Search for new physics from $B \to \pi \phi$

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We investigate the pure penguin process $B^- \to \pi^- \phi$ using QCD factorization approach to calculate hadronic matrix elements to the $\alpha_s$ order in some well-known NP models. It is shown that the NP contributions in R-parity conserved SUSY models and 2HDMs are not enough to saturate the experimental upper bounds for $B \to \phi \pi$. We have shown that the flavor changing $Z'$ models can make the branching ratios of $B \to \phi \pi$ to saturate the bound under all relevant experimental constraints.

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The process $B \to \phi \pi$, one of charmless two-body nonleptonic decays of $B$ mesons, is interesting because it is a pure penguin process. In particular, there are no annihilation diagram contributions for which results obtained with different methods are quite different [1, 2]. Therefore the calculations of the hadronic matrix elements relevant to the process are relatively reliable because of no contributions coming from diagrams of annihilation topology. It proceeds through $b \to d s s$ at the quark level, which is a $b \to d$ flavor changing neutral current (FCNC) process. It is sensitive to new physics (NP) because all contributions arise from the penguin diagrams in the standard model (SM).

The BaBar collaboration has recently reported the results of search for $B \to \phi \pi$ [3]:

$$Br(B^0 \to \phi \pi^0) = (0.12 \pm 0.13) \times 10^{-6},$$
$$< 0.28 \times 10^{-6},$$
$$Br(B^+ \to \phi \pi^+) < 0.24 \times 10^{-6},$$

which enhance the precision of measurements but still are of the same order of magnitude, i.e., $O(10^{-7})$, comparing with the previous results [4],

$$Br(B^0 \to \phi \pi^0) = (0.2^{+0.4}_{-0.3} \pm 0.1) \times 10^{-6},$$
$$< (1.2 \pm 0.8) \times 10^{-6},$$
$$Br(B^+ \to \phi \pi^+) < 0.41 \times 10^{-6}.$$

The SM predictions for these decays modes in both BBNS (QCDF) and Li et al. (PQCD) methods have been given [5] and the results given in the literature are much smaller than the data although there are significant disagreements among the literature. The twist-3 contributions to the decays are predicted to be small and $Br(B^+ \to \phi \pi^+) = (2 - 6) \times 10^{-9}$ is given by using the QCDF method improved in calculating integrals which contain endpoint singularities, including the twist-3 contributions [5].
agreed results are obtained in QCDF without including the twist-3 contributions in ref. [6]. The theoretical uncertainty in treating integrals which contain endpoint singularities is roughly 30%. Therefore, there is a room for new physics (NP).

The theoretical study for these decay modes in models beyond the standard model has also been done in a number of papers [3, 4, 5]. The branching ratio for \( Br(B^+ \rightarrow \phi\pi^+) \) has been calculated in constrained minimal supersymmetric standard model (CMSSM) without imposing the constraint from \( B_s \rightarrow \mu^+\mu^- \) [3]. In ref. [4] calculations are done in MSSM, the topcolor assisted technicolor model (TC2), and the model with an extra vector like down quark (VLDQ) respectively. Only for VLDQ \( Br(B^0 \rightarrow \phi\pi^0) \sim 10^{-7} \) can be obtained. The analysis in MSSM uses the values of the mass insertion parameters which are taken from the paper in 1996 [8] and does not consider the contributions from neutral Higgs boson induced operators. In ref. [7] the upper bound of \( Br(B^+ \rightarrow \phi\pi^+) \) in 2002 [3] is used to constrain parameters in R-parity violating supersymmetric models.

In the letter we show that \( O(10^{-7}) \) branching ratio for \( Br(B \rightarrow \phi\pi) \) can not be reached in MSSM and two Higgs doublet models (2HDM) I, II, and III when all relevant constraints from experiments are imposed. It can be reached in a flavor changing \( Z' \) model under all relevant experimental constraints.

