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Nuclear Physics B Proceedings Supplement 00 (2012) 1–5

Nuclear Physics B Proceedings Supplement

Recent Results on Hadronic B decays from Belle

J.H. Kim[a], On behalf of Belle Collaboration.

[a]Korea Institute of Science and Technology Information, Daejeon

Abstract

Charmless hadronic B decays are suppressed compared to other hadronic B decays and hence can be excellent probes for new physics beyond the Standard Model. We present recent results from Belle on $B \to hh$ decays where h is a pion or a kaon of any charge, and $B \to \phi\pi$ decays. The data samples are collected with the Belle detector at the KEKB e^+e^- collider operating at the $\Upsilon(4S)$ resonance. The $B \to hh$ results, including the branching fractions and CP asymmetries, are based on a full Belle data sample of 772 million $B\bar{B}$ pairs, while the $B \to \phi\pi$ results are based on 657 million $B\overline{B}$ pairs.

Keywords: $B \to \phi\pi$ decays, $B \to hh$ decays, Rare B decays, Hadronic B decays, Belle experiment, BEACH 2012

1. Introduction

Charmless B meson decays provide an excellent probe in to the accuracy of the Standard Model (SM). Measurement of branching fractions and A_{CP} can be to measure CKM parameters. Furthermore, These measurements can confirm theoretical predictions, or indicate the presence of New Physics (NP).

Although predictions for the branching fractions under various theoretical approaches suffer from large hadronic uncertainties in $B \to hh$ decays, direct CP asymmetries and ratios of branching fractions can still provide excellent sensitivity to NP, since many theoretical and experimental uncertainties cancel out in these quantities. For instance, the observed A_{CP} difference between $B^\pm \to K^\pm\pi^0$ and $B^0/\bar{B}^0 \to K^\pm K^\mp$ [1, 2, 3], also known as the $\Delta A_{K\pi}$ puzzle, can be explained by an enhanced color-suppressed tree [4] contribution or NP in the electroweak penguin loop [5]. Other variables sensitive to electroweak penguin contributions are the ratios of partial widths. Existing measurements on these ratios are consistent with theory expectations [6, 7, 8, 9], albeit with large errors. The experimental uncertainties, therefore, need to be improved to adequately compare data and SM predictions.

In the SM, $B^+ \to \phi\pi^+$ [10] and $B^0 \to \phi\pi^0$ are highly suppressed since they are forbidden at tree level and are only possible through $b \to d$ penguin process shown in Fig. 1(a). The expected SM branching fractions for these decays are $\mathcal{B}(B^+ \to \phi\pi^+) \sim 3.2 \times 10^{-8}$ and $\mathcal{B}(B^0 \to \phi\pi^0) \sim 6.8 \times 10^{-9}$ [11], in which the largest contribution comes from radiative corrections and ω-ϕ mixing. In some New Physics (NP) scenarios such as models with a Z' boson [12, 13] or the Constrained Minimal Supersymmetric Standard Model (CMSSM) [14], the branching fractions could be enhanced up to the 10^{-7} level. Figure 1(b) shows a typical CMSSM contribution to $B \to \phi\pi$. Since $B \to \phi\pi$ decays are very sensitive to NP, measurements of these decays may constrain and potentially reveal such contributions. Furthermore, measurements of $B \to \phi\pi$ decays also provide a means to study SM contributions from suppressed diagrams in other important decay modes such as $B^0 \to \phi K^0$ [15].

In this paper, we report on measurements of the branching fraction for $B \to K\pi, \pi\pi$ and KK decays other than $B^0 \to \pi^0\pi^0$, and of the direct CP asymmetries for the modes with flavor-specific final states and a search for $B^+ \to \phi\pi^+$ and $B^0 \to \phi\pi$. The data samples are collected with the Belle detector [16] at the KEKB e^+e^- collider operating at the $\Upsilon(4S)$ resonance [17]. The $B \to hh$ results, including the branching fractions

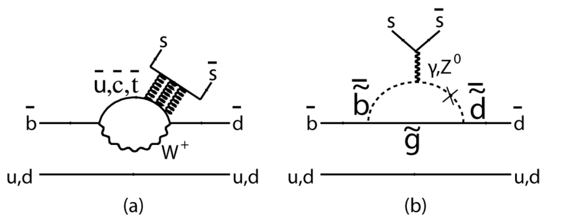

Figure 1: (a) The SM three-gluon hairpin penguin diagram for $B \to \phi\pi$ decays. (b) One of the CMSSM diagrams that contributes to $B \to \phi\pi$. In both (a) and (b), the $s\bar{s}$ quark pair hadronizes as a ϕ meson.

and CP asymmetries, are based on a full Belle data sample of 772 million $B\bar{B}$ pairs, while the $B \to \phi\pi$ results are based on 657 million $B\bar{B}$ pairs.

