Exclusive $B \to PV$ Decays and CP Violation in the General
two-Higgs-doublet Model

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Abstract

We calculate all the branching ratios and direct CP violations of $B \to PV$ decays in a most
general two-Higgs-doublet model with spontaneous CP violation. As the model has rich CP-
violating sources, it is shown that the new physics effects to direct CP violations and branching
ratios in some channels can be significant when adopting the generalized factorization approach
to evaluate the hadronic matrix elements, which provides good signals for probing new physics
beyond the SM in the future B experiments.

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I. INTRODUCTION

To understand the origin of CP violation (CPV) is an important subject not only for exploring the basic symmetry of space-time and elementary particles but also for understanding the evolution of our universe. It is well known that in the Standard Model (SM) of particle physics, CP violation is characterized by a single weak phase in Cabibbo-Kobayashi-Maskawa matrix \[1\], which can provide a well explanation for the direct CP violation \[\varepsilon'/\varepsilon\] established in kaon decays \[3\], and also direct CP violation \[4\] observed in B-meson decays \[5\]. Though the theory of the strong and electroweak (EW) interactions in SM has met with extraordinary success, it is widely believed that the SM can not be the final theory of particle physics, in particular because the Higgs sector of SM is not well understood yet and the CP phase in CKM matrix is not enough to understand the baryon and anti-baryon asymmetry in the universe. It was suggested that CP symmetry may be broken down spontaneously \[6\]. Many possible extensions of SM in Higgs sector have been proposed \[7\]. Other possible extensions of the SM have been explored, such as the Super Symmetric model (SUSY), little Higgs model and extra dimensions, which all make better the situation of the SM. But no single model is good enough to solve all the problems existing in the SM and it is then worthwhile to consider all the possibilities beyond SM. As one of the simplest extensions of the SM, the so-called two-higgs-doublet model (2HDM) which introduces an extra Higgs doublet without imposing the ad hoc discrete symmetries has been investigated widely from various considerations \[8, 9, 10, 11, 12, 13, 14, 15, 16, 17\]. Motivated solely from the origin of CP violation, a general two Higgs doublet model with spontaneous CP violation (Model III 2HDM) has been shown to provide one of the simplest and attractive models in understanding the origin and mechanism of CP violation at weak scale \[12, 13\]. In such a model, there exists more physical neutral and charged Higgs bosons and rich induced CP-violating sources from a single CP phase of vacuum. Of particular, the model III 2HDM allows flavor-changing neutral currents but suppressed by approximate U(1) flavor symmetry, which is different from the so-called model I and model II 2HDM in which a ad-hoc discrete symmetry \([Z_2]\) symmetry) has been imposed to avoid the FCNC.

It is known that the FCNC’s concerning the first two generations are highly suppressed from low-energy experiments, and those involving the third generation is not as severely suppressed as the first two generations. So the model III 2HDM can be parameterized in a way to satisfy the current experimental constraints. The constraints on Model III 2HDM from neutral meson mixings \([K^0 - \bar{K}^0, D^0 - \bar{D}^0, B^0 - \bar{B}^0]\) \[18\] and radiative decays of bottom quark \[19, 20, 21\] have been studied in details. In this note, we shall investigate the possible new effects of model III 2HDM on two-body charmless nonleptonic B decays \[B \rightarrow h_1 h_2\] with \(h_1, h_2\) being the charmless light hadrons. This is because those decays have triggered considerable theoretical interest in understanding SM. Also those decay channels are also thought to be sensitive and important in exploring new physics beyond the SM as they involve the so-called tree (current-current) \(b \rightarrow (u, c)\) and/or \(B \rightarrow (d, s)\) penguin amplitudes with both QCD and electroweak penguin transition participating. In the 2HDM, there are five Higgs particles including the \(H^0\) Higgs in SM, these extra Higgs will mediate all the penguin transitions. As the couplings involving Higgs bosons and fermions have complex CP phases in the model III 2HDM, CP violation effects occur even in the simplest case that all the tree-level FCNC couplings are negligible. With the improvement of experimental precision, more and more direct CPV have been observed.
and will be much precisely tested in the future experiments.

The paper is organized as follows. In Sec II, we first describe the theoretical frame including a brief introduction of the two-Higgs-doublet model with spontaneous CP violation, i.e., Model III 2HDM, and the effective Hamiltonian as well as the generalized factorization formula, which is our basic tool to estimate the branching ratios and CP asymmetry of B meson decays. In Sec III, we make a detailed calculation with numerical results evaluated from a factorization ansatz which allows us to express the matrix elements \( < h_1 h_2 | H_{eff} | B > \) as a product of two factors \( < h_1 | J_1 | B > < h_2 | J_2 | B > \), and make quantitative predictions. Our conclusions and discussions are presented in the last section.

II. THEORETICAL FRAMEWORK

A. Outline of the Two-Higgs-doublet Model

One of the important developments of SM is the so-called Higgs mechanism, i.e., a spontaneous symmetry breaking mechanism by which the gauge bosons and fermions can get their masses. In the SM, a single Higgs doublet of SU(2) is sufficient to break the \( SU(2)_L \times U(1)_Y \) symmetry to \( U(1)_{em} \) and generate mass to the gauge bosons and fermions. Nevertheless, the Higgs sector of the SM has not been experimentally tested although enormous efforts have been made. For the origin of CP violation, SM gives no explanation as there is only one single neutral Higgs in SM and its interaction coupling constants are fixed by the known parameters and the fermion masses. Many attempts have been made by both theoretists and experimentalists to explore the mechanisms of CP violation since the discovery of CP violation in 1964. Spontaneous CP violation requires at least two Higgs doublets. A consistent and simple model which provides a spontaneous CP violation mechanism was constructed completely in a general Two-Higgs-doublet model[12, 13]. Such a model III 2HDM not only explains the origin of CP violation in the SM, but also induces rich new resources of CP violation. The new sources of CP violation can lead to some new phenomenological effects which are promising to be tested by the future B factory and LHCb. In this note, we will focus on the phenomenological applications of the model III 2HDM in the two-body charmless hadronic \( B \rightarrow PV \) decays.

The two complex Higgs doublets in the Model III 2HDM are expressed as[12, 13, 14, 16, 17]:

\[
\phi_1 = \begin{pmatrix} \phi_1^\dagger \\ \phi_1^0 \end{pmatrix}, \phi_2 = \begin{pmatrix} \phi_2^\dagger \\ \phi_2^0 \end{pmatrix}
\]

The corresponding Higgs potential can simply be written in the following general form:

\[
V(\phi) = \lambda_1(\phi_1^\dagger \phi_1 - \frac{1}{2} v_1^2)^2 + \lambda_2(\phi_2^\dagger \phi_2 - \frac{1}{2} v_2^2)^2 + \lambda_3(\phi_1^\dagger \phi_1 - \frac{1}{2} v_1^2)(\phi_2^\dagger \phi_2 - \frac{1}{2} v_2^2) + \lambda_4[(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)] \\
+ \frac{1}{2} \lambda_5(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1 - v_1 v_2 \cos \delta)^2 + \lambda_6(\phi_1^\dagger \phi_2 - \phi_2^\dagger \phi_1 - v_1 v_2 \sin \delta)^2 \\
+ [\lambda_7(\phi_1^\dagger \phi_1 - \frac{1}{2} v_1^2)^2 + \lambda_8(\phi_2^\dagger \phi_2 - \frac{1}{2} v_2^2)^2][\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1 - v_1 v_2 \cos \delta],
\]

(2)
where $\lambda_i (i = 1, 2, ..., 8)$ are all real parameters. If all $\lambda_i$ are non-negative, the minimum occurs at:

$$
< \phi^0_1 > = v_1 e^{i \delta},
< \phi^0_2 > = v_2,
$$

(3)

With $v_1, v_2$ are the vacuum expectation values of $\phi_1, \phi_2$ respectively, and $\delta$ the relative phase of the vacuum. It is clear that in the above potential CP nonconservation can only occur through the vacuum with $\delta \neq 0$. Obviously, such a CP violation appears as an explicit one in the potential when $\lambda_6 \neq 0$.[13]

After a unitary transformation, it is natural and convenient to use the following basis:

$$
H_1 = \frac{1}{\sqrt{2}} \left[ \sqrt{2} G^+ \begin{bmatrix} v + \phi^0_1 + i G^0 \end{bmatrix} \right],
H_2 = \frac{1}{\sqrt{2}} \left[ \sqrt{2} H^+ \begin{bmatrix} \phi^0_2 + i A^0 \end{bmatrix} \right],
$$

(4)

with:

$$
< H^0_1 > = v e^{i \delta},
< H^0_2 > = 0,
$$

(5)

where $v = \sqrt{v_1^2 + v_2^2}$ and is related to the $W$ mass by $M_W = gv/2$. Here $H^0$ plays the role of the Higgs boson in the standard model. $H^\pm$ are the charged scalar pair with $H^\pm = \sin \beta \phi^\pm e^{-i \delta} - \cos \beta \phi^\mp$, where $\tan \beta = v_2/v_1$. And as for the neutral Higgs, $\phi_1, \phi_2$ are not the neutral mass eigenstates but linear combinations of CP-even neutral Higgs boson mass eigenstates, $H_0$ and $h_0$:

$$
H_0 = \phi^0_1 \cos \alpha + \phi^0_2 \sin \alpha,
$$

$$
h_0 = -\phi^0_1 \sin \alpha + \phi^0_2 \cos \alpha,
$$

(6)

where $\alpha$ is the mixing angle and when $\alpha = 0$, $(\phi^0_1, \phi^0_2)$ are identical with $(H_0, h_0)$. For simplicity, the mixing with the pseudoscalar $A^0$ is not considered here.