To begin with, we record the SM analysis in ref. [3] briefly. The \( \Delta B = 1 \) effective weak Hamiltonian in SM is given by

\[
\mathcal{H}_{\text{eff}}^{SM} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left( C_1 Q^p_1 + C_2 Q^p_2 + \sum_{i=3,\ldots,10} C_i Q_i + C_{\gamma\gamma} Q_{\gamma\gamma} + C_{8g} Q_{8g} \right) + \text{h.c.},
\]

where \( \lambda_p = V_{pb} V_{pd}^* \) are the left-handed current–current operators arising from W-boson exchange, \( Q_{3,\ldots,6} \) and \( Q_{7,\ldots,10} \) are QCD and electroweak penguin operators, and \( Q_{\gamma\gamma} \) and \( Q_{8g} \) are the electromagnetic and chromomagnetic dipole operators, respectively. Their explicit expressions can be found in, e.g., Ref. [10]. Due to the flavor and color structures of the final state \( \phi\pi \), the chromomagnetic dipole operator \( Q_{8g} \) does not contribute to the decays, and the tree operators \( Q_{1,2} \) contribute only through electromagnetic corrections which is small numerically. In QCDF up to the order of \( \alpha_s \), the decay amplitude for \( B^- \rightarrow \pi^- \phi \) is [5]

\[
A(B^- \rightarrow \pi^- \phi) = \sqrt{2} A(B^0 \rightarrow \pi^0 \phi) = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[ a_3 + a_5 - \frac{1}{2} (a_7^p + a_9^p) \right] f_\phi m_\phi F_{\pi^\pm}^2 (m_\phi^2) 2 \epsilon^\phi \cdot p_B,
\]

where

\[
\begin{align*}
a_3(\pi\phi) &= C_3 + \frac{1}{N} C_4 + \frac{\alpha_s}{4\pi} \frac{C_F}{N} C_4 F, \\
a_5(\pi\phi) &= C_5 + \frac{1}{N} C_6 + \frac{\alpha_s}{4\pi} \frac{C_F}{N} C_6 (-F - 12), \\
a_7^p(\pi\phi) &= C_7 + \frac{C_8}{N} + \frac{\alpha_s}{4\pi} \frac{C_F}{N} C_8 (-F - 12) + \frac{\alpha_{em}}{9\pi} P_{em}^p (C_1 + 3C_2), \\
a_9^p(\pi\phi) &= C_9 + \frac{1}{N} C_{10} + \frac{\alpha_s}{4\pi} \frac{C_F}{N} C_{10} F + \frac{\alpha_{em}}{9\pi} P_{em}^p (C_1 + 3C_2),
\end{align*}
\]

Due to the almost completely cancellations of the two terms in the Wilson coefficient combinations, \( C_3 + C_4/N_c \) and \( C_5 + C_6/N_c \), \( a_9 \) is the biggest among \( a_i \)'s, i.e., the contributions of the electroweak
penguin operators dominate. With values of input parameters in ref. [5], \( Br(B^+ \to \phi^+) = 4.5 \times 10^{-9} \) is obtained.

We now turn to MSSM and 2HDM. The effective Hamiltonian in 2HDM and MSSM can be written as [2, 11]

\[
H_{\text{eff}} = H_{\text{eff}}^{SM} + H_{\text{eff}}^{\text{new}},
\]

\[
H_{\text{eff}}^{\text{new}} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb} V_{pd}^* \left( \sum_{i=11,\ldots,16} [C_i Q_i + C_i' Q_i'] + \sum_{i=3,\ldots,10} C_i' Q_i' + C^T_{7\gamma} Q^T_{7\gamma} + C^T_{8g} Q^T_{8g} \right) + \text{h.c.},
\]

where \( Q_{11} \) to \( Q_{16} \) are the neutral Higgs penguin operators and their explicit forms can be found in Ref. [5, 11] with the substitution \( s \to d \). The primed operators, the counterpart of the unprimed operators, are obtained by replacing the chirality in the corresponding unprimed operators with opposite ones. In ref. [6] the neutral Higgs penguin operators \( Q_i, i = 11, \ldots, 16 \) are not considered.