2. Event Selection and Analysis

We define our event selection criteria for these measurements of $B \to hh$ decays and to search for $B \to \phi\pi$ decays as follows. In $B \to hh$ decays, charged tracks originating from a B decay are required to have a distance of closest approach with respect to the interaction point less than 4.0 cm along the beam direction (z-axis) and less than 0.3 cm in the transverse plane. To search for $B \to \phi\pi$, we combine $\phi \to K^+K^-$ candidates with either a π^+ or $\pi^0 \to \gamma\gamma$. Charged kaons and pions are identified with information from particle identication detectors, which are combined to form a $K-\pi$ likelihood ratio $R_{K,\pi} = \frac{L_K}{L_K+L_\pi}$, where L_K and L_π denote, respectively,the individual likelihoods for kaons and pions derived from ACC and TOF information and dE/dx measurements in the CDC. Track candidates with $R_{K,\pi} > 0.6$ (< 0.4) for $B \to hh$ decays and $R_{K,\pi} > 0.3$ (0.2) for $B \to \phi\pi$ decays are classified as kaons (pions). Furthermore, in $B \to hh$, A tighter $R_{K,\pi}$ requirement (> 0.7) is applied for the $\bar{K}^0K^+$ channel to reduce the $B^+ \to K^0\pi^+$ feed-across.Charged tracks found to be consistent with an electron or a muon are rejected. Candidate K^0 mesons are reconstructed in $K^0_S \to \pi^+\pi^-$ by requring the invariant mass of the pion pair to be $480\text{MeV}/c^2 < M_{\pi\pi} < 516\text{MeV}/c^2$ (corresponding to 5.2σ standard deviations (σ). Pairs of photons with invariant masses lying in the range of $115\text{MeV}/c^2 < M_{\pi\pi} < 152\text{MeV}/c^2$ (correspondding to 2.5 σ), are identified as π^0 candidates. The photon energy is required to be greater than 50 (100) MeV in the barrel (endcap) calorimeter. In $B \to \phi\pi$, Candidate π^0's are reconstructed from γ pairs that have invariant mass between 115.3 MeV/c^2 and 152.8 MeV/c^2, corresponding to $\pm 2.5\sigma$ standard deviations (σ). In addition, these photons are required to have energies greater than 0.2 GeV. A K^+K^- pair is required to have an invariant mass within the range 1.008 GeV/$c^2 < M_{K^+K^-} <$ 1.031 GeV/c^2 (± 2.5 times the ϕ full width).

B meson candidates are identified with two kinematic variables: beam-energy-constrained mass, $M_{\rm bc} = \sqrt{E^2_{\rm beam} - |\sum_i \vec{p_i}|^2}$, and energy difference $\Delta E = \sum_i E_i - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy, and $\vec{p_i}$ and E_i are the momenta and energies, respectively, of the daughters of the reconstructed B meson candidate in the center-of-mass (CM) frame. For $B \to hh$ decays having a π^0 in the final state, the correlation between $M_{\rm bc}$ and ΔE is relatively large due to photon shower leakage in the calorimeter. To reduce this correlation, $M_{\rm bc}$ is calculated by scaling the measured π^0 momentum. We fit B candidates that lie within the fit region defined by $|\Delta E| <$ 0.3 GeV and $M_{\rm bc} > 5.20$ GeV/c^2 for $B \to hh$, $|\Delta E| <$ 0.1 GeV and $M_{\rm bc} > 5.20$ GeV/c^2 for $B^+ \to \phi\pi^+$ and $|\Delta E| < 0.4$ GeV and $M_{\rm bc} > 5.20$ GeV/c^2 for $B^0 \to \phi\pi^0$.