Let us consider a Yukawa Lagrangian of the following form:

$$
\mathcal{L}_Y = \xi^U_{1ij} \tilde{Q}_{i,L} \phi_1 U_{j,R} + \xi^D_{1ij} \tilde{Q}_{i,L} \phi_1 D_{j,R} + \xi^U_{2ij} \tilde{Q}_{i,L} \tilde{\phi}_2 U_{j,R} + \xi^D_{2ij} \tilde{Q}_{i,L} \tilde{\phi}_2 D_{j,R} + H.c.,
$$

(7)

where $\phi_i (i = 1, 2)$ are the two Higgs doublets, $\tilde{\phi}_{1,2} = i \tau_2 \phi^*_i$, $Q_{i,L}(U_{j,R})$ with $i = (1, 2, 3)$ are the left-handed isodoublet quarks (right-handed up-type quarks), $D_{j,R}$ are the righthanded isosinglet down-type quarks, while $\xi^U_{1ij}$ and $\xi^D_{2ij}$ ($i, j = 1, 2, 3$ are family index) are generally the nondiagonal matrices of the Yukawa coupling. After diagonalizing the mass matrix of quark fields, the Yukawa Lagrangian that related to the decays
we considered in this paper can be written as:

\[
L_Y = -\frac{g}{2M_W} (H^0 \cos \alpha - h^0 \sin \alpha) (\bar{U} M_U U + \bar{D} M_D D) \\
- \frac{H^0 \sin \alpha + h^0 \cos \alpha}{\sqrt{2}} \left[ \bar{U} (\xi_U^1 \frac{1}{2} (1 + \gamma_5) + \xi_U^1 \frac{1}{2} (1 - \gamma_5)) U \\
+ \bar{D} (\xi_D^1 \frac{1}{2} (1 + \gamma_5) + \xi_D^1 \frac{1}{2} (1 - \gamma_5)) D \right] \\
+ \frac{i A_0}{\sqrt{2}} \left[ \bar{U} (\xi_U^1 \frac{1}{2} (1 + \gamma_5) - \xi_U^1 \frac{1}{2} (1 - \gamma_5)) U - \bar{D} (\xi_D^1 \frac{1}{2} (1 + \gamma_5) - \xi_D^1 \frac{1}{2} (1 - \gamma_5)) D \right] \\
- H^+ \bar{U} [V_{CKM} \xi_D^1 \frac{1}{2} (1 + \gamma_5) - \xi_D^1 \frac{1}{2} (1 - \gamma_5)] D \\
- H^- \bar{D} [\xi_U^1 V_{CKM} \frac{1}{2} (1 - \gamma_5) - V_{CKM}^\dagger \xi_U^1 \frac{1}{2} (1 + \gamma_5)] U, \tag{8}
\]

where \(U\) represents the mass eigenstates of \(u, c, t\) quarks and \(D\) represents the mass eigenstates of \(d, s, b\) quarks, \(V_{CKM}\) is the Cabibbo-Kobayashi-Maskawa matrix and \(\hat{\xi}^{U,D}\) are the FCNC couplings in the mass eigenstate, and they may be parameterized in terms of the quark mass:

\[
\xi_{ij}^{U,D} = \lambda_{ij} g \sqrt{m_i m_j} / 2M_W, \\
\hat{\xi}^U = \xi_U \cdot V_{CKM}, \\
\hat{\xi}^D = V_{CKM} \cdot \xi^D, \tag{9}
\]

The first two generations’ FCNC are naturally suppressed by the small quark masses, but the third generation has more space to get FCNC contributions. In this paper, we just choose the \(\xi^{U,D}\) to be diagonal \(\xi_{ii}^{U,D} \equiv \xi_i^{U,D} \quad (i = s, c, b, t)\), and neglect the first generation quarks’ contributions. So the really leading contribution arises from the diagram with a top quark in the loop and the relevant couplings will be \(\hat{\xi}^{U,D}_{ts}\) and \(\hat{\xi}^{U,D}_{tb}\), they are explicitly given by:

\[
\hat{\xi}^{U}_{ts} = \xi_{ts} V_{ts}, \quad \hat{\xi}^{U}_{tb} = \xi_{tb} V_{tb} \\
\hat{\xi}^{D}_{ts} = \xi_{ts} V_{ts}, \quad \hat{\xi}^{D}_{tb} = \xi_{tb} V_{tb}, \tag{10}
\]

From the above parameterization, the free parameters in this model are \(\lambda_{ij} \quad (i, j = s, c, t, b)\). Their values can be constrained through experiments.

In the model III 2HDM with spontaneous CP violation, the induced CP violation can be classified into the following four types via their interactions\[12, 13\]: i) from the CKM matrix; ii) from the charged Higgs couplings to the fermions \(\xi_{charged}\); iii) from the neutral Higgs couplings to the fermions \(\xi_{neutral}\); iv) from the CP nonconservation Higgs potential \(V(\phi)\) via mixings among scalars and pseudoscalar bosons.

The model allows flavor-changing-neutral-currents (FCNC) at tree level and via loop effects due to exchanges of Higgs bosons. One of the most stringent tests is from the radiative decay of B mesons and also from the inclusive decay rate of \(b \to s \gamma\) which has the least hadronic uncertainties. Other constraints could come from the \(B_0 - \bar{B}_0\) mixing, \(\rho_0\), \(R_b\) and the neutron electric dipole moment etc. In this note, we shall consider possible new effects in charmless hadronic two body decays of bottom mesons.
B. Effective Hamiltonian and Wilson coefficients

The effective Hamiltonian for charmless B decays with $\Delta B = 1$ is:

$$
\mathcal{H} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb} V_{ps}^* (C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3,\ldots,16} [C_i Q_i + C_i' Q'_i] + C_{7\gamma} Q_{7\gamma} + C_{8g} Q_{8g} + C_{7\gamma}' Q_{7\gamma}' + C_{8g}' Q_{8g}') + h.c.
$$

The operators $Q_{1,\ldots,10}, Q_{7\gamma}, Q_{8g}$ can be found in [24], of which the $Q_1$ and $Q_2$ are the current-current operators and $Q_3 - Q_6$ are QCD penguin operators. $Q_{7\gamma}$ and $Q_{8g}$ are, respectively, the magnetic penguin operators for $b \to s\gamma$ and $b \to sg$. Here the mass of the external strange quark is neglected compared to the external bottom-quark mass.

The additional new operators related to the neutral Higgs mediated processes ($b \to s\bar{q}q$) are [25]:

$$
\begin{align*}
Q_{11} &= (\bar{s}b)(s + P) \sum (\bar{q}q)(s - P), \\
Q_{12} &= (\bar{s}_i b_j)(s + P) \sum (\bar{q}_j q_i)(s - P), \\
Q_{13} &= (\bar{s}b)(s + P) \sum (\bar{q}_j q_i)(s + P), \\
Q_{14} &= (\bar{s}_i b_j)(s + P) \sum (\bar{q}_j q_i)(s + P), \\
Q_{15} &= (\bar{s}\sigma^{\mu\nu}(1 + \gamma_5)b) \sum (\bar{q}\sigma^{\mu\nu}(1 + \gamma_5)q), \\
Q_{16} &= (\bar{s}_i \sigma^{\mu\nu}(1 + \gamma_5)b_j) \sum (\bar{q}_j \sigma^{\mu\nu}(1 + \gamma_5)q_i),
\end{align*}
$$

where $(\bar{q}_1 q_2)_{S+P} = \bar{q}_1 (1 \pm \gamma_5) q_2, \ q = u, d, s, c, b$. The operators $Q'_i$ in Eq(11) are obtained from the $Q_i$ by exchanging $L \leftrightarrow R$. As the primed operators’s contributions are suppressed by $m_s/m_b$, we shall neglect their effects in our present considerations. The Wilson Coefficients $C_i, i = 1,\ldots,10$ have been calculated at LO [22, 23] and NLO [24] in SM and also at LO in 2HDM [26, 27]. Here we list their initial coefficient functions in the
2HDM[27, 28]:

\begin{align*}
C_1(M_W) &= \frac{11}{2} \frac{\alpha_s(M_W)}{4\pi}, \\
C_2(M_W) &= 1 - \frac{11}{6} \frac{\alpha_s(M_W)}{4\pi} - \frac{35}{18} \frac{\alpha}{4\pi}, \\
C_3(M_W) &= -\frac{\alpha_s(M_W)}{24\pi} \{ \tilde{E}_0(x_t) + E_0^{III}(y) \} + \frac{\alpha}{6\pi} [2B_0(x_t) + C_0(x_t)], \\
C_4(M_W) &= \frac{\alpha_s(M_W)}{8\pi} \{ \tilde{E}_0(x_t) + E_0^{IV}(y) \}, \\
C_5(M_W) &= -\frac{\alpha_s(M_W)}{24\pi} \{ \tilde{E}_0(x_t) + E_0^{IV}(y) \}, \\
C_6(M_W) &= \frac{\alpha_s(M_W)}{8\pi} \{ \tilde{E}_0(x_t) + E_0^{IV}(y) \}, \\
C_7(M_W) &= \frac{\alpha(M_W)}{6\pi} [4C_0(x_t) + \tilde{D}_0(x_t)], \\
C_8(M_W) &= 0, \\
C_9(M_W) &= \frac{\alpha}{6\pi} [4C_0(x_t) + \tilde{D}_0(x_t) + \frac{1}{\sin^2 \theta_W} (10B_0(x_t) - 4C_0(x_t))], \\
C_{10}(M_W) &= 0, \tag{13}
\end{align*}

and the LO \( C_{7\gamma}, C_{8g} \) are sufficient:

\begin{align*}
C_{7\gamma}(M_W) &= -\frac{A(x_t)}{2} - \frac{A(y)}{6} |\lambda_{tt}|^2 + B(y) |\lambda_{tt}\lambda_{bb}| e^{i\theta}, \\
C_{8g}(M_W) &= -\frac{D(x_t)}{2} - \frac{D(y)}{6} |\lambda_{tt}|^2 + E(y) |\lambda_{tt}\lambda_{bb}| e^{i\theta}, \tag{14}
\end{align*}

where \( x_t = m_t^2/M_W^2 \), and \( y = m_t^2/M_{H^{\pm \pm}}^2 \). The Inami-Lim functions \( A, B, D, E \ldots \) are known in SM and 2HDM[26].

For the new operators \( Q_{(1,12,...,16)} \), the corresponding Wilson coefficients \( C_i, i = 11, ...16 \) at leading order have been calculated in[25, 29]:

\begin{align*}
C_{11}(M_W) &= \frac{\alpha}{4\pi} \frac{m_b}{m_{b^*}} (C_{Q_1} - C_{Q_2}), \\
C_{13}(M_W) &= \frac{\alpha}{4\pi} \frac{m_b}{m_{b^*}} (C_{Q_1} + C_{Q_2}), \\
C_{12}(M_W) &= C_{14}(M_W) = C_{15}(M_W) = C_{16}(M_W) = 0, \tag{15}
\end{align*}

Here the explicit expression of \( C_{Q_1}, C_{Q_1} \) can be found in[29].

For the \( B \to PV \) processes, the Wilson coefficient functions must run from the \( M_W \) scale to the scale of \( O(m_b) \). For \( C_1 - C_{10} \), the NLO corrections should be included. While for \( C_{8g} \) and \( C_{7\gamma} \), LO results are sufficient. The details for the running Wilson coefficients can be found in Ref.[24]. As for the neutral Higgs boson induced operators, the one loop anomalous dimension matrices can be divided into two distangled groups[25]:

\begin{align*}
\gamma^\text{RL} &= \begin{pmatrix}
O_{11} & O_{12} \\
O_{11} & -16 & 0 \\
O_{12} & -6 & 2
\end{pmatrix} \tag{16}
\end{align*}
and
\[
\gamma^{\text{RR}} = \begin{pmatrix}
O_{13} & O_{14} & O_{15} & O_{16} \\
O_{13} & -16 & 0 & 1/3 \\
O_{14} & -6 & 2 & -1/2 \\
O_{15} & 16 & -48 & 16/3 \\
O_{16} & -24 & -56 & 6 & -38/3
\end{pmatrix}
\] (17)

As no NLO Wilson coefficients \( C_i, i = 11, 12, \ldots, 16 \) are available, we may just use the LO Wilson coefficients for a numerical estimation.

### C. Generalized Factorization formula

For our present purpose, we may use the generalized factorization method [30, 31, 32, 33] to evaluate the hadronic matrix elements. We know that in full theory, the leading order QCD corrections to the weak transition is of the form \( \alpha_s \ln(M_W^2 - p^2) \) for massless quarks, where \( p \) is the off-shell momentum of external quark lines and depends on the system under consideration. We can choose a renormalization scale \( \mu \) and separate \( \ln(M_W^2 - p^2) = \ln(M_W^2/\mu^2) + \ln(\mu^2 - p^2) \). The first part \( \ln(M_W^2/\mu^2) \) is included in the Wilson coefficients \( c(\mu) \) and summed over to all orders in \( \alpha_s \) using the renormalization group equation, while the second part is due to the matrix element evaluations and is small. It is related to the tree matrix element via:

\[
\langle O(\mu) \rangle = g(\mu) \langle O \rangle_{\text{tree}}
\] (18)

with:

\[
g(\mu) \sim 1 + \alpha_s(\mu)(\gamma \ln \frac{\mu^2}{-p^2} + c)
\] (19)

where the \( \mu \) dependence of the matrix elements is approximately extracted out to the function \( g(\mu) \), that is:

\[
\langle H_{\text{eff}} \rangle = c(\mu)g(\mu)\langle O \rangle_{\text{tree}} = c^{\text{eff}}\langle O \rangle_{\text{tree}}
\] (20)

the effective Wilson coefficients \( c^{\text{eff}} \) should be in principle renormalization scale independent. Thus it is necessary to incorporate QCD and EW corrections to the operators:

\[
\langle O_i(\mu) \rangle = [I + \frac{\alpha_s(\mu)}{4\pi}\hat{m}_s(\mu) + \frac{\alpha}{4\pi}\hat{m}_e(\mu)]_{ij}\langle O \rangle_{\text{tree}},
\] (21)

with

\[
c^{\text{eff}}_i = [I + \frac{\alpha_s(\mu)}{4\pi}\hat{m}_s(\mu) + \frac{\alpha}{4\pi}\hat{m}_e(\mu)]_{ij}c_j(\mu),
\] (22)

The perturbative QCD and EW corrections to the matrices \( \hat{m}_s \) and \( \hat{m}_e \) from the vertex and penguin diagrams can be found in [33, 34, 35].
Using the following parameterization for decay constant and form factors:

\[
< 0|A_\mu|P(q) > = i f_P q_\mu, < 0|V_\mu|V(p, \epsilon) >= f_V m_V \epsilon_\mu,
\]

we arrive at

\[
X^{BPV} \equiv < V|(\bar{q}_2 q_3)_{V-A}| > P|(\bar{q}_1 b)_{V-A}| B > = 2 f_V m_V F_1^{BPV}(m_V^2)(\epsilon \cdot p_B),
\]

\[
X^{BV_P} \equiv < P|(\bar{q}_2 q_3)_{V-A}| > V|(\bar{q}_1 b)_{V-A}| B > = 2 f_P m_V A_0^{BPV}(m_P^2)(\epsilon \cdot p_B),
\]

Using the Fierz Transformation,

\[
(V - A)(V + A) \rightarrow -2(S - P)(S + P),
\]

\[
(V - A)(V - A) \rightarrow (V - A)(V - A)
\]

One can easily obtain all the \(Q_{11,12,13,14,15,16}\) tree level matrix elements. For the new operators \(Q_{11,12,13,14,15,16}\), the additional factorization formulas are:

\[
< V(k, \epsilon^*)|\bar{q}\sigma^{\mu\nu}q|0 > = -(\epsilon^*_\mu k_\nu - \epsilon^*_\nu k_\mu) f_V^0,
\]

\[
< P(p)|\bar{q}\sigma^{\mu\nu}q|B(p_P) > = \frac{i}{m_B + m_P} \left( q^2 (p + p_B)_\mu - (m_B^2 - m_P^2) q_\mu \right) f_P^0,
\]

with \(k = p_B - p\) and \(q = p_B - p\). \(f_V^0\) and \(f_P^0\) are the tensor decay constant of vector meson and the tensor form factor relevant to \(B \rightarrow P\) decays. \(\epsilon^*\) is the polarization vector of vector meson. The hadronic matrix element is given by

\[
< V(k, \epsilon^*)|\bar{q}\sigma^{\mu\nu}q|0 > < P(p)|\bar{q}\sigma_{\mu\nu}b|B(p_B) > = \frac{2 f_V^0 f_P^0 m_V^2}{m_B + m_P} (\epsilon^* \cdot p_B),
\]

