: Charmless Hadronic $B$ decays, Time-Dependent CP Violation, $\sin^2\beta$ Measurement.

PACS: 13.25.Hw, 12.15.Hh, 11.30.Er, 13.66.Bc, 14.40.Cs, 13.25.Gv, 13.25.Jx, 13.20.Jf.

INTRODUCTION

The measurement of CP violation in $B$ meson decays provides crucial tests of the Standard Model (SM) and of the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1].

CKM-suppressed $b\rightarrow q\bar{q} s$ ($q = u, d, s$) processes are dominated by a single loop (penguin) amplitude, that, assuming penguin dominance and neglecting higher order contributions, is expected to have the same phase $\beta$ of the CKM-favored $b\rightarrow c\bar{c}s$ transition [2]. In many extensions of the SM new heavy particles may appear in the loop [3], giving rise to deviations from this expectation. These deviations are expected to be channel dependent. The measurement of the phase difference between $B^0\rightarrow K^*(892)^+\pi^-$ and $\bar{B}^0\rightarrow K^*(892)^-\pi^+$ can be used to constrain the CKM parameters in the $(\bar{\rho}, \bar{\eta})$ plane [4].

TIME-DEPENDENT DECAY RATES

The CKM phase $\beta$ is accessible experimentally through the interference between the decay of mixed and unmixed $B$ meson into a CP eigenstate. This interference is observable through the time evolution of the decay.

In the studies reported in this presentation, one $B^0$ from $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ is reconstructed in $\eta'K^0_s$, $\eta'K^0_s$, $\omega K^0_s$, or $K^0_SK^0_S$ CP eigenstate, or in $\pi^+\pi^- K^0_S$ or $K^+K^- K^0_S$ non-CP eigenstate final state ($B_{\text{sig}}$), and its vertex fitted using all charged daughter tracks. In $K^0_SK^0_S$ mode, where no charged track is present at $B^0$ meson decay vertex, $B_{\text{sig}}$ vertex is identified using the $K^0_S$ reconstructed flight directions and the knowledge of the average interaction point [5]. From the remaining particles in the event we reconstruct the decay vertex of the other $B$ meson ($B_{\text{tag}}$) and identify its flavor, through the analysis of the decay product of $B_{\text{tag}}$ [6].
The distribution of the difference $\Delta t \equiv t_{CP} - t_{tag}$ of the proper decay times of $B$ mesons into $CP$-eigenstate final states is given by

$$f(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left\{ 1 \pm \left[ -\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t) \right] \right\}$$

(1)

where $\eta_f$ is the $CP$ eigenvalue of the final state $f$ and $\tau$ is the $B^0$ meson lifetime. The upper (lower) sign denotes a decay accompanied by a $B^0(\bar{B}^0)$ tag, and $\Delta m_d$ is the mixing frequency.

For three body non-$CP$-eigenstate final state, the $CP$-violating parameters are a function of the position over the Dalitz Plot (DP). In this case Eq. (1) is written as

$$f(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left\{ |A|^2 + |\bar{A}|^2 \pm \left[ \eta_f 2Im[\bar{A}A^*] \sin(\Delta m_d \Delta t) - (|A|^2 - |\bar{A}|^2) \cos(\Delta m_d \Delta t) \right] \right\}$$

(2)

Let the decay $B^0 \rightarrow X_1 X_2 X_3$ proceed through $N$ intermediate states: the amplitude $A$ depends only on the Mandelstam invariants $s_{12}$ and $s_{23}$, and in the isobar approximation is

$$A(s_{12}, s_{23}) = \sum_{j=1}^{N} |c_j| e^{-i\phi_j} R_j(m_j) X_L(|\vec{p} * |r')X_L(|\vec{q} |r) T_j(L, \bar{p}, \bar{q})$$

(3)

where $c_j$ and $\phi_j$ are the relative magnitude and phase of the decay mode $j$, $R_j(m)$ is the lineshape term, $X_L$ are Blatt-Weisskopf barrier factors [7], $T_j$ is the angular distribution, $\vec{p}$ ($\vec{q}$) is the momentum of the prompt particle (one of the resonance daughters), $L$ is the orbital angular momentum between $\vec{p}$ and the resonance momentum, and asterisk denotes $B$ rest frame. For a decay into a quasi-two-body $CP$ eigenstate, one can extract the parameters $\beta_{eff} = \frac{1}{2} \arg (c_1 \bar{c}_1^*)$ and $\alpha_{ch}(k) = [||\vec{e}_k||^2 - |c_k|^2]/[|\vec{e}_k|^2 + |c_k|^2]$. For a decay into quasi-two-body non-$CP$ eigenstate, we measure the charge asymmetry and the phase between the two conjugate states $\Delta \Phi(k) = \arg (c_k \bar{c}_k^*)$.