The main background arises from the continuum process, $e^+e^- \to q\bar{q}$, where $q = u, d, s, c$. To suppress this, observables based on the event topology are utilized. The event shape in the CM frame is spherical for $B\bar{B}$ events and jet-like for continuum events. This difference is exploited by the event-shape variable, which is a Fisher discriminant formed out of modified Fox-Wolfram moments [18, 19] calculated in the CM frame. The angle of the B flight direction (θ^*_B) with respect to the beam axis provides additional discrimination since it is distributed as $(1-\cos^2\theta^*_B)$ for B decays but flat for continuum. The distance in the z direction (Δz) between the signal B vertex [20] and that of the other B is used in the continuum suppression if $|\Delta z|$ is less than 0.2 cm. In addition, the helicity angle (θ_H) discriminates between the signal and continuum events for $B \to \phi\pi$ decays, where θ_H is the angle between the final state K^+ direction and the B meson direction in the ϕ rest frame.

$$L_{S(q\bar{q})} = \prod_i L^i_{S(q\bar{q})}, \quad (1)$$

where $L^i_{S(q\bar{q})}$ denotes the signal ($q\bar{q}$) likelihood of the continuum suppression variable i. The variable used for continuum suppression is the likelihood ratio (R_S) defined as

$$R_S = \frac{L_S}{L_S + L_{q\bar{q}}}. \quad (2)$$

In $B \to hh$ decays, a loose continuum suppression requirement is applied with $R_S > 0.2$. The variable R_S is then transformed to $R'_S = ln(\frac{R_S-0.2}{1.0-R_S})$, whose distribution for signal or backgrounds is easily modeled by analytical functions.

Additional background suppression in $B \to \phi\pi$ decays is achieved through the use of a B-flavor tagging algorithm [21], which provides two outputs: $q = \pm 1$ indicating the flavor of the other B in the event, and r, which takes a value between 0 and 1 and is the quality of the flavor determination. Events with a high value of r are considered to be well-tagged. The continuum background is reduced by applying a qr-dependent selection requirement on R_S. This requrement is optimized in three qr regions for $B^+ \to \phi\pi^+$: $-1 \le qr < -0.5$, $-0.5 \le qr < -0.1$, and $-0.1 \le qr \le 1$. For $B^0 \to \phi\pi^0$, since we do not distinguish the B flavor, we use three r intervals: $0 \le r < 0.25$, $0.25 \le r < 0.70$, and $0.70 \le r \le 1$.

Background contributions from $\Upsilon(4S) \to B\bar{B}$ events are investigated with a large GEANT3-based [22] Monte Carlo (MC) simulation sample that includes B decays to final states with and without charm mesons. After all selection requirements are imposed, In both $B \to hh$ and $B \to \phi\pi$ decays, backgrounds with charm mesons are found to be negligible; charmless backgrounds from B decays populates the negative ΔE region with small overlap with the signal, so its contribution can be extracted from a fit.

Signal yields for $B \to hh$ ($B \to \phi\pi$) decays are obtained by performing a three (two)-dimensional extended unbinned maximum likelihood (ML) fit to the observables $M_{\rm bc}$, ΔE and R'_S ($M_{\rm bc}$ and ΔE). Especially, we perform three separate simultaneous fits for pairs of modes that feed across into each other in $B \to hh$ decays: (a) $B^0 \to K^+\pi^-$ and $B^0 \to \pi^+\pi^-$, (b) $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$ and $B^+ \to K^0\pi^+$ and $B^+ \to K^0K^+$. The $B^0 \to K^+K^-$ channel is fitted alone.

We study control samples to correct for differences between data and MC simulations for the fitted means and widths of the observables. After all, we consider the systematic uncertainties in the efficiency, $N_{B\bar{B}}$ and the yield extraction.

3. Results of $B \to hh$ and $B \to \phi\pi$ decays

In this section, we report on the preliminary results of $B \to hh$ decays and the result of $B \to \phi\pi$ decays. Out of the five flavor-specific decay modes presented in Table 1 for $B \to hh$ decays, clear evidence for direct CP asymmetry is found only in the $B^0 \to K^+\pi^-$ channel. Compared to our previous measurement of $A_{CP}(K^\pm\pi^\mp)$ [1], the current result, $A_{CP}(K^\pm\pi^\mp) = -0.069 \pm 0.014 \pm 0.007$, differs by 1.3σ due to a smaller measured central value in the last set of 535×10^6 $B\bar{B}$ pairs, Aside from this difference, the measurement is consistent with