The contributions of new operators to the decay amplitude for \( B^- \to \pi^- \phi \) is

\[
A^{\text{new}}(B^- \to \pi^- \phi) = \sqrt{2} A^{\text{new}}(B^0 \to \pi^0 \phi) = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[ a'_1 + a'_5 - \frac{1}{2} (a''_2 + a''_3) + r^{\phi}_{\chi}(a_{11} + a_{13}) \right] f_\phi m_\phi F_{\to \pi^0} \frac{m_\pi}{m_B} \cdot p_B,
\]

where we have neglected \( O(m_B^2/m_\pi^2) \) terms,

\[
r^{\phi}_{\chi}(\mu) = \frac{m_B}{4\epsilon \cdot p_B} \frac{f^{T}}{f^{\phi}},
\]

\( a'_i, i = 3, 5, 7, 9 \), come from the contributions of the primed operators and their expressions can be obtained by replacing the Wilson coefficients in the corresponding unprimed operators with primed ones, \( a_{11,13} \) come from the contributions of neutral Higgs boson induced operators which we shall discuss later on.

In MSSM new contributions to \( a_i, i = 3, 5 \) and the contributions to \( a'_i, i = 3, 5 \) come from the gluino-bottom loop and depend on the mass insertion parameters \( (\delta^d_{AA})_{13}, A = L, R \). The constraints on \( (\delta^d_{AA})_{13}, A = L, R \) from the mass difference \( \Delta M_d \) have been reanalyzed, using NLO QCD corrections of Wilson coefficients and recent lattice calculations of the B parameters for hadronic matrix elements of local operators [12]. Depending on the average mass of squarks and the gluino mass as well the CKM angle \( \gamma \), \( (\delta^d_{AA})_{13}, A = L, R \), is constrained to be \( O(10^{-2}) \) in the \( (\delta^d_{LL})_{13} = (\delta^d_{RR})_{13} \) case which is assumed in ref. [6]. So in this case the new contributions to \( a_i, i = 3, 5 \) and the contributions to \( a'_i, i = 3, 5 \) are negligibly small, compared with the SM. Only for the case of single \( (\delta^d_{LL})_{13} \) (or \( (\delta^d_{RR})_{13} \)) non zero, \( (\delta^d_{LL})_{13} \) (or \( (\delta^d_{RR})_{13} \)) can reach \( O(10^{-1}) \) under the constraint from the mass difference \( \Delta M_d \) [12] and consequently the SUSY contributions can make the branching ratios of \( B \to \phi \pi \) reached \( O(10^{-8}) \).

The contributions of neutral Higgs boson induced operators, \( a_{11,13} \), are as follows.

\[
a_{11,13} = -\frac{\alpha_s}{4\pi} \frac{C_F}{N} (f^I_s + f^II_s) C_{Q_{12,14}},
\]

\[13\]
The Yukawa Lagrangian for quarks can be written as \[17\]

\[ L = \sum_{f=u,c,t} \bar{f}(\gamma^{\mu} \tau^a + \lambda^a) f \phi_s \]

Note that there are no contributions of neutral Higgs boson induced operators at the leading order in the \( \alpha_s \) expansion in the approximation omitting \( O(m^2_{\phi}/m^2_{\pi}) \) terms because of their Dirac structure.

In MSSM and 2HDM model I, II, \( C_{11,13}(m_W) \sim 0.037 \) because of the constraint from \( B_d \to \mu^+ \mu^- \)\[13\]. So the \( \alpha_s \) corrections from neutral Higgs boson induced operators are negligible.

In model III 2HDM there are neutral Higgs boson-mediated FCNC at the tree level \[14, 15, 16\].