The tree level matrix elements of \(Q_{11,12,13,14,15,16}\) can be factorized as \((b \rightarrow s\) for example):

\[
< PV|Q_1|B > = a_{11} \frac{m_P^2}{(m_b + m_s)(m_q + m_q')}, < P|(\bar{q}q)_{V-A}|0 > < V|(\bar{s}b)_{V-A}| B >,
\]

\[
< PV|Q_2|B > = -\frac{1}{2} a_{12} < P|(\bar{q}q)_{V-A}|0 > < V|(\bar{s}b)_{V-A}| B > = \frac{1}{2} a_{12} < V|(\bar{q}q)_{V-A}|0 > < P|(\bar{s}b)_{V-A}| B >,
\]

\[
< PV|Q_3|B > = -a_{13} \frac{m_P^2}{(m_b + m_s)(m_q + m_q')}, < P|(\bar{q}q)_{V-A}|0 > < V|(\bar{s}b)_{V-A}| B >,
\]

\[
< PV|Q_4|B > = -\frac{1}{2} a_{14} \frac{m_P^2}{(m_b + m_s)(m_q + m_q')}, < P|(\bar{q}q)_{V-A}|0 > < V|(\bar{s}b)_{V-A}| B > = \frac{1}{4} < V|\bar{q}\sigma^{\mu\nu}q|0 > < P|\bar{s}\sigma_{\mu\nu}b| B >,
\]

\[
< PV|Q_5|B > = 2 a_{15} < V|\bar{q}\sigma^{\mu\nu}q|0 > < P|\bar{s}\sigma_{\mu\nu}b| B >,
\]

\[
< PV|Q_6|B > = -a_{16} < V|\bar{q}\sigma^{\mu\nu}s|0 > < P|\bar{q}\sigma_{\mu\nu}b| B > = 6 a_{16} \frac{m_P^2}{(m_b + m_q)(m_q' + m_s)} < P|(\bar{q}s)_{V-A}|0 > < V|(\bar{s}b)_{V-A}| B >,
\]
with:

\[
\begin{align*}
a_{11} &= c_{11} + \frac{c_{12}}{N_c}, \\
a_{12} &= c_{12} + \frac{c_{11}}{N'_c}, \\
a_{13} &= c_{13} + \frac{c_{12}}{N'_c}, \\
a_{14} &= c_{14} + \frac{c_{13}}{N'_c}, \\
a_{15} &= c_{15} + \frac{c_{16}}{N'_c}, \\
a_{16} &= c_{16} + \frac{c_{15}}{N'_c},
\end{align*}
\]

(29)

\(N'_c\) is the effective color number relative to the new six operators, which is set to be universal in all the decay channels. In this paper we fix it to be \(N'_c = 3\) to estimate the neutron higgs effects. As for the SM operators, besides the perturbative QCD and EW corrections to the hadronic matrix elements that can be factorized into the effective Wilson coefficients, there still exists the nonfactorizable effects, such as the spectator quark effects, annihilation diagrams and space-like penguins. Consider an arbitrary operator of the form \(O = \bar{q}_i \gamma^\alpha \Gamma q_j \bar{q}_k \gamma^\beta \Gamma' q^\alpha\) which arises from the Fierz transformation of a singlet-singlet operator with \(\Gamma\) and \(\Gamma'\) being some combinations of Dirac matrices. By using the identity:

\[
O = \frac{1}{3} \bar{q}_1 \Gamma q_2 \bar{q}_3 \Gamma' q_4 + \frac{1}{2} \bar{q}_1 \lambda^\alpha \Gamma q_2 \bar{q}_3 \lambda^\alpha \Gamma' q_4,
\]

(30)

the matrix element of \(M \rightarrow P_1 P_2\) can be expanded as:

\[
\begin{align*}
< P_1 P_2 | O | M > &= \frac{1}{3} < P_1 | \bar{q}_1 \Gamma q_2 |0> < P_2 | \bar{q}_3 \Gamma' q_4 | M >_f + \frac{1}{3} < P_1 | \bar{q}_1 \Gamma q_2 |0> < P_2 | \bar{q}_3 \Gamma' q_4 | M >_{nf} \\
&+ \frac{1}{2} < P_1 P_2 | \bar{q}_1 \lambda^\alpha \Gamma q_2 \bar{q}_3 \lambda^\alpha \Gamma' q_4 | M >.
\end{align*}
\]

(31)

The last two terms on r.h.s are nonfactorizable, and their contributions are included in the effective color number \(N_{c_{eff}}\). To evaluate the decay amplitudes, it is useful to introduce the combination of Wilson coefficients

\[
\begin{align*}
a_{2i}^{eff} &= c_{2i}^{eff} + \frac{1}{(N_{c_{eff}})_{2i-1}} c_{2i-1}^{eff}, \\
a_{2i-1}^{eff} &= c_{2i-1}^{eff} + \frac{1}{(N_{c_{eff}})_{2i-1}} c_{2i}^{eff},
\end{align*}
\]

(32)

The values of \(N_{c_{eff}}\) can be found in [32], that is:

\[
N_{c_{eff}}(V - A) \equiv (N_{c_{eff}})_{1} \approx (N_{c_{eff}})_{2} \approx (N_{c_{eff}})_{3} \approx (N_{c_{eff}})_{4} \approx (N_{c_{eff}})_{9} \approx (N_{c_{eff}})_{10}, \\
N_{c_{eff}}(V + A) \equiv (N_{c_{eff}})_{5} \approx (N_{c_{eff}})_{6} \approx (N_{c_{eff}})_{7} \approx (N_{c_{eff}})_{8},
\]

(33)

As shown in [32] that in general \(N_{c_{eff}}(V - A) \neq N_{c_{eff}}(V + A)\). The satisfied choice is that \(N_{c_{eff}}(V - A) < 3 < N_{c_{eff}}(V + A)\). And it is reasonable to take the value of \(N_{c_{eff}}(V - A) = 2, N_{c_{eff}}(V + A) = 5\). From now on, we will drop the superscript ”eff” through the paper for convenience.

III. \(B \rightarrow PV\) DECAYS IN MODEL III 2HDM

Based on the effective Hamiltonian obtained via the operator product expansion and renormalization group evaluation, one can write down the amplitude for \(B \rightarrow PV\) decays
and calculate the branching ratios and CP violating asymmetries once a method is derived for computing the hadronic matrix elements. For purpose of this paper, we are going to explore the new physics contributions to the exclusive decays $B \to PV$ in the general model III 2HDM with spontaneous CP violation. For a numerical estimation, we will employ the generalized factorization approach described in the previous section.

We begin with the following definitions for the branching ratio and CP violation asymmetry:

$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|A|^2 + |\bar{A}|^2},$$

$$BR(B \to PV) = \frac{1}{2} \frac{p_\epsilon^3}{8\pi m_V^2} \tau_B |\bar{A}|^2 + |A|^2 |/(\epsilon \cdot p_B)^2, \quad (34)$$

where $A$ and $\bar{A}$ are the decay amplitudes of $B$ and $\bar{B}$ respectively, $\epsilon$ is the polarization vector of the vector meson. The input parameters in calculation are listed in Table.I.

| $\tau_{B_d}$ | $\tau_{B_s}$ | $M_{B_d}$ | $M_{B_s}$ | $m_b$ |
|------------|------------|----------|----------|--------|
| $1.528 \times 10^{-12}$ ps | $1.472 \times 10^{-12}$ ps | $5.28$ GeV | $5.37$ GeV | $4.2$ GeV |
| $m_t$ | $m_u$ | $m_d$ | $m_c$ | $m_s$ |
| $174$ GeV | $3.2$ MeV | $6.4$ MeV | $1.1$ GeV | $0.105$ GeV |
| $m_{\bar{B}}$ | $m_{B_0}$ | $m_{\eta}$ | $m_{\eta'}$ | $m_{\phi}$ |
| $0.14$ GeV | $0.135$ GeV | $0.547$ GeV | $0.958$ GeV | $0.77$ GeV |
| $m_{\rho \pm}$ | $m_{\rho_0}$ | $m_{\phi}$ | $m_{K^\pm}$ | $m_{K^0}$ |
| $0.77$ GeV | $0.782$ GeV | $1.02$ GeV | $0.494$ GeV | $0.498$ GeV |
| $m_{K^* \pm}$ | $m_{K^{*0}}$ | $\Lambda_{QCD}$ | $f_\pi$ | $f_K$ |
| $0.892$ GeV | $0.896$ GeV | $225$ MeV | $0.132$ GeV | $0.16$ GeV |
| $f_\rho$ | $f_\omega$ | $f_{K^*}$ | $f_\phi$ | $f_{\rho}^T$ |
| $0.21$ GeV | $0.195$ GeV | $0.221$ GeV | $0.237$ GeV | $0.147$ GeV |
| $f_{\rho}^T$ | $f_{K^*}^T$ | $f_\phi^T$ |
| $0.133$ GeV | $0.156$ GeV | $0.183$ GeV |

In the model III 2HDM, $\lambda_{ij}(i, j = c, s, b, t), m_{H^\pm}, m_{h_0}, m_{A_0}, m_{H_0}$ are free parameters that should be constrained from experiments. It was shown from $B_{d,s}^0 - \bar{B}_{d,s}^0$ mixing that the parameters $|\lambda_{cc}|$ and $|\lambda_{ss}|$ can reach to be around $100$ [21], and their phases are not constrained too much. In our present considerations, we simply fix their phases to be $\pi/4$.
TABLE II: The relevant Form Factors at $q^2 = 0$ for $B \to P$ transitions from LCSR$^{36,37,39}$ (the first row), sum rule in Heavy Quark Effective Field Theory$^{42}$ (the second row) and BSW model$^{40}$ (the third row). The values in the square brackets are the $B \to \eta'$ form factors.

