Branching Ratios and CP Asymmetries of B Decays to a Vector and a Pseudoscalar Meson

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(December, 1997)

Abstract

We consider two body decays of B meson into a light vector (V) and a pseudoscalar (P) meson. The constraint obtained from the \( B \to P P \) modes on the parameter space of the input parameters is imposed also on \( B \to V P \) modes. In particular we constrain \( \xi \equiv (1/N_c) \) for those modes from recently measured \( B \to \omega K, \phi K \) and are able to get a satisfactory pictures for all modes where data exists. Modes that should be seen shortly and those with possibly large CP asymmetries are identified.
Recently CLEO [1,2] has reported information on the branching ratios of a number of exclusive modes where $B$ decays into a pair of pseudoscalars ($P$) or a vector ($V$) and a pseudoscalar meson. In some cases they have seen the decay for the first time and in other cases they have improved the bounds. Among the $B$ to $PP$ modes it was found that the branching ratio of the mode $B \to \eta ' K$ is larger than expected. We have shown that [3] by a suitable choice of parameters, this large branching ratio can be explained in the context of factorization technique without invoking any new physics or high charm content in $\eta'$. The same parameter space is also found to account for other $B \to PP$ modes (e.g. $B \to \pi K$ and $B \to \pi \pi$) consistent with the experimental data. The parameters involved in the above process are 1) effective number of color $\xi(\equiv 1/N_c)$, 2) CKM angles and phases 3) Form factors 4) the QCD scale and 5) the light quark masses. In this paper we calculate all $B \to VP$ modes using the same parameter space as was used in the case of $B \to PP$ modes, with the exception of $\xi$. This is because $\xi$ which takes account of non-factorizable contributions could in principle be different in $VP$ final states. We also need one new form factor which appears in the matrix element of the states involving $B$ meson and a vector meson. We use the experimental bound on $B \to \omega K$ and $B \to \phi K$ to put restriction on $\xi$ and the new form factor. We then predict the branching ratios and the CP asymmetries for all the other modes, some of which are expected to be measured soon.

The calculations proceed in two steps. First we consider the effective short distance Hamiltonian in the next to leading order (NLO). We then use the generalized factorization approximation to derive hadronic matrix elements by saturating the vacuum state in all possible ways. The effective weak Hamiltonian for hadronic $B$ decays can be written as

\[
H_{\Delta B=1} = \frac{4G_F}{\sqrt{2}} \left[ V_{ub} V_{uq}^* (c_1 O_1^u + c_2 O_2^u) + V_{cb} V_{cq}^* (c_1 O_1^c + c_2 O_2^c) - V_{tb} V_{tq}^* \sum_{i=3}^{12} c_i O_i \right] + h.c., \quad (1)
\]

where $O_i$’s are defined as

\[
O_1^f = \bar{q}_a \gamma_\mu L f_\beta \bar{f}_\beta \gamma^\mu L b_\alpha, \quad O_2^f = \bar{q}_a \gamma_\mu L f \bar{f} \gamma^\mu L b,
\]
\[ O_{3(5)} = \bar{q} \gamma_\mu L \Sigma q' \gamma^\mu L(R) q', \quad O_{4(6)} = \bar{q}_\alpha \gamma_\mu L \Sigma q'_\beta \gamma^\mu L(R) q'_\alpha, \]
\[ O_{7(9)} = \frac{3}{2} \bar{q} \gamma_\mu L \Sigma e q' \bar{q}' \gamma^\mu L(R) q', \quad O_{8(10)} = \frac{3}{2} \bar{q}_\alpha \gamma_\mu L \Sigma e q' \bar{q}' \beta \gamma^\mu L(R) q'_\alpha, \quad (2) \]

where \( L(R) = \frac{1 \mp \gamma_5}{2} \), \( f \) can be \( u \) or \( c \) quark, \( q \) can be \( d \) or \( s \) quark, and \( q' \) is summed over \( u, d, s, \) and \( c \) quarks. \( \alpha \) and \( \beta \) are the color indices, \( c_i \) is the Wilson coefficients (WCs). \( O_{7-10} \) are the electroweak penguin operators due to \( \gamma \) and \( Z \) exchange, and the "box" diagrams at loop level. We shall ignore the smaller contributions from the dipole penguin operators. The initial values of the WC are derived from the matching condition at the \( m_W \) scale. However we need to renormalize them [4] when we use these coefficients at the scale \( m_b \). We will use the effective values of WC at the scale \( m_b \) from the ref [3]. We have shown that in \( B \to PP \) case there is very little \( \mu \) dependence in the final states.

