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CP Violation in $b \to s$ Penguins at the B Factories

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Abstract. Measurements of CP violating observables of the decays $B^0 \to \phi K^0$, $B^0 \to \eta' K_S$, $B^0 \to \rho K_S$, $B^0 \to K^+K^-K^0$ and $B^0 \to K_SK_SK_S$ are presented. In addition limits on the branching fractions of $B^0 \to \phi\pi^0$, $B^0 \to \phi\pi^+$, $B \to K^*K_S$, $B \to \eta'\pi^0$, $B \to \eta\pi^0$, $B \to \eta'\eta$, and $B^0 \to K_SK_SK_L$ are reported.

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INTRODUCTION

The decays of B^0 mesons to charmless final states through $b \to s$ penguins transitions are currently of great interest. There are a number of modes (such as $B^0 \to \phi K^0$ and $B^0 \to \eta' K^0$) which are expected to be dominated by $b \to s$ penguin amplitudes. Neglecting Cabibbo-Kobayashi-Maskawa (CKM) suppressed amplitudes, the mixing-induced CP violation parameter S for these modes should equal $\sin 2\beta$, which is well measured in $B^0 \to J/\psi K^0$ decays [1]. Within the Standard Model (SM), only small deviations from this prediction are expected [2]. If heavy non-SM particles appear in additional penguin diagrams, new CP-violating phases could enter and S would not equal $\sin 2\beta$ [3]. Observation of a significant discrepancy would be a clear signal of new physics.

Initial measurements of the most easily accessible of these modes were made at the B factories [4] which offered a tantalising hint of new physics. Recently this area has been investigated in greater detail, with increased statistics permitting access to a greater range of modes. As well as allowing the investigation of CP violation in a wider variety of decays analyses can also be performed that limit the effects of SM pollution, making any observed deviation a more significant sign of new physics.

THE *BABAR* AND BELLE DETECTORS

The *BABAR* detector is located on at the PEP-II asymmetric-energy e^+e^- storage ring at SLAC. The *BABAR* detector is described in detail elsewhere [5]. Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker (SVT), consisting of five layers of double sided detectors, and a 40-layer central drift chamber (DCH), both operating in the 1.5 T magnetic field of a solenoid. Charged-particle identification is provided by the average energy loss in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. An electromagnetic calorimeter (EMC) comprised of CsI(Tl) crystals is used for

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measuring the energy of electromagnetic showers as well as particle identification. The instrumented flux return (IFR) provides particle identification for muons and neutral hadrons. The results presented here used an integrated luminosity of $210\,\mathrm{fb}^{-1}$, corresponding to 227×10^{6} $B\overline{B}$ pairs, collected at the $\Upsilon(4S)$ resonance (centre-of-mass (CM) energy $\sqrt{s}=10.56\,\mathrm{GeV}$).

The Belle experiment [6] at the KEK-B asymmetric $e^{+}e^{-}$ collider consists of a silicon vertex detector (SVD) and a 50-layer central drift chamber (CDC) to provide tracking and vertexing, an array of aerogel threshold Cherenkov counters (ACC) complemented by an arrangement of time-of-flight scintillation counters (TOF) to provide particle identification, an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals is used for measuring the energy of electromagnetic showers and an instrumented flux return (KLM) is used for muon and neutral hadron identification. The results presented here used an integrated luminosity of $357\,\mathrm{fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance.

ANALYSIS TECHNIQUES

The analyses discussed here share many common techniques. For example, the tightly controlled kinematic conditions at the b-factories mean that where a B_d is fully reconstructed (all its decay products are seen and well measured in the detector) the kinematics of the B can be described in two variables: ΔE and m_{ES}. ΔE is defined as the reconstructed energy of the B minus E_{BEAM} (half the known CM energy of the incoming $e^{+}e^{-}$ pair). m_{ES} is the mass of the B ($\sqrt{(E^{2}-p^{2})}$) with E_{BEAM} substituted in. Decay modes including a K_L can not be fully reconstructed (the K_L can be observed via calorimeter or instrumented flux return but its momentum will not be accurately measured). In this case ΔE and m_{ES} collapse into a single kinematic variable which can be used to discriminate signal from background.

In all of the modes under discussion the numerically dominant background is $q\overline{q}$ (where $q=udsc$). Such light quark events have a jet like shape, where $b\overline{b}$ decays are essentially isotropic. This can be exploited through the use of variables describing the shape of the event with the general strategy being to combine multiple variables in a neural net or a Fisher discriminant.

Other means of separating signal from background vary between analysis. Mass cuts can be applied to sub decays (for example that of the π^{0}), a "flight length" cut can be applied to the decay vertex of any K^{0}_{S} in the event and where a particular angular distribution of decay products is expected (for example $B^{0}\to\rho K_{S}$) helicity can also be used as a discriminating factor.

The common technique for extracting branching fractions (BF) and upper limits is the use of multi-variate extended maximum likelihood fits. Components are included for signal, light quark background and any B backgrounds that are significant.

Measurement of time dependant CP parameters require measurements of both B flavour (specifically the flavour of the non-reconstructed B) and Δt, the difference in decay times of the two Bs. Δt is determined from the the separation of the two B decay vertices and the known boost to the centre of mass, and B flavour is determined from the decay products of the un-reconstructed B.