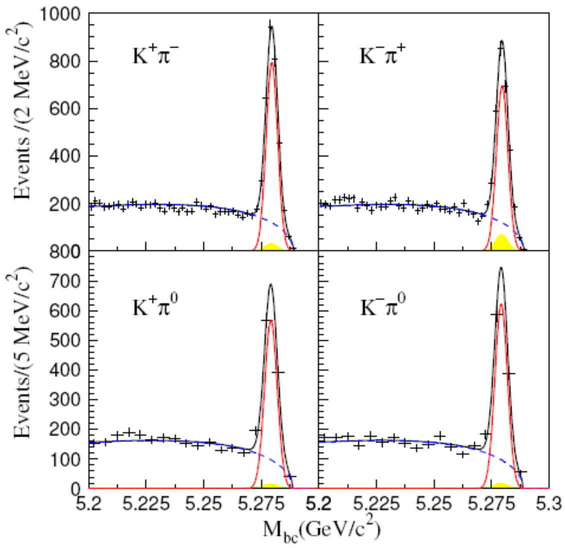

Figure 2: The $M_{\rm bc}$ distribution for $B^0/\bar{B}^0 \to K^\pm\pi^\mp$ (top) and $B^\pm \to K^\pm\pi^0$ (bottom).

our previous publication and other experimental results [2, 24, 25]. Furthermore, the updated difference of CP asymmetries $\Delta A_{K\pi} = A_{CP}(K^\pm\pi^0) - A_{CP}(K^\pm\pi^\mp)$ is given by $+0.112 \pm 0.027 \pm 0.007$ with significance of 4.0σ; this confirms our earlier result, as evident in Fig. 2. The ratios of partial widths for $B \to K\pi$ and $B \to \pi\pi$ can be used to search for NP [26, 27, 28]. These ratios are obtained from the measurements listed in Table 1. The ratio of charged to neutral B meson lifetime, $\tau_{B^+}/\tau_{B^0} = 1.079 \pm 0.007$ [29], is used to convert branching fraction ratios into partial width ratios. The total uncertainties are reduced because of the cancellation of common systematic uncertainties. These ratios are compatible with SM expectations [26, 27, 28, 30] and supersede our previous results [31]. The partial widths and CP asymmetries are used to test the violation of a sum rule [32] given by $A_{CP}(K^+\pi^-)+A_{CP}(K^0\pi^+)\frac{\Gamma(K^0\pi^+)}{\Gamma(K^+\pi^-)} - A_{CP}(K^+\pi^0)\frac{2\Gamma(K^+\pi^0)}{\Gamma(K^+\pi^-)} - A_{CP}(K^0\pi^0)\frac{2\Gamma(K^0\pi^0)}{\Gamma(K^+\pi^-)} = 0$ and the difference is found to be $-0.270 \pm 0.132 \pm 0.060$ (1.9σ significance), using $A_{CP}(K^0\pi^0) = +0.14 \pm 0.13 \pm 0.06$ [33]; this is still compatible with the SM prediction. All of these results provide useful constraints to NP models and our uncertainties are now comparable with those of the corresponding theoretical calculations.

Figure 3 shows the ΔE and $M_{\rm bc}$ projections of the fit for the selected B candidates of $B \to \phi\pi$ decays. There are a total of 373 $B^+ \to \phi\pi^+$ and 272 $B^0 \to \phi\pi^0$ candidates in the data sample. We determine the signal

Table 1: Signal yields, prroduct of efficiencies (ϵ) and sub-decay branching fractions ($\mathcal{B}_S$) [23], measured branching fractions ($\mathcal{B}$) direct CP asymmetries (A_{CP}) after the correction and significance of CP asymmetries ($\mathcal{S}$) for individual modes of $B \to hh$ decays. The first and second quoted errors are statistical and systematic, respectively. Upper limit is given the 90 % confidence level.

Mode	Yield	$\epsilon \times \mathcal{B}_S$ (%)	$\mathcal{B}(10^{-6})$	A_{CP}	$\mathcal{S}$ (σ)
$K^+\pi^-$	7525 ± 127	48.82	20.00 ± 0.34 ± 0.60	-0.069 ± 0.014 ± 0.007	4.4
$\pi^+\pi^-$	2111 ± 89	54.79	5.04 ± 0.21 ± 0.18		
$K^+\pi^0$	3731 ± 92	38.30	12.62 ± 0.31 ± 0.56	+0.043 ± 0.024 ± 0.002	1.8
$\pi^+\pi^0$	1846 ± 82	40.80	5.86 ± 0.26 ± 0.38	+0.025 ± 0.043 ± 0.007	0.6
K^0K^+	134 ± 23	15.64	1.11 ± 0.19 ± 0.05	+0.014 ± 0.168 ± 0.002	0.1
$K^0\pi^+$	3229 ± 71	17.46	23.97 ± 0.53 ± 0.71	-0.011 ± 0.021 ± 0.006	0.5
$K^0\bar{K}^0$	103 ± 15	10.61	1.26 ± 0.19 ± 0.05		
$K^0\pi^0$	961 ± 45	12.86	9.68 ± 0.46 ± 0.50		
K^+K^-	35 ± 29	47.72	0.10 ± 0.08 ± 0.04 (< 0.20)		