The generalized factorizable approximation has been quite successfully used in two body \( D \) decays as well as \( B \to D \) decays [3]. The method includes color octet non factorizable contribution by treating \( \xi \equiv 1/N_c \) as an adjustable parameter [3, 8]. Other work related to our paper includes ref. [3, 11] who have considered \( B \to \omega K \) and \( B \to \omega \pi \). These results are consistent with ours when restricted to our choice of parameter space. Work also exists on decays purely based on \( SU(3) \) symmetry [11]. This approach though more general, lacks detailed predictions that we can make using generalized factorization. Let us now describe the parametrization of the matrix elements and the decay constants in the case of \( B \to VP \) decays [3].

\[
\langle M(p')|V_\mu|B(p)\rangle = [(p + p')_\mu - \frac{m_B^2 - m_M^2}{q^2} q_\mu]F_1(q^2) + \frac{m_B^2 - m_M^2}{q^2} q_\mu]F_0(q^2) \quad (3)
\]
\[
\langle V(\epsilon, p')|(V_\mu - A_\mu)|B(p)\rangle = \frac{2}{m_B + m_V} i \epsilon^a p^a p'^a V(q^2)
- (m_B + m_V)[\epsilon_\mu - \frac{\epsilon^a q}{q^2} q_\mu]A_1(q^2)
+ \frac{\epsilon^a q}{m_B + m_V}[(p + p')_\mu - \frac{m_B^2 - m_M^2}{q^2} q_\mu]A_2(q^2)
- \epsilon^a q [2m_V q_\mu A_0(q^2)]
\quad (4)
\]

and the decay constants are given by:
\[ \langle 0 | A_\mu | M(p) \rangle = iM p_\mu, \quad \langle 0 | \epsilon V | V(\epsilon, p) \rangle = iV p \epsilon \epsilon, \]  
\tag{5}

where \( M, V, V_\mu \) and \( A_\mu \) denote a pseudoscalar meson, vector meson, a vector current and an axial-vector current, respectively, and \( q = p - p' \). Note that \( F_1(0) = F_0(0) \) and we can set \( F_{0,1}^{B \to M}(q^2 = m_M^2) \approx F_{0,1}^{B \to M}(0) \) since these form factors are pole dominated by mesons at scale \( m_B^2 \). Among all the form factors in the \( \langle V(\epsilon, p') | (V_\mu - A_\mu) B(p) \rangle \) matrix element, only \( A_0 \) survives when we calculate the full \( B \to VP \) decay amplitude. The \( A_0 \) is related to \( A_1 \) and \( A_2 \):

\[ A_0(0) = \frac{m_B + m_V}{2m_V} A_1(0) - \frac{m_B - m_V}{2m_V} A_2(0). \]  
\tag{6}

The form factors are related to each other by flavor SU(3) symmetry. For a current of the type \( \bar{u} \gamma_\mu (1 - \gamma_5) b \) we have following values of \( A_0 \) for \( B \) decaying into \( K^*, \omega \) and \( \rho \):

\[ A_0^{B \to \omega} = \frac{G}{\sqrt{2}}, \quad A_0^{B \to K^*} = G, \quad A_0^{B \to \rho} = \frac{G}{\sqrt{2}}. \]

The values of the form factors present in the decay amplitude of \( B \) into pseudoscalars are:

\[ F_{0,1}^{B \to K} = F, \quad F_{0,1}^{B \to \pi^{\pm}} = F, \quad F_{0,1}^{B \to \pi^0} = \frac{F}{\sqrt{2}}, \]  
\[ F_{0,1}^{B \to \eta'} = F \left( \frac{\sin \theta}{\sqrt{6}} + \frac{\cos \theta}{\sqrt{3}} \right), \quad F_{0,1}^{B \to \eta} = F \left( \frac{\cos \theta}{\sqrt{6}} - \frac{\sin \theta}{\sqrt{3}} \right). \]  
\tag{7}