A nonzero value of the parameter $C_f$ or $\alpha_{ch}$ would indicate direct $CP$ violation. In these modes we expect $-\eta_f S_f \equiv -\eta_f \sin 2\beta_{eff} \approx \sin 2\beta$. Deviations $\Delta S_f = S_f - \sin 2\beta$ from this expectation may appear even within the SM [8, 9], and are estimated in several theoretical approaches [8, 10].

**ANALYSIS TECHNIQUE**

Analyses presented here are based on a sample of $465 \times 10^6 B\bar{B}$ pairs ($383 \times 10^6$ for $B^0 \rightarrow K_S^0 \pi^+ \pi^-$), collected at a center-of-mass energy equal to the mass of the $Y(4S)$ resonance at the PEP-II asymmetric $e^+e^-$ collider, at the SLAC National Accelerator Laboratory, and recorded by the BABAR detector [11]. The $B$ meson is reconstructed into the above-mentioned $CP$ eigenstates. The $B$ meson is kinematically characterized by the variables $\Delta E \equiv E_B - \frac{1}{\sqrt{3}} \sqrt{s}$ and $m_{ES} \equiv \sqrt{s/4 - |\vec{p}_B|^2}$, where $(E_B, \vec{p}_B)$ is the $B$ four-momentum vector expressed in $Y(4S)$ rest frame.
Background arises primarily from random combinations of particles in $e^+e^-\rightarrow q\bar{q}$ events ($q=u,d,s,c$). We suppress this background with requirements on the event shape variables and on the energy, invariant mass and particle identification signature of the decay products. All events are required to have $|\Delta t|<20$ ps and $\sigma_{\Delta t}<2.5$ ps.

For each mode, results are obtained from an extended maximum likelihood fit with input variables $\Delta E$, $m_{ES}$, $\Delta t$, and the output of a multivariate discriminant combining different event shape variables. In $\omega K^0_s$ decay we also use $\omega$ mass and angular variables into the fit. $K^0_s$ momentum is determined using a $B$ mass constraint, hence $m_{ES}$ is fully correlated to $\Delta E$, and is not used into the fit in $\eta'K^0_s$ modes. The likelihood for a given event is the sum of the signal, continuum and the $B$-background components, weighted by their respective event yields. In $K^0_s\pi^+\pi^-$ and $K^0_sKK^-$ modes, a time-dependent DP analysis is performed. The DP model includes $f_0(980)$, $\rho^0(770)$, $K^{*\pm}(892)$, $(K\pi)^0_{\pm}$, $f_2(1240)$, $f_2(1300)$, $\chi_{c0}$ ($f_0(980)$, $\phi(1020)$, $X(1550)$), $f_2(1270)$, $\chi_{c0}$, $D^\pm$, $D^\mp$) and non resonant component for $K^0_s\pi^+\pi^-$ ($K^0_sKK^-$) decay mode. In $K^0_sKK^-$ analysis, the fit is first performed on the whole DP, and then in the low (high) mass region $m_{K^+K^-} < 1.1$ GeV/$c^2$ ($m_{K^+K^-} > 1.1$ GeV/$c^2$), fixing all the parameters to the values found in the whole DP fit, except the ones involving the $f_0(980)$ ($\phi(1020)$) resonance.

**RESULTS**

In Table 1 and 2 we report the results for $CP$-violating parameters in analyses of the decay of a $B^0$ meson into a $CP$ eigenstates and a three body non-$CP$ eigenstates final state (DP analyses), respectively [12]. Results for $K^0_sK^+K^-$ and $K^0_sK^0_sK^0$ are preliminary.