| Decay Channel | $B_q \to \pi$ | $B_q \to K$ | $B_q \to \eta(\prime)$ | $B_s \to K$ | $B_s \to \eta(\prime)$ |
|---------------|-------------|-------------|-----------------|-------------|-----------------|
| $F_0$         |             |             |                 |             |                 |
| LCSR          | 0.258       | 0.331       | 0.275 [-]       | --          | --              |
| SRHQEFT       | 0.285       | 0.345       | 0.247 [-]       | 0.296       | 0.281 [-]       |
| BSW           | 0.333       | 0.379       | 0.307[0.254]    | 0.274       | 0.335[0.282]    |

TABLE III: The relevant Form Factors at $q^2 = 0$ for $B \to V$ transitions from LCSR$^{36,37,39}$ (the first row), sum rule in Heavy Quark Effective Field Theory$^{42}$ (the second row) and BSW model$^{40}$ (the third row).

| Decay Channel | $B_q \to \rho$ | $B_q \to \omega$ | $B_q \to K^*$ | $B_s \to \phi$ | $B_s \to K^*$ |
|---------------|---------------|-----------------|--------------|---------------|--------------|
| $A_0$         |               |                 |              |               |              |
| LCSR          | 0.303         | 0.281           | 0.374        | 0.474         | 0.363        |
| SRHQEFT       | 0.363         | 0.341           | 0.400        | 0.397         | 0.337        |
| BSW           | 0.281         | 0.280           | 0.321        | 0.475         | 0.364        |

to see their effects. For $\lambda_{tt}$ and $\lambda_{bb}$, the constraints come from the experimental results of $B - \bar{B}$ mixing, $\Gamma(b \to s\gamma), \Gamma(b \to c\tau\bar{\nu}_\tau), \rho_0, R_b$ and the electric dipole moments (EDMS) of the electron and neutron$^{14,16,25,29,43}$. For a numerical calculation, we are going to consider the following three typical parameter spaces which are allowed by the present experiments:

Case A: $|\lambda_{tt}| = 0.15; |\lambda_{bb}| = 50,$
Case B: $|\lambda_{tt}| = 0.3; |\lambda_{bb}| = 30,$
Case C: $|\lambda_{tt}| = 0.03; |\lambda_{bb}| = 100,$

(35)

and:

$\theta_{tt} + \theta_{bb} = \pi/2,$

(36)

For the Higgs mass, the following values are assumed:

$m_{A_0} \simeq 120GeV, \ m_{h_0} \simeq 115GeV,$
$m_{H_0} \simeq 160GeV, \ m_{H^\pm} \simeq 200GeV$

(37)

All the numerical results are presented in Table V ~ Table IX.

IV. CONCLUSIONS AND DISCUSSIONS

As the charged Higgs mediated one loop FCNC effects to the $\Delta B = 1$ charmless decays are mostly characterized through the Wilson coefficient $C_{eff}^{\gamma s}$, which is included
in the $C_{(3,4,5,6,7,8)}^{eff}$, and there are no new operators beyond the basic operators $Q_{1,2...10}$, their contributions to the Wilson coefficients are given in Table.III. On the contrary, the neutral Higgs mediated processes will bring in new operators $Q_{(11,12,...,16)}$ with the new Wilson coefficients $C_{(11,12,...,16)}$. They are nonzero when the neutral Higgs couples to the second and third generation of quarks, and the numerical results are presented in Table.IV. From the above calculations, it is seen that in some decay channels, the new physics contributions can be significant, especially to CP violations.

a). As we have set the Yukawa couplings $\lambda_{iu}$ and $\lambda_{id}$ to be zero, so the neutral Higgs contributions to $B \rightarrow (\rho, \omega, K^*)\pi, (\rho, \omega)K$ decays are actually ignored, only the charged Higgs give new contributions. One can see that the branching ratio of $B \rightarrow K^0\rho^0$ decay in the model III 2HDM is the same as SM prediction (about $1.55 \times 10^{-6}$), which is far below the large central value of experimental result ($5.4 \pm 0.9) \times 10^{-6}$. Though the annihilation diagram and exchange diagram are not taken into account, their contributions are still not enough to give such an enhancement. So one needs to find some new mechanism to explain this discrepancy. The same situation also appears in the $B \rightarrow K^-\rho^+, K^-\pi^+$ decays, where the experimental results are much larger than theoretical predictions both in SM and 2HDM when simply using the generalized factorization approach. Though the branching ratios could be enhanced by using improved QCD Factorization(QCDF) [44], the resulting values are still smaller than the measured results. b). The model III 2HDM prediction for the CP violation of $B_d \rightarrow K\phi$ decay is $5 \sim 7$ times larger than the SM prediction, which can be a signal to look for new physics in future experiments. But the prediction of the branching ratio are both smaller than the experimental one. c). The SM and model III 2HDM predictions for branching ratio of $B_d \rightarrow K^{*0}\pi^0$ are the same in size and all consistent with the experimental result at 1$\sigma$ level. While the new physics prediction for CPV can flip the sign of the SM one and be $1 \sim 5$ times larger in size and still within 1$\sigma$ error of the experiments. d). In $B_d \rightarrow K^*(\eta, \eta')$ decays, new physics effects to CPV becomes significant. In $B \rightarrow K^*\eta$, the 2HDM prediction is negative but the SM one is positive. In $B \rightarrow K^*\eta'$, the 2HDM prediction can be as large as 40%, which is about seven times of SM prediction. e). In $B_d \rightarrow \rho^+\pi^-$ decay, the model III 2HDM prediction can enhance the CP violation from about $-20\%$ in SM to about $-30\%$. Both SM and 2HDM predictions for the branching ratio of $B_d \rightarrow \rho^0\pi^0$ decay are much smaller than the experimental result. Such an inconsistence cannot be improved even in QCD factorization method [44]. As for CP violation, the SM and model III 2HDM predictions have opposite sign with the magnitude ($10 \sim 15\%$). As the current experimental error is still too big to draw a conclusion, much more precise measurement is needed to test it. f). In $B_d \rightarrow \omega\pi$ decays, the new physics effects to CP violation may be distinct with the SM prediction, as it not only flips the sign but also enhances the magnitude by a factor of three.

For $B_0^\Gamma \rightarrow PV$ decays, the new physics contribution can be large in some decay channels. a). In $B_s \rightarrow K^*\eta$, the 2HDM prediction enhanced the direct CP violation to about $-50\%$ compared to the SM prediction $-28.8\%$, but for $B_s \rightarrow K^*\eta'$, the new physics contribution is destructive and reduce the SM prediction $-37\%$ to about $-20\%$. b). In $B_s \rightarrow \rho\eta^{(*)}$ decays, new physics contribution to branching ratio is destructive but gives an enhancement to the CPV to about four times of the SM prediction. c). In $B_s \rightarrow \phi\eta^{(*)}$ decays, new physics effects to branching ratios and CPV are both significant. d). In $B_s \rightarrow K^0\bar{K}^{0*}$ decay, 2HDM can give about $25 \sim 70\%$ enhancement to the branching
ratio. e). In $B \rightarrow K^0\phi$ decay, new physics effect to CPV is very significant, the SM prediction is almost zero, but the new physics effects can enhance it to about $-10\%$.

For $B_u \rightarrow PV$ decays, there are also some new effects from the extra Higgs contributions: a). In $B_u \rightarrow \pi^-K^*0$ decay, the 2HDM prediction of CPV can be ten times of the SM one and are more closer to the experimental value. b). In $B_u \rightarrow K^-\phi$ decay, CPV can be about $10\%$ in 2HDM, which is much larger than the SM prediction $1.44\%$ and is within $2\sigma$ level of experimental results. c). In $B_u \rightarrow K^{*-}\eta$ decays, new physics contribution reduced the CPV to about a half or a quarter of the SM one and is much closer to the experimental result. d). In $B_u \rightarrow \rho^-\eta$ decay, 2HDM prediction for CPV is $2 \sim 3$ times of the SM one and much closer to the experimental central value. e). In $B_u \rightarrow \pi^-\phi$ decay, new physics enhancement for the branching ratio and direct CPV can be all significant.

f). In $B_u \rightarrow K^{*-}K^0$ decay, 2HDM predictions for CPV are $20 \sim 24\%$, which is very much larger than the SM prediction $−1.73\%$. On the contrary, in $B_u \rightarrow K^{*0}K^-\phi$ decay, 2HDM prediction for CPV can be much smaller than the SM one.

From the above results, we see that in some decay channels, the theoretical predictions for branching ratios are still far from the experimental results not only in SM but also in model III 2HDM, such as $B \rightarrow K\rho, K^*\pi$ decays. And even using the improved QCDF, the situation cannot be improved much. There must be some new mechanism to improve those situations. For simplicity, we have not considered the possible effects of final state interaction (FSI) and the contributions from annihilation and exchange diagrams although they may play a significant role in some decay channels. As for factorization part, in principle, $N_{c}^{eff}$ can vary from channel to channel as in the case of charm decay. However, in the energetic two-body $B$ decays, $N_{c}^{eff}$ is expected to be process insensitive $^{30, 32}$, and the preferred values are obtained from the data to be $N_{c}^{eff}(V - A) = 2, N_{c}^{eff}(V + A) = 5^{30, 32}$. In a numerical calculation, we have considered only three cases for parameter choice in a general model III 2HDM to be consistent with the experimental results. Also we have totally neglected the first generation Yukawa couplings and the off-diagonal matrix elements of the Yukawa coupling matrix, such as $\lambda_{tc, sb}$ etc. to eliminate the FCNC at tree level. However, it is still possible that FCNC involving the third generation quarks exists at tree level, so the constraints can be less stronger to get nonzero off-diagonal elements.