Details of individual analyses can be found here [7].

TABLE 1. Modes useful for limiting SM pollution.

Mode	*BABAR* $BF \times 10^{-6}$	Belle $BF \times 10^{-6}$	Theoretical Limit $\times 10^{-6}$ [8]
$B^0 \to \phi\pi^0$	$< 2.8, 90\% CL$	-	0.002
$B^- \to \phi\pi^-$	$< 2.4, 90\% CL$	-	0.005
$B^0 \to K^* K^0_S$	$< 1.9, 90\% CL$	-	0.29
$B^0 \to \eta'\pi^0$	$< 2.1, 90\% CL$	$2.8 \pm 1.0 \pm 0.3$	0.17
$B^0 \to \eta\pi^0$	$< 1.3, 90\% CL$	$< 2.3, 90\% CL$	0.28
$B^0 \to \eta'\eta$	$< 1.7, 90\% CL$	-	0.16

RESULTS

Unless otherwise stated, all results here are preliminary.

Two Body Modes

$B^0 \to \phi K^0$ is perhaps the most well known of the modes under discussion here. It offers high statistics and low theoretical errors [2]. Both *BABAR* and Belle investigate this mode with the $K^0 \to K^0_S$ and K^0_L. When these two modes are combined (with account taken for the different *CP* eigenvalues) *BABAR* measures $S = 0.50 \pm 0.25 \pm 0.06$, $C = 0.00 \pm 0.23 \pm 0.05$ and Belle measures $S = 0.44 \pm 0.27 \pm 0.05$, $C = 0.14 \pm 0.17 \pm 0.07$. These measurements are consistent with the SM and each other.

$B^0 \to \eta' K^0$ is another mode with high statistics and low theoretical errors. Again $K^0 \to K^0_S$ and K^0_L modes are combined. *BABAR* measures $S = 0.36 \pm 0.13 \pm 0.03$, $C = 0.16 \pm 0.09 \pm 0.02$ and Belle measures $S = 0.62 \pm 0.12 \pm 0.04$, $C = 0.04 \pm 0.08 \pm 0.06$. These measurements are consistent with the SM and each other.

As well as allowing more accurate measurements of well known modes, the wealth of available statistics makes new modes available for study. One example is $B^0 \to \rho K_S$, made challenging by the breadth of the ρ. This mode has been recently observed at *BABAR*, and its *CP* violation properties measured. Measurements of $S = 0.17 \pm 0.52 \pm 0.26$, $C = 0.64 \pm 0.41 \pm 0.25$ are entirely consistent with the standard model.

Limits on Standard Model Pollution

If S is seen to deviate from $\sin 2\beta$ (as measured in $B^0 \to J/\psi K^0$ decays [1]) it will be necessary to rule out all effects that may occur within the SM before new physics can be inferred. These will come from effects that are suppressed relative to the leading order diagrams, and can be studied in decays from which the leading order diagrams are absent but are otherwise identical. A summary of results from such modes is given in table 1. $B^0 \to \phi\pi^0$, $B^- \to \phi\pi^-$ and $B^0 \to K^* K^0_S$ tell us about $B^0 \to \phi K^0$, and $B^0 \to \eta'\pi^0$, $B^0 \to \eta\pi^0$ and $B^0 \to \eta'\eta$ give us information about $B^0 \to \eta' K^0$.

Three Body Modes

If the events already used for $B^0 \to \phi K^0$ are excluded, $B^0 \to K^+K^-K^0$ can measure of S and C. This is not a single pure CP eigenstate, but angular analysis shows it to be almost totally CP even. When a small correction factor is applied for the CP odd content Belle measures $S = 0.60 \pm 0.18 \pm 0.04 \pm 0.16$, $C = 0.06 \pm 0.11 \pm 0.07$ and *BABAR* measures $S = 0.41 \pm 0.18 \pm 0.07 \pm 0.11$, $C = 0.23 \pm 0.13 \pm 0.07$. The last error on S comes from the CP even content. The results are consistent with the SM.

$B^0 \to K_S K_S K_S$ is another useful mode. Its analysis is made more difficult by the need for a non standard method of vertexing (as all the K_S^0s will have flown to some extent). *BABAR* measures $S = 0.63 \pm 0.30 \pm 0.04$, $C = 0.10 \pm 0.25 \pm 0.05$ and Belle measures $S = 0.58 \pm 0.36 \pm 0.08$, $C = 0.50 \pm 0.23 \pm 0.06$.

BABAR has attempted to observe $B^0 \to K_S K_S K_L$. It has not yet been seen, but upper limits of 6.4×10^{-6} and 14×10^{-6} (90% CL) have been placed on the branching fraction, depending if phase space assumptions are (or are not, respectively) used in the calculation.

CONCLUSION

The CP violation of $b \to s$ penguin modes is rapidly developing area. As established modes become precision measurements it is becoming increasing important to put limits on possible SM pollution. Also new modes are becoming available, allowing a more comprehensive picture to form. The prospect of observing new physics remains tantalising.

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