In ref. [3], we find \( F = 0.36 \) gives a good fit to \( B \to PP \) data and we shall find that \( G = 0.28 \) in ref. [9,12] provides a good fit to \( B \to VP \) decays. The values of the decay constants (in MeV) we use are [3,8,12,13]:

\[ f_\omega = 195, \quad f_{K^*} = 214, \quad f_\rho = 210, \quad f_\pi = 134, \quad f_K = 158, \quad f_1 = f_\pi, \quad f_8 = 1.75 f_\pi. \]

The decay constant \( f_{\eta'}^{\pi,s} \) and \( f_{\eta'}^{\pi,s} \) are obtained by combining \( f_1 \) and \( f_8 \) with a \( \eta - \eta' \) mixing angle \( \theta \), where \( \theta = -25^\circ \). The particular choices \( f_1 \) and \( f_8 \) and \( \theta \) value allow us to fit the \( B \to \eta' K \) experimental bound without violating any other experimental constraints. In processes involving \( \eta' \), when estimating we have included the effects of anomaly [3,13,14].

For the preferred value of \( \gamma \), we use ref. [3] where the ratio of the branching ratio of \( B \to \eta' K \) and the branching ratio of \( B \to \pi K \) has been studied. The ratio does not depend
on the form factors and it has been found that the small value of the weak phase $\gamma \simeq 35^0$ is preferred. It has also been pointed out that in order to satisfy the experimental constraint on the branching ratio of $B \to \pi^+\pi^-$ mode, the smaller $|V_{ub}/V_{cb}| = 0.07$ is preferred.

Now we discuss the constraints on $\xi$ that can be obtained from the branching ratio of $B \to \phi K$ and $B \to \omega K$. Recent measurement at CLEO \[^2\] yield the following bounds:

\[
BR(B^\pm \to \omega K^\pm) = (1.5^{+0.7\, -0.6}_\pm \pm 0.3) \times 10^{-5},
\]

\[
BR(B^\pm \to \phi K^\pm) < 0.53 \times 10^{-5}.
\]

In the figure 1 we have plotted the branching ratio of $B^\pm \to \omega K^\pm$ averaged over particle-antiparticle decays as a function of $\xi$ for $\mu = m_b$. We calculate the branching ratio by multiplying the partial width of the particular mode by the total rate $\tau_B = 1.49$ ps. We can see from the figure that only the large values of $\xi > 0.6$ or small values of $\xi < 0.15$ are experimentally allowed. For most of the $\xi$ values, the penguin part of the amplitude is larger than the tree part by almost an order of magnitude. The region of $\xi$ (0.3 - 0.5) where the branching ratio is smallest, the penguin part and the tree part are of the same order. Here the CP asymmetry is also very large ($\sim 69\%$). The asymmetry is however small (at the most 4\%) for the $\xi$ values which are allowed by the experiment. The branching ratio is not sensitive to the form factor $A_0$.

In the figure 2 we plot the branching ratio $B^\pm \to \phi K^\pm$ averaged over particle-antiparticle decays as a function of $\xi$ for $\mu = m_b$. From the figure we see that only the lower values of $\xi(< .3)$ are allowed. In this mode there is no tree contribution, and also does not depend on $A_0$. Considering this B decay mode and the mode discussed above, we can conclude that only the lower values of $\xi \leq 0.2$ are allowed by the $B \to VP$ decays.

In the figure 3 we show the branching ratio $B^\pm \to \omega\pi^\pm$ averaged over the particle-antiparticle decays as a function of $\xi$ for $\mu = m_b$. The tree part is larger than the penguin part by an order of magnitude. There exists a CLEO observation \[^4\] ($(1.1^{+0.6}_\pm -0.5 \pm 0.2) \times 10^{-5}$) for this mode, but the experimental result has large errors. When the result improve this mode will be a crucial test for factorization hypothesis. As it stands now there is mild
disagreement with data that prefers larger ξ values. This rate can be enhanced somewhat by larger G. We show this as an example for G =0.35 in the figure 3 by a dashed line. For the rest of the decays we have used G =0.28.