In conclusion, we have shown that the new Higgs bosons in the general model III 2HDM with spontaneous CP violation can bring out some significant effects in some charmless $B$-meson decays, which can be good signals in the future B factory experiments to test the SM and look for new physics from more precise measurements.

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[1] M.Kobayashi and T.Maskawa, Prog.Theor.Phys.49,652(1973).
[2] Y.L.Wu, Phys.Rev. D64, 016001 (2001), hep-ph/0012371.
   For a review also see: S. Bertolini, "Theory Status of $\varepsilon'/\varepsilon$", Frascati Phys. Ser. 28 275-290 2002, hep-ph/0206095.
[3] Alavi-Harati, et al. [KTeV Collaboration], Phys. Rev. D67 012005, (2003);
   J.R. Batley, et al. [NA48 Collaboration], Phys. Lett. B544 97 (2002).
[4] Y.L. Wu and Y.F. Zhou, Phys.Rev. D71 0217005 (2005); hep-ph/0409221.
   Y.L. Wu, Y.F. Zhou and C. Zhuang, Phys.Rev. D74 094007 (2006), hep-ph/0609006.
[5] K. Abe et al. [Belle Collaboration], Phys. Rev. Lett. 93, 021601 (2004);
   B. Aubert et al. [BaBar Collaboration], Phys. Rev. Lett. 93, 131801 (2004).
[6] T.D. Lee, Phys. Rev. D8, 1226 (1973); Phys. Rep. 9, 143 (1974).
[7] The Higgs Hunter’s Guide by J.Gunion et al., Addison Wesley, New York, 1990. P. Sikivie, Phys. Lett. B65, 141 (1976);
   S.L.Glashow and S.Weinberg, Phys. Rev. D15, 1958(1977);
   H.E. Haber, G.L. Kane and T. Sterling, Nucl. Phys. B161, 493 (1979);
   N.G. Deshpande and E. Ma, Phys. rev. D18, 2574 (1978);
   H. Georgi, Hadronic J. 1, 155 (1978);
   J.F. Donoghue and L.-F. Li, Phys. Rev. D19, 945 (1979);
   A.B. Lahanas and C.E. Vayonakis, Phys. Rev. D19, 2158 (1979);
   L.F. Abbott, P. Sikivie and M.B. Wise, Phys. Rev. D21, 1393 (1980);
   G.C. Branco, A.J. Buras and J.M. Gerard, Nucl. Phys. B259, 306 (1985);
   B. McWilliams and L.-F. Li, Nucl. Phys. B179, 62 (1981);
   J.F. Gunion and H.E. Haber, Nucl. Phys. B272, 1 (1986);
   J. Liu and L. Wolfenstein, Nucl. Phys. B289, 1 (1987);
   J.F.Cheng, C.S.Huang and X.H.Wu, Nucl. Phys. B701, 54 (2004);
   R.Barbieri and L.J.Hall, hep-ph/0510243.
[8] T.P.Cheng and M.Sher, Phys. Rev. D 35, 3484(1987); M.Sher and Y.Yao, Phys. Rev. D44, 1461(1991);
[9] A. Antaramian, L.J. Hall, and A. Rasin, Phys. Rev. Lett. 69, 1871 (1992).
[10] W.S. Hou, Phys. Lett. B296, 179 (1992);
   D.W. Chang, W.S. Hou and W.Y. Keung, Phys. Rev. D48, 217 (1993);
   M.J. Savage, Phys. Lett. B266, 135 (1991).
[11] L.J. Hall and S. Weinberg, Phys. Rev. D48, 979 (1993).
[12] Carnegie-Mellon Univ. report, CMU-HEP94-01, hep-ph/9404241, 1994 (unpublished);
   Y.L. Wu, in: Proceedings at 5th Conference on the Intersections of Particle and Nuclear Physics, St. Petersburg, FL, 31 May- 6 Jun 1994, pp338, edited by S.J. Seestrom (AIP; New York, 1995), hep-ph/9406306.
[13] Y.L.Wu and L.Wolfenstein, Phys.Rev.Lett 73,1762(1994).
[14] D.Atwood, L.Reina and A. Soni, phys. Rev. D55, 3156 (1997).
[15] Y.B.Dai, C.S.Huang and H.W.Huang, Phys.Lett.B390,257 (1997).
[16] D. Bowser-Chao , K. Cheung, and Wai-Yee Keung, Phys.Rev. D59 115006, (1999).
[17] K. Kiers, A. Soni, and G.H. Wu, Phys. Rev. D59,096001(1999).
[18] Y.L. Wu and Y.F. Zhou, Phys.Rev. D61 096001 (2000), hep-ph/9906313.
[19] L. Wolfenstein and Y.L. Wu, Phys. Rev. Lett., 73, 2809 (1994).
[20] Y.L. Wu, Chin. Phys. Lett. 16 339 (1999), hep-ph/9805439.
[21] C.S.Huang, J.T.Li, Int.J.Mod.Phys.A20,161(2005).
[22] G. Buchalla, A.J. Buras and M.K. Harlander, Nucl. Phys. B337 (1990) 313.
[23] E.A. Paschos and Y.L. Wu, Mod. Phys. Lett. A6 (1991) 93.
[24] G. Buchalla, A.J. Buras and M.E. Lautenbacher, Rev. Mod. Phys. 68, (1125) 1996;
   A. Buras, M. Jamin, M. Lautenbacher and P.H. Weisz, Nucl. Phys. B400 (1993) 37, 75;
   A. Buras, M. Jamin and M. Lautenbacher, Nucl. Phys. B408 (1993) 209;
   M. Cuichini, E. Franco, G. Martinelli and L. Reina, Phys. Lett. B301 (1993) 263;
   M. Cuichini et al., Nucl. Phys. B415 (1994) 403.
[25] C.S. Huang, and S.H. Zhu, Phys. Rev. D68, 114020(2003).
[26] B. Grinstein, R. Springer and M.B. Wise, Nucl. Phys. B339, 269 (1990); A. Ali and C.
   Greub, Phys. Lett. B259, 182 (1991).
[27] Z.J.Xiao, C.S.Li, Phys. Rev. D63, 074005(2001).
[28] Z.J.Xiao, C.Zhuang, Eur. Phys. J. C 33, 349(2004).
[29] Y.B.Dai, C.S. Huang, J.T.Li and W.J.Li, Phys. Rev. D67, 096007(2003).
[30] H.Y. Cheng, B.Tseng, Phys. Rev. D58, 094005(1998).
[31] A. Ali, G. Kramer and C.D. Lü, Phys. Rev. D59, 014005, (1999).
[32] Y.H. Chen, H.Y. Cheng, B. Tseng and K.C. Yang, Phys. Rev. D60, 094014(1999).
[33] A. Ali, G. Kramer and C.D. Lü, Phys. Rev. D58, 094009(1998).
[34] D.S. Du, Y.D. Yang and G.H. Zhu, Phys. Rev. D59, 014007 (1999).
[35] H. Leutwyler, Nucl. Phys. B (Proc. Suppl.) 64, 223 (1998).
[36] P. Ball and R. Zwicky, Phys. Rev. D71, 014015 (2005).
[37] P. Ball and M. Boglione, Phys. Rev. D68, 094006 (2003).
[38] D. Becirevic et al., JHEP 0305 (2003) 007.
[39] P. Ball and R. Zwicky, Phys. Rev. D71, 014029 (2005).
[40] M. Wirbel, B. Stech and M. Bauer, Z. Phys. C29, 637 (1985). M. Bauer, B. Stech and M.
   Wirbel, Z. Phys. C34, 103 (1987).
[41] J. Cao, F.G. Cao, T. Huang and B.Q. Ma, Phys. Rev. D58, 113006 (1998).
[42] Y.L. Wu, M. Zhong, Y.B. Zuo, Int. J. Mod. Phys. A21, 6125 (2006); [hep-ph/0604007]
[43] E. O. Iltan, J. Phys. G27, 1723, (2001).
[44] M. Beneck and M. Neubert, Nucl. Phys. B675, 333 (2003).
APPENDIX A: THE EFFECTIVE WILSON COEFFICIENTS