The Yukawa Lagrangian for quarks can be written as \[17\]

\[ \mathcal{L}_Y = -\bar{U}M_UU - \bar{D}MD_D - \frac{g}{2M_W}(H^0 \cos \alpha - h^0 \sin \alpha) \left( \bar{U}M_UU + \bar{D}MD_D \right) \\
+ \frac{i\hat{g}}{2M_W} G^0 \left( \bar{U}M_U \gamma^5 U - \bar{D}MD \gamma^5 D \right) \\
+ \frac{g}{\sqrt{2M_W}} G^-DV_{\text{CKM}} \left[ M_U \frac{1}{2}(1 + \gamma^5) - M_D \frac{1}{2}(1 - \gamma^5) \right] U \\
- \frac{g}{\sqrt{2M_W}} G^+ \bar{U}V_{\text{CKM}} \left[ M_D \frac{1}{2}(1 + \gamma^5) - M_U \frac{1}{2}(1 - \gamma^5) \right] D \\
- \frac{H^0 \sin \alpha + h^0 \cos \alpha}{\sqrt{2}} \left( \xi^U \frac{1}{2}(1 + \gamma^5) + \xi^D \frac{1}{2}(1 - \gamma^5) \right) U \\
+ \frac{\theta \xi^D \frac{1}{2}(1 + \gamma^5) + \xi^D \frac{1}{2}(1 - \gamma^5)}{D} \\
+ \frac{iA^0}{\sqrt{2}} \left[ \bar{U} \left( \xi^U \frac{1}{2}(1 + \gamma^5) - \xi^D \frac{1}{2}(1 - \gamma^5) \right) U - \bar{D} \left( \xi^D \frac{1}{2}(1 + \gamma^5) - \xi^U \frac{1}{2}(1 - \gamma^5) \right) D \right] \\
- \frac{H^+ \bar{U} V_{\text{CKM}} \xi^D \frac{1}{2}(1 + \gamma^5) - \xi^U \frac{1}{2}(1 - \gamma^5)}{D} \\
- \frac{H^+ \bar{D} \xi^D \frac{1}{2}(1 - \gamma^5) - \xi^U \frac{1}{2}(1 + \gamma^5)}{U} , \tag{16} \]

where \( U \) and \( D \) represents the mass eigenstates of \( u, c, t \) quarks and \( d, s, b \) quarks respectively, the matrices \( \xi^{D,U} \) are in general non-diagonal which parameterize the couplings of Higgs to quarks. The Yukawa Lagrangian for leptons can similarly be written.

With the above Lagrangian, the Wilson coefficients of \( Q_i, i = 11, \ldots, 16 \), relevant to \( b \to d\bar{s}s \) are easily obtained:

\[ C_{11,13}(m_W) = \frac{\sqrt{2}}{G_F(-\lambda_t)} \left( -\frac{1}{8} \xi_{sd} \xi_{ss} \right) \left( \frac{\sin^2 \alpha}{m_H^2} + \frac{\cos^2 \alpha}{m_H^2} + \frac{1}{m_A^2} \right) m_b. \]
where we have assumed $\xi_{ij}$ is symmetric and real for simplicity. The parameters $\xi_{bd,ss}$ of the model can be estimated from experiments. We can extract $\xi_{bd}$ from the mass difference $\Delta M_{B_d}$ of neutral $B_d$ mesons. In order to determine $\xi_{ss}$ we use the data of $\tau \to \mu \mu^+\mu^-$, $B_d \to \mu^+\mu^-$ and $\tau \to \mu P (P = \pi^0, \eta, \eta')$. The parameter $\xi_{bd}$ has been estimated from the measured $B_d - \bar{B}_d$ mass difference, and $\xi_{db} \leq 7.3 \times 10^{-6}$ is given [18]. We reanalyze the mass difference and get $\xi_{db} \leq 0.8 \times 10^{-4}$ which is much larger than that in [18]. With the latest limits from experiments, $Br(B_d \to \mu \mu) \leq 3.9 \times 10^{-8}$ [19] and $Br(\tau \to \mu \mu \mu) \leq 1.9 \times 10^{-7}$ [20] at 90% C.L., we obtain the updated results of the upper bounds of $\xi_{\mu \mu}$ and $\xi_{\mu \tau}$, $\xi_{\mu \mu} \leq 0.34$ and $\xi_{\mu \tau} \leq 0.004$. Finally we can determine the bound on $\xi_{ss}$ from $\tau \to \mu \pi^0 (\eta, \eta')$ decays [21] and the result is $\xi_{ss} \leq 0.26$. Using the bounds of $\xi_{bd}$ and $\xi_{ss}$, we deduce that $C_{13}(m_W)$ can roughly reach 0.1 with $m_A = m_H = 300$ GeV, $m_h = 120$ GeV, which leads to that the $\alpha_s$ corrections from neutral Higgs boson induced operators can contribute to the branching ratio of $Br(B^+ \to \phi \pi^+)$ by about $2.0 \times 10^{-10}$ which is much smaller than that in SM and consequently negligible.