The branching ratios of other B → VP modes, we have calculated, are all smaller than the experimental bound currently available. In Table 1 we have shown the average branching ratios of all the charged B decay modes to a vector and a pseudoscalar for |ΔS| = 0 and 1, where S is the strangeness quantum number. In Table 2, we shown the branching ratios of the neutral B decays to a vector and a pseudoscalar and Table 3 we have shown the available experimental bounds [2] at 90 % C.L. except those entries with errors which are the observed branching ratios.

Now we discuss some of the modes whose BR are close to the recently obtained CLEO data. We also discuss the CP asymmetries of these modes. It appears from Table 1 and Table 2 that some of the B → ρπ modes and B → K∗π modes will be observed soon. The mode B^0 → ρ^+π^- has the tree part larger than the penguin part in the amplitude by one order of magnitude for any value of ξ. The BR decreases from the maximum value of 3×10^-5 calculated at ξ =0, as ξ increases. The asymmetry is ∼4% over the full range of ξ. The experimental bound on this mode at 90 % C.L. is 8.8×10^-5. The mode B^0 → ρ^-π^+ (not \( \bar{B}^0 \rightarrow \rho^-\pi^+ \)) has the tree part larger than the penguin part in the amplitude by three order of magnitude for any value of ξ. The BR decreases from the maximum value of 6.4×10^-5 calculated at ξ =0, as ξ increases. The asymmetry is less than 1% over the full range of ξ. The experimental bound on this mode at 90 % C.L. is 8.8×10^-5. Note that, for both those modes asymmetry measurement will need tagging. The mode B^+ → ρ^0π^+ has the penguin part and the tree part of the same order for the ξ values between 0 and 0.2. For ξ’s larger than that, the tree part is larger than the penguin part by an order of magnitude. The asymmetry varies between 0 to 29 %, the maximum occurs at ξ = 0. The BR increases as ξ increases. The experimental bound at 90 % C.L. is 5.8 ×10^-5, which is little larger than the largest theoretical BR 1.4×10^-5 which occurs at ξ =1. The mode B^0 → K^{*+}π^- has the penguin part larger than the tree part in the amplitude by one order of magnitude.
for any value of $\xi$. The BR decreases from the maximum value of $1.43 \times 10^{-5}$ calculated at $\xi = 0$ as $\xi$ increases. The asymmetry varies between 5 to 7% over the full range of $\xi$. The experimental bound on this mode at 90 % C.L. is $6.7 \times 10^{-5}$. The mode $B^+ \rightarrow K^{*0}\pi^+$ is also a pure penguin process. The BR decreases from the maximum value of $1 \times 10^{-5}$ (at $\xi = 0$) as $\xi$ increases. The experimental bound on the BR on this mode at 90 % C.L. is $3.9 \times 10^{-5}$. The mode $B^0 \rightarrow K^{*0}\pi^0$ has the penguin part larger than the tree part in the amplitude by two order of magnitude for lower values of $\xi$ ($\xi < 0.4$). For larger values of $\xi$, the tree part and the penguin part become comparable and gives rise to large CP asymmetry. The BR from the maximum value of $3.89 \times 10^{-6}$ calculated at $\xi = 0$ decreases as $\xi$ increases. The asymmetry is between 0 to 30% over the full range of $\xi$. The experimental bound on this mode at 90 % C.L. is $2 \times 10^{-5}$. The mode $B^0 \rightarrow K^{*+}\pi^0$ has the penguin part in the amplitude to be larger by an order of magnitude than the tree part for almost any value of $\xi$. The BR decreases from the maximum value of $8.6 \times 10^{-6}$ (at $\xi = 0$) as $\xi$ increases. The asymmetry is $\sim 5\%$ for any value of $\xi$. The experimental bound on this mode at 90 % C.L. is $8 \times 10^{-5}$.

Apart from the above discussed modes there exists some more modes, where large CP asymmetry can be observed. For example, $B^+ \rightarrow \rho^+\eta$ mode has as large as 35 % CP asymmetry at $\xi = 0$ and $\sim 33\%$ at $\xi = 0.2$. The BR is expected to be $5.40 \times 10^{-6}$ at $\xi = 0$ and $5.88 \times 10^{-6}$ at $\xi = 0.2$. The mode $B^+ \rightarrow \rho^+\eta'$ has large CP asymmetry $\sim 31\%$ at $\xi = 0$ and at $\xi = 0.2$. The BR is expected to be $3.19 \times 10^{-6}$ at $\xi = 0$ and $2.99 \times 10^{-6}$ at $\xi = 0.2$. There are no experimental bounds on the above modes yet. The mode $B^0 \rightarrow \rho^0\pi^0$ has CP asymmetry $\sim 11\%$ at $\xi = 0$ and $\sim 24\%$ at $\xi = 0.2$. The BR calculated at $\xi = 0$ is $1.44 \times 10^{-6}$ and at $\xi = 0.2$ is $1.81 \times 10^{-7}$. The experimental limit is $1.8 \times 10^{-5}$.