yields to be $N_s(B^+ \to \phi\pi^+) = 4.5^{+5.1}_{-4.3}$ and $N_s(B^0 \to \phi\pi^0) = -2.2^{+2.1}_{-1.2}$, where the quoted error is statistical only. We observe no significant signal for $B^+ \to \phi\pi^+$ or $B^0 \to \phi\pi^0$ decays. The upper limit ($\mathcal{B}_{UL}$) is determined as

$$\frac{\int_0^{\mathcal{B}_{UL}} \mathcal{L}(\mathcal{B})d\mathcal{B}}{\int_0^{\infty} \mathcal{L}(\mathcal{B})d\mathcal{B}} = 0.90, \quad (3)$$

where $\mathcal{L}(\mathcal{B})$ is the likelihood value and $\mathcal{B}$ is the branching fraction. The branching fraction is determined as the number of the signal events divided by the number of $B\bar{B}$ pairs and the reconstruction efficiency. We include systematic errors by convolving the likelihood function with a Gaussian whose width is equal to the total systematic error. The upper limits on the branching fractions are found to be $\mathcal{B}(B^+ \to \phi\pi^+) < 3.3\times10^{-7}$ and $\mathcal{B}(B^0 \to \phi\pi^0) < 1.5 \times 10^{-7}$ at the 90% CL.

4. Conclusion

We have measured the branching fractions and direct CP asymmetries for $B \to K\pi, \pi\pi$ and KK decays using 772×10^6 pairs, which is the final data set at Belle. We confirm a large $\Delta A_{K\pi}$ value with the world's smallest uncertainty. Including this result, the current world average is +0.124±0.022 (5.6σ significance) [34]. We find no significant deviation from SM expectations on the partial width ratios and the $A_{CP}(K\pi)$ sum rule, and these measurements continue to constrain the parameter space for NP. We report new upper limit for $B^0 \to K^+K^-$ that is improved by a factor of two over the current most restrictive limit [31] and is consistent with the latest LHCb result [25]. Compared to previous studies, all systematic uncertainties are decreased.

Using 657×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ with the Belle experiment, we find no significant signals for

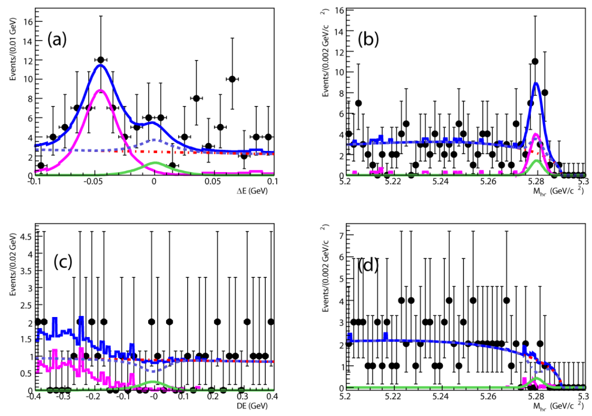

Figure 3: Projection of the data (points with error bars) in the fit region. The fit projections onto ΔE (left) and $M_{\rm bc}$ (right) for reconstructed $B^+ \to \phi\pi^+$ (top) and $B^0 \to \phi\pi^0$ (bottom); the sum of signal and $q\bar{q}$ (blue-dotted), $q\bar{q}$ (red-dashed), nonresonant $B \to K^+K^-\pi$ background (green-solid), other B background (magenta-solid) and the total (blue-solid).

$B^+ \to \phi\pi^+$ and $B^0 \to \phi\pi^0$. We set upper limits of $\mathcal{B}(B^+ \to \phi\pi^+) < 3.3 \times 10^{-7}$ and $\mathcal{B}(B^0 \to \phi\pi^0) < 1.5 \times 10^{-7}$ at the 90% CL.

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