Finally we consider flavor changing Z' Models. Because the contributions of electroweak operators dominate in SM it is expected that the new contributions from flavor changing Z' models in which Z' mediates vector and axial vector interactions would enhance the branching ratios of $B \to \phi \pi$ significantly. The flavor changing Z' Models have been extensively studied [22]. For our purpose we write the Z' interaction Lagrangian in the gauge basis as

$$\mathcal{L}_{Z'} = -g' J'_\mu Z'^\mu,$$

$$J'_\mu = \sum_{i,j} \psi_i^\dagger \gamma_\mu [\epsilon_{\psi_L} i_{ij} P_L + (\epsilon_{\psi_R}) i_{ij} P_R] \psi_j^I, \quad (18)$$

where $g'$ is the gauge coupling constant of the $U(1)'$ group at the $M_W$ scale\(^1\), the sum extends over all fermion fields in the SM. There are in general FCNCs at the tree level in the Lagrangian [18]. In the mass eigenstate basis, the chiral Z' coupling matrices are respectively given by

$$B^X_{u,d} \equiv V_{ux} \epsilon_{ux} V_{ux}^\dagger, \quad B^X_d \equiv V_{dx} \epsilon_{dx} V_{dx}^\dagger, \quad (X = L, R) \quad (19)$$

where $V_{ux}$ and $V_{dx}$ are the transformation matrices which make up-type quarks and down-type quarks into the mass eigenstates from the gauge eigenstates respectively. The usual CKM matrix is given by $V_{CKM} = V_{uL} V_{dL}^\dagger$. We assume that the first two generation diagonal elements of $B^X_q (q = u, d)$ are equal: $B^X_{qq} = B^X_{uu} = B^X_{dd}$ [24, 27]. The effective Hamiltonian of the $b \to dq\bar{q}$ transitions due to the Z' mediation is

$$H_{Z'}^{\text{eff}} = \frac{2G_F}{\sqrt{2}} \left( \frac{g' M_{Z'}}{g_Z M_{Z'}} \right)^2 B^{L*}_{db}(\bar{b}d)V_{-A} \sum_q \left( B^{L}_{qq}(\bar{q}q)V_{-A} + B^{R}_{qq}(\bar{q}q)V_{+A} \right) + \text{h.c.}, \quad (20)$$

where $M_{Z'}$ is the mass of $Z'$ which is larger than 850 GeV for $g' \sim g_Z$ [23],

$$g_Z = \frac{e}{\sin \theta_W \cos \theta_W}. \quad (21)$$

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\(^1\) We neglect the renormalization running effects from the $M_Z^2$ scale to the $M_W$ scale through the paper due to uncertainties in the parameters of the models.
Thus, the $Z'$ mediated FCNC interaction would induce the color singlet QCD and electroweak penguin operators. It is straightforward to get the contributions to the Wilson coefficients of those operators from above effective Hamiltonian, (21). Then the effective Hamiltonian relevant to $B \to \phi\pi$ in a $Z'$ model can be written as

$$H_{\text{eff}} = H_{\text{eff}}^{SM} + H_{\text{eff}}^{Z'},$$

where $\lambda_t = V_{tb}^* V_{td}$, and

$$C_{3(5)}^{Z'} = -\frac{2}{3\lambda_t} \left( \frac{g_2 M_Z}{g_1 M_{Z'}} \right)^2 B_{db}^L \left( B_{uu}^L + 2 B_{dd}^L \right),$$

$$C_{9(7)}^{Z'} = -\frac{4}{3\lambda_t} \left( \frac{g_2 M_Z}{g_1 M_{Z'}} \right)^2 B_{db}^L \left( B_{uu}^L - B_{dd}^L \right).$$