In conclusion, we have calculated branching ratio and CP asymmetry of all the $B \rightarrow VP$ decay modes. We find that if we keep $\xi < 0.2$ and use the constraint obtained from the $B \rightarrow PP$ modes on the parameter space of the input parameters, we can fit the recently obtained experimental bounds on the branching ratios of the $B \rightarrow VP$ modes. We have pointed out that some of the modes show large CP asymmetry in that region of $\xi$ and the
branching ratios of some of the modes are also very close to the present bounds and can be expected to be observed soon. This will definitely determine conclusively the applicability of the factorization technique to these modes, may also help to establish the CP asymmetries.

Acknowledgements

We would like to acknowledge K.T. Mahanthappa and Jim Smith for helpful discussions. This work was supported in part by the US Department of Energy Grants No. DE-FG06-854ER-40224 and DE-FG03-95ER40894.
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Table Caption:

**Table 1**: The branching ratios and the asymmetries of all the charged B decay modes into a vector and a pseudoscalar meson for $\xi=0$ and 0.2 are shown.

**Table 2**: The branching ratios and the asymmetries of all the neutral B decay modes into a vector and a pseudoscalar meson for $\xi=0$ and 0.2 are shown.

**Table 3**: The bounds on the branching ratios at 90% C.L. on various modes, except for those entries with error, which are the observed modes.

Figure Captions:

**Fig. 1**: Branching ratio for the average of $B^{\pm} \rightarrow \omega K^{\pm}$ as a function of $\xi$. The curve is for $A_{0}^{B \rightarrow \omega} = \frac{0.28}{\sqrt{2}}$.

**Fig. 2**: Branching ratio for the average of $B^{\pm} \rightarrow \phi K^{\pm}$ as a function of $\xi$.

**Fig. 3**: Branching ratio for the average of $B^{\pm} \rightarrow \omega \pi^{\pm}$ as a function of $\xi$. The solid line is drawn for $A_{0}^{B \rightarrow \omega} = \frac{0.28}{\sqrt{2}}$ and the dashed line is drawn for $A_{0}^{B \rightarrow \omega} = \frac{0.35}{\sqrt{2}}$. Note that the statistical significance for observing this mode is only 2.9 $\sigma$. 