TABLE IV: The effective Wilson coefficients $C_{(1,2\ldots10)}^{eff}$ in $b \to s$ process in SM and 2HDM at $\mu = m_b = 4.2 GeV$

| Model | SM | Case A | Case B | Case C |
|-------|----|--------|--------|--------|
| $C_1^{eff}$ | 1.17 | 1.17 | 1.17 | 1.17 |
| $C_2^{eff}$ | $-0.37$ | $-0.37$ | $-0.37$ | $-0.37$ |
| $C_3^{eff}$ | $0.024 + 0.0035I$ | $0.024 + 0.006I$ | $0.024 + 0.0048I$ | $0.024 + 0.0075I$ |
| $C_4^{eff}$ | $-0.050 - 0.010I$ | $-0.05 - 0.018I$ | $-0.05 - 0.014I$ | $-0.05 - 0.023I$ |
| $C_5^{eff}$ | $0.015 + 0.0035I$ | $0.015 + 0.006I$ | $0.015 + 0.005I$ | $0.015 + 0.0075I$ |
| $C_6^{eff}$ | $-0.064 - 0.010I$ | $-0.064 - 0.018I$ | $-0.064 - 0.014I$ | $-0.064 - 0.023I$ |
| $C_7^{eff}$ | $-0.00028 - 0.00024I$ | $-0.00035 - 0.00024I$ | $-0.00035 - 0.00024I$ | $-0.00035 - 0.00024I$ |
| $C_8^{eff}$ | $0.00055$ | $0.00061$ | $0.00061$ | $0.0006$ |
| $C_9^{eff}$ | $-0.011 - 0.00024I$ | $-0.011 - 0.00024I$ | $-0.011 - 0.00024I$ | $-0.011 - 0.00024I$ |
| $C_{10}^{eff}$ | $0.0038$ | $0.0034$ | $0.0034$ | $0.0034$ |

TABLE V: The Wilson coefficients $C_{(11,12\ldots16)}^{eff}$ at $\mu = m_b = 4.2 GeV$

| Parameter Space | Case A | Case B | Case C |
|----------------|--------|--------|--------|
| $C_{11}^c$ | $-0.089 + 0.12I$ | $-0.089 + 0.19I$ | $-0.11 + 0.13I$ |
| $C_{12}^c$ | 0 | 0 | 0 |
| $C_{13}^c$ | $-0.031 - 0.051I$ | $-0.054 - 0.072I$ | $-0.030 - 0.055I$ |
| $C_{14}^c$ | $-0.00063 - 0.0010I$ | $-0.0011 - 0.0015I$ | $-0.00061 - 0.0011I$ |
| $C_{15}^c$ | $0.00035 + 0.00057I$ | $0.00061 + 0.00080I$ | $0.00034 + 0.00062I$ |
| $C_{16}^c$ | $-0.0011 - 0.00175I$ | $-0.0019 - 0.0025I$ | $-0.0010 - 0.0019I$ |
| $C_{11}^s$ | $-0.0085 + 0.012I$ | $-0.0085 + 0.018I$ | $-0.010 + 0.012I$ |
| $C_{12}^s$ | 0 | 0 | 0 |
| $C_{13}^s$ | $-0.0030 - 0.0049I$ | $-0.0052 - 0.0069I$ | $-0.0029 - 0.0052I$ |
| $C_{14}^s$ | $-0.00060 - 0.00010I$ | $-0.00011 - 0.00014I$ | $-0.00059 - 0.00010I$ |
| $C_{15}^s$ | $0.00033 + 0.000055I$ | $0.00058 + 0.000078I$ | $0.00032 + 0.000059I$ |
| $C_{16}^s$ | $-0.00010 - 0.00017I$ | $-0.00018 - 0.00024I$ | $-0.0001 - 0.00018I$ |
APPENDIX B: NUMERICAL RESULTS OF $B \to PV$ DECAYS

TABLE VI: CP averaged branching ratios (in units of $10^{-6}$)(first line) and direct CPV (second line) for charmless $B^0_d \to PV$ decays in SM and 2HDM. $N^e_{f f}(V-A), N^e_{c c}(V-A)$ are fixed to be 2 and 5 respectively and $N^e_c = 3$. The parameter spaces are: Case A: ($|\lambda_{tt}| = 0.15, |\lambda_{bb}| = 50, \theta = \pi/2$), Case B: ($|\lambda_{tt}| = 0.03, |\lambda_{bb}| = 100, \theta = \pi/2$), Case C: ($|\lambda_{tt}| = 0.3, |\lambda_{bb}| = 30, \theta = \pi/2$). And $\lambda_{cc} = \lambda_{ss} = 100e^{i\pi/4}$.

| Decay channel                | SM | Case A (2HDM) | Case B (2HDM) | Case C (2HDM) | Exp  |
|------------------------------|----|---------------|---------------|---------------|------|
| $B^0_d \to K^0\rho^0$       | 1.56 | 1.55          | 1.55          | 1.56          | 5.4 ± 0.9  |
|                             | 1.7% | 2.10%         | 1.97%         | 2.20%         | –   |
| $B^0_d \to K^-\rho^+$       | 2.01 | 1.94          | 1.97          | 1.91          | 9.9^{+1.6}_{-1.5}  |
|                             | -3.6% | -3.83%        | -3.90%        | -3.76%        | (17^{+15}_{-16})% |
| $B^0_d \to K^{*-}\pi^+$     | 3.24 | 3.92          | 3.56          | 4.33          | 9.8 ± 1.1  |
|                             | 24.5% | 27.5%         | 26.2%         | 28.2%         | (−5 ± 14)% |
| $B^0_d \to K^{*0}\pi^0$     | 1.47 | 1.47          | 1.46          | 1.51          | 1.7 ± 0.8  |
|                             | -2.50% | 7.20%        | 2.30%         | 11.5%         | (−1^{+27}_{-26})% |
| $B^0_d \to K^0\phi$         | 4.80 | 5.22          | 5.23          | 5.18          | 8.3^{+1.2}_{-1.0}  |
|                             | 1.40% | 5.96%         | 10.0%         | 10.3%         | –   |
| $B^0_d \to K^*\eta$         | 9.41 | 10.4         | 10.7          | 10.8          | 16.1 ± 1.0  |
|                             | 1.86% | -2.68%        | -3.85%        | -1.93%        | (19 ± 5)% |
| $B^0_d \to K^*\eta'$        | 1.33 | 1.18          | 1.49          | 1.20          | 3.8 ± 1.2  |
|                             | 5.50% | 32.7%         | 22.1%         | 40.4%         | (−8 ± 25)% |
| $B^0_d \to K^0\omega$       | 0.43 | 0.44          | 0.44          | 0.44          | 4.8 ± 0.6  |
|                             | 0.00% | 0.33%         | 0.32%         | 0.32%         | –   |
| $B^0_d \to \rho^-\pi^+$     | 15.8 | 15.3          | 15.1          | 15.1          | 24.0 ± 2.5  |
|                             | -4.3% | -4.4%         | -4.3%         | -4.4%         | –   |
| Decay channel          | SM  | Case A (2HDM) | Case B (2HDM) | Case C (2HDM) | Exp  |
|------------------------|-----|---------------|---------------|---------------|------|
| $B^0_d \to \rho^+\pi^-$ | 17.3| 16.3          | 17.7          | 15.0          | 24.0 ± 2.5 |
|                        | −18.8% | −26.5%      | −26.4%        | −26.4%        | –    |
| $B^0_d \to K^{0*}K^0$  | 0.23 | 0.24          | 0.24          | 0.25          | < 1.9 |
|                        | −11.5% | −10.1%       | −14.6%        | −6.45%        | –    |
| $B^0_d \to K^0K^{*0}$  | 0.038| 0.037         | 0.036         | 0.037         | –    |
|                        | −1.73% | 20.3%       | 22.0%         | 24.3%         | –    |
| $B^0_d \to \phi\eta$   | 0.0039| 0.0038        | 0.0038        | 0.0038        | < 0.6 |
|                        | 1.13% | 1.35%         | 1.25%         | 1.45%         | –    |
| $B^0_d \to \phi\eta'$  | 0.0023| 0.0022        | 0.0024        | 0.0022        | < 1.0 |
|                        | 1.13% | 1.35%         | 1.25%         | 1.45%         | –    |
| $B^0_d \to \phi\pi$    | 0.015| 0.0017        | 0.0017        | 0.0016        | < 0.28 |
|                        | 3.90% | 1.35%         | 1.25%         | 1.45%         | –    |
| $B^0_d \to \rho^0\pi^0$| 0.80 | 0.81          | 0.82          | 0.80          | $1.8^{+0.6}_{-0.5}$%
|                        | −10.5% | 14.4%       | 13.7%         | 14.9%         | ($-49_{-83}^{+70}$)% |
| $B^0_d \to \rho\eta$   | 0.82 | 0.88          | 0.83          | 0.92          | < 1.5 |
|                        | 12.3% | 6.93%         | 3.21%         | 6.91%         | –    |
| $B^0_d \to \rho\eta'$  | 0.50 | 0.55          | 0.54          | 0.57          | < 3.7 |
|                        | 5.88% | 6.33%        | 6.87%         | 6.20%         | –    |
| $B^0_d \to \omega\pi$  | 0.60 | 0.56          | 0.53          | 0.59          | < 1.2 |
|                        | −4.97% | 12.4%       | 12.7%         | 12.1%         | –    |
| $B^0_d \to \omega\eta$ | 0.84 | 0.77          | 0.80          | 0.73          | < 1.9 |
|                        | −13.9% | −11.1%      | −9.04%        | −11.2%        | –    |
| $B^0_d \to \omega\eta'$| 0.53 | 0.46          | 0.50          | 0.44          | < 2.8 |
|                        | −19.7% | −25.0%       | −26.0%        | −26.1%        | –    |
TABLE VIII: CP averaged branching ratios (in units of $10^{-6}$) (first line) and direct CPV (second line) for charmless $B_s^0 \rightarrow PV$ decays in SM and 2HDM.