The chiral $Z'$ couplings are subjected to constraints from relevant experimental measurements. The constraint to $B_{bd}^L$ has been analyzed [24, 25]. It is shown [24] that the observed $\Delta M_{B_d}$ and $\sin 2\beta$ leads to

$$y |\text{Re}(B_{db}^L)^2| < 5 \times 10^{-8},$$

where $y = \left( \frac{\lambda_{Z'}}{g_2 M_{Z'}} \right)^2$, if only left-handed couplings are considered. Taking $y \sim 10^{-3}$ [24], one has

$$B_{db}^L \sim 0.7 \times 10^{-2}$$

When both left-handed and right handed couplings are included, the constraints are

$$y |\text{Re}[(B_{db}^L)^2 + (B_{db}^R)^2] - 3.8\text{Re}(B_{db}^L B_{db}^R)| < 5 \times 10^{-8},$$

$$y |\text{Im}[(B_{db}^L)^2 + (B_{db}^R)^2] - 3.8\text{Im}(B_{db}^L B_{db}^R)| < 5 \times 10^{-8},$$

which are not as stringent as eq. (25) because of the possible cancellation among different terms.

Using the latest observed $\Delta M_{B_d}$, ref. [25] shows that

$$B_{db}^L \sim 10^{-2}$$

To solve the $\pi K$ puzzle some people have examined new physics in the electroweak penguin sector, in particular, the $Z'$ models [26, 27]. Using the experimental data of Br($B \to \pi K$ in and before 2003, one has [27]

$$R_c = 1.15 \pm 0.12, \quad R_n = 0.78 \pm 0.10,$$

which should be roughly equal to one in the SM. It is shown that to explain the deviations a constraint on $B_{db}^L B_{dd}^X$ must be imposed [27]

$$\xi_{LL} \equiv y \left| \frac{B_{db}^L B_{dd}^X}{V_{tb} V_{ts}} \right| \approx 0.01 \ (\text{solution A}) \ or \ 0.019 \ (\text{solution B})$$

(31)
in the case of $\xi^{LL} = \xi^{LR}$. We reanalyze the constraint using the new data of $Br(B \to \pi K)$ in this year [3]. According to the new data, one has $\overline{A}$, instead of eq. (30),

$$R_c = 1.11 \pm 0.08, \quad R_n = 1.00 \pm 0.07. \quad (32)$$

With the values, the solution B in ref. [27] is excluded in 1σ bounds, but the solution A remains survived. So from eqs. (29,31), we have

$$B_{dd}^X \sim 10. \quad (33)$$

The $Z'$ flavor changing couplings also contribute to $B^0 \to \pi^0 \pi^0$. The constraint from $Br(B^0 \to \pi^0 \pi^0)$ is:

$$0.129 < \left| 0.0887 + 0.0820i + (1.277B_{dd}^L - B_{dd}^R) B_{db}^L \right|^2 < 0.178 \quad (34)$$

Form eqs. (26,33), the above constraints are satisfied.

Now we obtain the branching ratio of $B \to \pi \phi$ in the $Z'$ models for the values of parameters which satisfy the constraints discussed above:

$$Br(\pi \phi) = 1.17 \times 10^{-5} \left| 0.0184 + 0.00607i - (B_{dd}^L + B_{dd}^R) B_{db}^L \right|^2 \sim 10^{-7}, \quad (35)$$

which is in agreement with the recent data.

In summary, we have studied the pure penguin process $B^- \to \pi^- \phi$ using QCD factorization approach to calculate hadronic matrix elements to the $\alpha_s$ order in some well-known NP models. We have shown that the NP contributions in R-parity conserved SUSY models and 2HDMs are not enough to saturate the experimental upper bounds for $B \to \phi \pi$. We have also shown that the flavor changing $Z'$ models can make the branching ratios of $B \to \phi \pi$ to saturate the bounds under all relevant experimental constraints. Therefore, if the data will remain in $O(10^{-7})$ in the future it will give a signal of NP effects and provide a clue to discriminate well-known NP models.

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