| modes | BR at $\xi=0$ | BR at $\xi=0.2$ | asymmetry at $\xi=0$ | asymmetry at $\xi=0.2$ |
|-------|---------------|-----------------|---------------------|---------------------|
| $B^+ \rightarrow \phi K^+$ | $3.42 \times 10^{-7}$ | $3.24 \times 10^{-6}$ | 0% | 0% |
| $B^+ \rightarrow \omega K^+$ | $1.18 \times 10^{-5}$ | $2.71 \times 10^{-6}$ | $\sim 2\%$ | $\sim 4\%$ |
| $B^+ \rightarrow \rho^0 K^+$ | $1.95 \times 10^{-7}$ | $1.18 \times 10^{-7}$ | $\sim -4\%$ | $\sim -9\%$ |
| $B^+ \rightarrow \rho^+ K^0$ | $2.39 \times 10^{-8}$ | $6.43 \times 10^{-8}$ | 0% | 0% |
| $B^+ \rightarrow K^{*0} \pi^+$ | $9.96 \times 10^{-6}$ | $7.96 \times 10^{-6}$ | 0% | 0% |
| $B^+ \rightarrow K^{*+} \pi^0$ | $8.59 \times 10^{-6}$ | $8.19 \times 10^{-6}$ | $\sim 5\%$ | $\sim 5\%$ |
| $B^+ \rightarrow K^{*+} \eta'$ | $1.20 \times 10^{-6}$ | $1.50 \times 10^{-6}$ | $\sim -2\%$ | $\sim -2\%$ |
| $B^+ \rightarrow K^{*+} \eta$ | $4.09 \times 10^{-6}$ | $3.62 \times 10^{-6}$ | $\sim -7\%$ | $\sim -8\%$ |
| $B^+ \rightarrow \omega \pi^+$ | $5.81 \times 10^{-7}$ | $2.3 \times 10^{-6}$ | $\sim -5\%$ | $\sim 5\%$ |
| $B^+ \rightarrow \rho^{0+} \pi^+$ | $4.26 \times 10^{-7}$ | $1.6 \times 10^{-6}$ | $\sim -29\%$ | $\sim -13\%$ |
| $B^+ \rightarrow \rho^{+0} \pi^0$ | $1.16 \times 10^{-5}$ | $1.26 \times 10^{-5}$ | $\sim 4\%$ | $\sim 4\%$ |
| $B^+ \rightarrow \rho^{+} \eta'$ | $3.19 \times 10^{-6}$ | $2.99 \times 10^{-6}$ | $\sim -31\%$ | $\sim -31\%$ |
| $B^+ \rightarrow \rho^{+} \eta$ | $5.40 \times 10^{-6}$ | $5.88 \times 10^{-6}$ | $\sim -35\%$ | $\sim -33\%$ |
| $B^+ \rightarrow K^{*0} K^+$ | $3.52 \times 10^{-7}$ | $2.81 \times 10^{-7}$ | 0% | 0% |
| $B^+ \rightarrow K^{*+} K^0$ | $5.16 \times 10^{-10}$ | $1.66 \times 10^{-9}$ | 0% | 0% |
| $B^+ \rightarrow \phi \pi^+$ | $3.75 \times 10^{-7}$ | $8.73 \times 10^{-8}$ | 0% | 0% |
| Modes | BR at $\xi=0$ | BR at $\xi=0.2$ | Asymmetry at $\xi=0$ | Asymmetry at $\xi=0.2$ |
|-------|--------------|----------------|---------------------|---------------------|
| $B^0 \rightarrow \phi K^0$ | $3.42 \times 10^{-7}$ | $3.24 \times 10^{-6}$ | $0\%$ | $0\%$ |
| $B^0 \rightarrow \omega K^0$ | $8.6 \times 10^{-6}$ | $1.49 \times 10^{-6}$ | $\sim -2\%$ | $\sim -1\%$ |
| $B^0 \rightarrow \rho^0 K^0$ | $8.21 \times 10^{-7}$ | $3.94 \times 10^{-7}$ | $\sim 1\%$ | $\sim 0\%$ |
| $B^0 \rightarrow \rho^- K^+$ | $9.47 \times 10^{-7}$ | $8.33 \times 10^{-7}$ | $\sim -4\%$ | $\sim -4\%$ |
| $B^0 \rightarrow K^{*0} \pi^0$ | $3.89 \times 10^{-6}$ | $2.84 \times 10^{-6}$ | $\sim 2\%$ | $\sim 1\%$ |
| $B^0 \rightarrow K^{*+} \pi^-$ | $1.43 \times 10^{-5}$ | $1.30 \times 10^{-5}$ | $\sim 6\%$ | $\sim 6\%$ |
| $B^0 \rightarrow K^{*0} \eta'$ | $4.12 \times 10^{-7}$ | $8.22 \times 10^{-7}$ | $\sim 1\%$ | $\sim 0\%$ |
| $B^0 \rightarrow K^{*0} \eta$ | $8.86 \times 10^{-6}$ | $5.55 \times 10^{-6}$ | $\sim 1\%$ | $\sim 0\%$ |
| $B^0 \rightarrow \rho^+ \pi^-$ | $3.04 \times 10^{-5}$ | $2.72 \times 10^{-5}$ | $\sim 4\%$ | $\sim 4\%$ |
| $B^0 \rightarrow \rho^- \pi^+ | 6.38 \times 10^{-6}$ | $5.69 \times 10^{-6}$ | $\sim 1\%$ | $\sim 1\%$ |
| $B^0 \rightarrow \rho^0 \pi^0$ | $1.44 \times 10^{-6}$ | $1.81 \times 10^{-7}$ | $\sim 11\%$ | $\sim 24\%$ |
| $B^0 \rightarrow \rho^0 \eta'$ | $3.55 \times 10^{-6}$ | $2.48 \times 10^{-6}$ | $\sim 11\%$ | $\sim 4\%$ |
| $B^0 \rightarrow \rho^0 \eta$ | $6.68 \times 10^{-6}$ | $3.78 \times 10^{-6}$ | $\sim 8\%$ | $\sim 4\%$ |
| $B^0 \rightarrow \omega \pi^0$ | $1.53 \times 10^{-7}$ | $9.6 \times 10^{-9}$ | $\sim 3\%$ | $\sim -65\%$ |
| $B^0 \rightarrow \omega \eta'$ | $3.56 \times 10^{-6}$ | $2.49 \times 10^{-6}$ | $\sim 5\%$ | $\sim 2\%$ |
| $B^0 \rightarrow \omega \eta$ | $7.09 \times 10^{-6}$ | $3.94 \times 10^{-6}$ | $\sim 8\%$ | $\sim 4\%$ |
| $B^0 \rightarrow K^{*0} \bar{K}^0$ | $3.52 \times 10^{-7}$ | $2.81 \times 10^{-7}$ | $0\%$ | $0\%$ |
| $B^0 \rightarrow \bar{K}^{*0} K^0$ | $5.16 \times 10^{-10}$ | $1.66 \times 10^{-9}$ | $0\%$ | $0\%$ |
| $B^0 \rightarrow \phi q'$ | $4.13 \times 10^{-8}$ | $9.62 \times 10^{-9}$ | $0\%$ | $0\%$ |
| $B^0 \rightarrow \phi \eta$ | $1.37 \times 10^{-7}$ | $3.18 \times 10^{-8}$ | $0\%$ | $0\%$ |
| $B^0 \rightarrow \phi \pi^0$ | $1.87 \times 10^{-7}$ | $4.36 \times 10^{-8}$ | $0\%$ | $0\%$ |
Table 3