| Decay channel          | SM    | Case A (2HDM) | Case B (2HDM) | Case C (2HDM) |
|------------------------|-------|---------------|---------------|---------------|
| $B_s^0 \rightarrow K^{*+}\pi^-$ | 8.34  | 8.73          | 8.34          | 8.44          |
|                        | -0.13%| -0.12%        | -0.13%        | -0.13%        |
| $B_s^0 \rightarrow K^{+}\rho^-$   | 26.7  | 27.7          | 26.5          | 26.2          |
|                        | -4.3% | -4.3%         | -4.3%         | -4.4%         |
| $B_s^0 \rightarrow K^{*0}\pi^0$  | 0.21  | 0.20          | 0.21          | 0.21          |
|                        | 5.0%  | 5.1%          | 5.1%          | 5.1%          |
| $B_s^0 \rightarrow \rho K^0$      | 0.59  | 0.70          | 0.66          | 0.73          |
|                        | 16.5% | 14.2%         | 14.7%         | 13.6%         |
| $B_s^0 \rightarrow K^0\omega$     | 0.70  | 0.73          | 0.69          | 0.68          |
|                        | -18.3%| -18.3%        | -18.4%        | -18.1%        |
| $B_s^0 \rightarrow K^*\eta$       | 0.29  | 0.32          | 0.31          | 0.33          |
|                        | -28.8%| -43.2%        | -49.9%        | -42.8%        |
| $B_s^0 \rightarrow K^*\eta'$      | 0.20  | 0.23          | 0.21          | 0.25          |
|                        | -37.1%| -21.2%        | -21.3%        | -17.7%        |
| $B_s^0 \rightarrow K^-K^{*+}$     | 1.98  | 2.27          | 2.24          | 2.31          |
|                        | -3.6% | -3.3%         | -3.4%         | -3.2%         |
| $B_s^0 \rightarrow K^+K^{*-}$     | 5.49  | 6.97          | 6.81          | 7.02          |
|                        | 24.5% | 22.8%         | 20.3%         | 21.6%         |
| $B_s^0 \rightarrow \rho\eta$      | 0.21  | 0.04          | 0.04          | 0.04          |
|                        | 3.6%  | 18.4%         | 18.4%         | 18.3%         |
| $B_s^0 \rightarrow \rho\eta'$     | 0.12  | 0.03          | 0.02          | 0.03          |
|                        | 3.6%  | 18.3%         | 18.4%         | 18.4%         |
| $B_s^0 \rightarrow \phi\pi$      | 0.21  | 0.04          | 0.03          | 0.04          |
|                        | 0.00% | 0.00          | 0.00          | 0.00          |
| $B_s^0 \rightarrow \omega\eta$   | 0.02  | 0.02          | 0.02          | 0.02          |
|                        | 43.1% | 40.0%         | 39.6%         | 40.1%         |
| $B_s^0 \rightarrow \omega\eta'$  | 0.01  | 0.01          | 0.01          | 0.01          |
|                        | 43.1% | 40.0%         | 39.6%         | 40.1%         |
| $B_s^0 \rightarrow \phi\eta$     | 12.2  | 17.9          | 17.7          | 20.0          |
|                        | 2.2%  | -12.3%        | -10.6%        | -14.2%        |
| $B_s^0 \rightarrow \phi\eta'$    | 0.61  | 1.68          | 1.92          | 2.23          |
|                        | 15.6% | -21.2%        | -21.3%        | -17.7%        |
| $B_s^0 \rightarrow K^0 K^*$      | 5.78  | 8.03          | 7.00          | 9.14          |
|                        | 1.27% | 4.10%         | 2.29%         | 5.0%          |
| $B_s^0 \rightarrow K^{*0} K$     | 1.28  | 1.03          | 1.00          | 1.06          |
|                        | 1.0%  | 1.2%          | 2.2%          | 1.0%          |
| $B_s^0 \rightarrow \phi K^0$     | 0.14  | 0.12          | 0.12          | 0.12          |
|                        | 0.23% | -9.7%         | -8.8%         | -11.7%        |
TABLE IX: CP averaged branching ratios (in units of $10^{-6}$) for charmless $B_{u}^{-} \to PV$ decays in SM and 2HDM.

| Decay channel     | Case A 2HDM | Case B (2HDM) | Case C (2HDM) | Exp.     |
|-------------------|-------------|---------------|---------------|----------|
| $B_{u}^{-} \to K^{-} \rho^{0}$ | 0.59        | 0.58          | 0.58          | 0.56     | $4.25^{+0.55}_{-0.56}$ |
|                   | $-1.88\%$  | $-2.40\%$    | $-2.32\%$    | $-2.38\%$| $(31^{+11}_{-10})\%$ |
| $B_{u}^{-} \to K^{*-} \pi^{0}$ | 2.62        | 2.80          | 3.25          | 2.80     | $6.9 \pm 2.3$          |
|                   | 18.9\%     | 22.3\%        | 20.4\%        | 22.3\%  | $(4 \pm 29)\%$         |
| $B_{u}^{-} \to K^{0} \rho^{-}$ | 1.09        | 1.10          | 1.10          | 1.10     | $< 48$                  |
|                   | 0.34\%     | 1.15\%        | 0.75\%        | 1.15\%  | $-$                     |
| $B_{u}^{-} \to \pi^{-} K^{*0}$ | 3.67        | 3.88          | 3.66          | 3.88     | $11.3 \pm 1.0$         |
|                   | $-1.28\%$  | $-12.9\%$     | $-5.41\%$     | $-12.9\%$| $(-8.6 \pm 5.6)\%$    |
| $B_{u}^{-} \to K^{-} \omega$  | 2.22        | 2.17          | 2.20          | 2.17     | $6.9 \pm 0.5$          |
|                   | 0.00\%     | $-0.33\%$     | $-0.32\%$     | $-0.33\%$| $(5 \pm 6)\%$          |
| $B_{u}^{-} \to K^{-} \phi$   | 5.16        | 5.92          | 5.57          | 5.93     | $8.30 \pm 0.65$        |
|                   | 14.4\%     | 11.7\%        | 10.0\%        | 10.3\%  | $(3.4 \pm 4.4)\%$     |
| $B_{u}^{-} \to K^{*-} \eta$  | 9.36        | 10.51         | 11.09         | 10.6    | $19.5^{+1.6}_{-1.5}$   |
|                   | 13.6\%     | 6.73\%        | 10.2\%        | 4.52\%  | $(2 \pm 6)\%$          |
| $B_{u}^{-} \to K^{*-} \eta'$ | 1.53        | 1.32          | 1.38          | 1.37     | $4.9^{+21.1}_{-1.9}$   |
|                   | 52.2\%     | 55.4\%        | 52.4\%        | 56.9\%  | $(30^{+32}_{-37})\%$  |
| $B_{u}^{-} \to \pi^{0} \rho^{-}$ | 11.4        | 11.1          | 11.3          | 11.1    | $10.8^{+11.4}_{-1.5}$  |
|                   | $-3.0\%$   | $-3.1\%$      | $-3.0\%$      | $-3.1\%$| $(2 \pm 11)\%$        |
| $B_{u}^{-} \to \pi^{-} \rho^{0}$ | 7.36        | 7.75          | 7.50          | 7.75     | $8.7^{+10.1}_{-1.1}$   |
|                   | 4.2\%      | 4.1\%         | 4.2\%         | 4.1\%   | $(7^{+11.2}_{-13})\%$  |
| $B_{u}^{-} \to \pi^{-} \omega$ | 6.85        | 6.50          | 6.65          | 6.50     | $6.7 \pm 0.6$         |
|                   | $-4.7\%$   | $-4.8\%$      | $-4.7\%$      | $-4.8\%$| $(-4 \pm 7)\%$        |
| $B_{u}^{-} \to \rho^{-} \eta$ | 11.1        | 13.2          | 11.0          | 10.8    | $5.3^{+11.2}_{-11}$    |
|                   | $-0.90\%$  | $-2.35\%$     | $-3.34\%$     | $-2.36\%$| $(1 \pm 16)\%$        |
| $B_{u}^{-} \to \rho^{-} \eta'$ | 14.0        | 12.7          | 13.7          | 12.8    | $9.1^{+3.7}_{-3.8}$    |
|                   | $-9.9\%$   | $-10.1\%$     | $-9.60\%$     | $-10.1\%$| $(-4 \pm 28)\%$       |
| $B_{u}^{-} \to \pi^{-} \phi$ | 0.0036      | 0.016         | 0.016         | 0.016   | $< 0.24$               |
|                   | 1.13\%     | 15.5\%        | 7.96\%        | 15.5\%  | $-$                    |
| $B_{u}^{-} \to K^{*-} K^{0}$  | 0.038       | 0.037         | 0.036         | 0.037   | $-$                    |
|                   | $-1.73\%$  | 20.3\%        | 22.0\%        | 24.3\%  | $-$                    |
| $B_{u}^{-} \to K^{-} K^{*0}$  | 0.25        | 0.27          | 0.26          | 0.27    | $< 5.3$               |
|                   | $-37.1\%$  | $-5.13\%$     | $-14.6\%$     | $-6.45\%$| $-$                    |