**TABLE 1.** Results of analyses of $b\rightarrow s$ decays into $CP$ eigenstates. For each decay mode we report $-\eta_fS_f$ and $C_f$. The first error is statistical, the second systematic.

| Decay Mode | $-\eta_fS_f$ | $C_f$ |
|------------|--------------|------|
| $\eta'K^0$ | $0.57\pm0.08\pm0.02$ | $-0.08\pm0.06\pm0.02$ |
| $\omega K^0_s$ | $0.55\pm0.29\pm0.02$ | $-0.22\pm0.20\pm0.03$ |
| $K^0_sK^0_sK^0$ | $0.90\pm0.20\pm0.04$ | $-0.18\pm0.17\pm0.03$ |

In $K^0_s\pi^+\pi^-$ and $K^0_sK^+K^-$ low mass region, the likelihood function has two minima. In $B^0\rightarrow f_0(980)K^0_s$ with $f_0(980)\rightarrow K^+K^-$, the second solution is disfavored by the result from $f_0(980)\rightarrow \pi^+\pi^-$. In $K^0_s\pi^+\pi^-$ analysis we measure $\chi_{ch}(K^*(892)^+\pi^-) = 0.20\pm0.10\pm0.02$, where the first (second) error is statistical (systematic). We also exclude $-137^o<\Delta\Phi(K^*(892)^+\pi^-)<-5^o$ at 95% confidence level.

**CONCLUSIONS**

We have reported the results of measurements of $CP$-violating parameters in several $b\rightarrow s$ hadronic $B$ meson decays. All the results are consistent with the SM. Results are
in agreement with and supersede previous BABAR measurements.

**TABLE 2.** Results of DP $b\to s$ analyses. For each decay mode we report $\beta_{\text{eff}}$, and $\mathcal{A}_{\text{ch}}$, for both solutions. The first error is statistical, the second systematic.

| Decay Mode           | Solution I     | Solution II    |
|----------------------|----------------|----------------|
|                      | $\beta_{\text{eff}}$ ($^\circ$) | $\mathcal{A}_{\text{ch}}$ | $\beta_{\text{eff}}$ ($^\circ$) | $\mathcal{A}_{\text{ch}}$ |
| $K^0_s \pi^+ \pi^-$  |                |                |
| $f_0(980)K^0_s$      | 36.0 ± 9.8 ± 3.0 | 0.08 ± 0.19 ± 0.05 | 56.2 ± 10.4 ± 3.0 | 0.23 ± 0.19 ± 0.05 |
| $\rho^0(770)K^0_s$   | 10.2 ± 8.9 ± 3.6 | 0.05 ± 0.26 ± 0.10 | 33.4 ± 10.4 ± 3.6 | 0.14 ± 0.26 ± 0.10 |
| $\phi K^0_s$         | 7.4 ± 7.4 ± 1.1  | 0.14 ± 0.19 ± 0.02 | 8.0 ± 8.0 ± 1.1  | 0.13 ± 0.18 ± 0.02 |
| $f_0(980)K^0_s$      | 8.6 ± 7.4 ± 1.7  | 0.01 ± 0.26 ± 0.07 | 197.1 ± 10.9 ± 1.7 | 0.49 ± 0.25 ± 0.07 |

**ACKNOWLEDGMENTS**

I’d like to thank all my BABAR colleagues for their support and in particular Fernando Palombo and Alfio Lazzaro.

**REFERENCES**

1. N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
2. Belle Collaboration, K.-F. Chen et al., Phys. Rev. Lett. 98, 031802 (2007); BABAR Collaboration, B. Aubert et al., Phys. Rev. D 79, 072009 (2009).
3. Y. Grossman and M. P. Worah, Phys. Lett. B 395, 241 (1997); D. Atwood and A. Soni, Phys. Lett. B 405, 150 (1997); M. Ciuchini, E. Franco, and L. Silvestrini, Phys. Rev. D 74, 054001 (2006); M. Gronau, J. L. Rosner, and J. Zupan, Phys. Lett. B 596, 107 (2004); M. Beneke and M. Neubert, Nucl. Phys. B 75, 333 (2003).
4. D. London and A. Soni, Phys. Rev. D 40, 61 (1997).
5. M. Beneke, Phys. Lett. B 620, 143 (2005); H. Y. Cheng, C.-K. Chua, and A. Soni, Phys. Rev. D 72, 014006 (2005), Phys. Rev. D 71, 014030 (2005); S. Fajfer, T. N. Pham, and A. Prapotnik-Brndnik Phys. Rev. D 72, 114001 (2005); A. R. Williamson and J. Zupan, Phys. Rev. D 74, 014003 (2006); M. Gronau, J. L. Rosner, and J. Zupan, Phys. Rev. D 79, 093003 (2006).