| $|\Delta S| = 1$          | modes                  | Experimental BR ($\times 10^{-5}$) |
|--------------------------|------------------------|------------------------------------|
| $B^+ \to \phi K^+$       |                        | $< 0.53$                           |
| $B^0 \to \phi K^0$       |                        | $< 4.2$                            |
| $B^+ \to \omega K^+$     |                        | $1.5^{+0.7}_{-0.6} \pm 0.3$       |
| $B^+ \to \rho^0 K^+$     |                        | $< 1.4$                            |
| $B^0 \to \rho^- K^+$     |                        | $< 3.3$                            |
| $B^+ \to \rho^+ K^0$     |                        | $< 6.4$                            |
| $B^0 \to \rho^0 K^0$     |                        | $< 3.0$                            |
| $B^0 \to K^{*0} \eta'$   |                        | $< 4.2$                            |
| $B^0 \to K^{*0} \eta$    |                        | $< 3.3$                            |
| $B^+ \to K^{*+} \eta'$   |                        | $< 29.0$                           |
| $B^+ \to K^{*+} \eta$    |                        | $< 20.4$                           |
| $B^0 \to K^{*+} \pi^-$   |                        | $< 6.7$                            |
| $B^0 \to K^{*0} \pi^0$   |                        | $< 2.0$                            |
| $B^+ \to K^{*+} \pi^0$   |                        | $< 8.0$                            |
| $B^+ \to K^{*0} \pi^+$   |                        | $< 3.9$                            |

| $\Delta S = 0$           | modes                  | Experimental BR ($\times 10^{-5}$) |
|--------------------------|------------------------|------------------------------------|
| $B^+ \to \rho^0 \pi^+$   |                        | $< 5.8$                            |
| $B^0 \to \rho^0 \pi^+$   |                        | $< 8.8$                            |
| $B^0 \to \rho^0 \pi^0$   |                        | $< 1.8$                            |
| $B^+ \to \omega \pi^+$   |                        | $1.1^{+0.6}_{-0.5} \pm 0.2$       |
| $B^+ \to \phi \pi^+$     |                        | $< 0.56$                           |
| $B^0 \to \phi \pi^0$     |                        | $< 0.65$                           |
Fig. 1

Fig. 2
