$B\rightarrow\pi^+\pi^-$, $K\pi$, $K\eta'$ decays and new physics effects in the general two-Higgs-doublet model: An update

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In this paper, we reexamine the new physics contributions to seven well measured $B\rightarrow PP$ decays in the standard model (SM) and the general two-Higgs-doublet model (model III) and compare the theoretical predictions with the new data. Within the considered parameter space we find that (a) the measurements of the branching ratios for $B\rightarrow\pi^+\pi^-$, $K^-\pi^+$, and $K^0\pi^+$ lead to a strong constraint on the form factor $F_0^{B\pi}(0)$: $F_0^{B\pi}(0)=0.24\pm0.03$, and (b) the new physics enhancements to the penguin-dominated $B\rightarrow K\pi$ and $K\eta'$ decays are significant in size, $\sim(40$–$65)\%$ with respect to the SM predictions, and play an important role in restoring the consistency between the data and theory.

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As is well known, one of the main objectives of B experiments is to probe for the possible effects of new physics beyond the standard model (SM). Precision measurements of the B meson system can provide insight into very high energy scales via the indirect loop effects of new physics [1,2].

Up to now, the CLEO, BaBar, and Belle Collaborations [3–5] have observed eighteen two-body charmless hadronic $B_{u,d}$ meson decay modes. Seven well measured $B\rightarrow PP$ (here P refers to the light pseudoscalar mesons) decays are

$$B\rightarrow\pi^{\pm}\pi^{\mp},\ K\pi,\ K\eta'. \tag{1}$$

These decay modes are closely related through isospin symmetry and SU(3) flavor symmetry, phenomenologically very interesting due to their key role in extracting the unitary angles α and γ, and the appearance of the so-called $\eta' K$ puzzle: the observed $B\rightarrow K\eta'$ decay rates [3–5] are much larger than what was expected in the standard model based on the effective Hamiltonian with generalized factorization (GF) approach [6–9]. To accommodate the data, one may need an additional contribution unique to the η' meson in the framework of the SM [10–13], or enhancements from new physics models beyond the SM [14,15].

In a previous paper [14], we considered the second possibility and calculated the new physics effects on the two-body charmless hadronic B meson decays in the general two-Higgs-doublet models (2HDM's) [16]. In this paper, we focus on seven well measured $B\rightarrow PP$ decay modes and compare the theoretical predictions with the newest data. We still use the low-energy effective Hamiltonian with GF approach [8,9] to calculate the new physics contributions. For recent studies of $B\rightarrow PP$ decays in the SM with the QCD factorization [Beneke-Buchalla-Neubert-Sachrajida (BBNS)] and perturbative QCD (PQCD) approaches [17,18], one can see the papers [19–22] and references therein.

For the inclusive three-body decays $b\rightarrow s\overline{q}q$ with $q\in\{u,d,s\}$ the effective Hamiltonian can be written as [6,8]

$$\mathcal{H}_{eff}(\Delta B=1)=\frac{G_F}{\sqrt{2}}\left\{\sum_{j=1}^{2}C_j(V_{ub}V_{us}^{*}Q_j^u+V_{cb}V_{cs}^{*}Q_j^c)-V_{tb}V_{ts}^{*}\left[\sum_{j=3}^{10}C_jQ_j+C_gQ_g\right]\right\}. \tag{2}$$

The explicit expressions for all operators can be found easily, for example see Ref. [8]. For $b\rightarrow d\overline{q}q$ decays, one simply makes the replacement $s\rightarrow d$. Following Ref. [8], we also neglect the effects of the electromagnetic penguin operator $Q_{7\gamma}$, the weak annihilation and exchange diagrams. Within the SM and at scale M_W, the Wilson coefficients $C_1(M_W),\ldots,C_{10}(M_W)$ at next-to-leading logarithmic order (NLO) and $C_g(M_W)$ at leading logarithmic order (LO) have been given, for example, in Ref. [6].

In a recent paper [23], Chao *et al.* studied the decay $b\rightarrow s\gamma$ in model III (the third type of 2HDM's) by assuming that only the couplings $\lambda_{tt}=|\lambda_{tt}|e^{i\theta_t}$ and $\lambda_{bb}=|\lambda_{bb}|e^{i\theta_b}$ are nonzero. They found that the constraint on M_{H^+} imposed by the CLEO data of $b\rightarrow s\gamma$ can be greatly relaxed by considering the phase effects of λ_{tt} and λ_{bb}. From the studies of Refs. [2,23], we know that for model III the parameter space,

$$\lambda_{ij}=0,\quad \text{for}\ \ ij\neq tt,\quad \text{or}\quad bb,$$
$$|\lambda_{tt}|=0.3,\quad |\lambda_{bb}|=35,\quad \theta=(0^0-30^0),$$
$$M_{H^+}=(200\pm100)\ \ \text{GeV}, \tag{3}$$

are allowed by the available data, where $\theta=\theta_{bb}-\theta_{tt}$. In this paper, we calculate the new physics contributions to seven B meson decay modes in the Chao-Cheung-Keung (CCK) scenario of model III [23].

Following the same procedure as in the SM, it is straightforward to calculate the new γ-, Z^0-, and gluonic penguin

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TABLE I. Measurements of the branching ratio $\mathcal{B}(B\to PP)$ (in units of 10^{-6}) as reported by CLEO, BaBar, and Belle Collaborations. The last column lists the world average.

Decay mode	CLEO	BaBar	Belle	Average
$B^0\to\pi^+\pi^-$	$4.3^{+1.6}_{-1.5}\pm0.5$	$4.1\pm1.0\pm0.7$	$5.6^{+2.3}_{-2.0}\pm0.4$	4.4 ± 0.9
$B^0\to K^+\pi^-$	$17.2^{+2.5}_{-2.4}\pm1.2$	$16.7\pm1.6\pm1.3$	$19.3^{+3.4+1.5}_{-3.2-0.6}$	17.3 ± 1.5
$B^+\to K^+\pi^0$	$11.6^{+3.0+1.4}_{-2.7-1.3}$	$10.8^{+2.1}_{-1.9}\pm1.0$	$16.3^{+3.5+1.6}_{-3.3-1.8}$	12.1 ± 1.7
$B^+\to K^0\pi^+$	$18.2^{+4.6}_{-4.0}\pm1.6$	$18.2^{+3.3}_{-3.0}\pm2.0$	$13.7^{+5.7+1.9}_{-4.8-1.8}$	17.4 ± 2.6
$B^0\to K^0\pi^0$	$14.6^{+5.9+2.4}_{-5.1-3.3}$	$8.2^{+3.1}_{-2.7}\pm1.2$	$16.0^{+7.2+2.5}_{-5.9-2.7}$	10.7 ± 2.7
$B^+\to K^+\eta'$	$80^{+10}_{-9}\pm7$	$70\pm8\pm5$	$79^{+12}_{-11}\pm9$	75 ± 7
$B^0\to K^0\eta'$	$89^{+18}_{-16}\pm9$	$42^{+13}_{-11}\pm4$	$55^{+19}_{-16}\pm8$	56 ± 10

diagrams induced by the exchanges of charged Higgs bosons that appeared in model III (for details of the calculations, see Ref. [14]). In the naive dimensional regularization (NDR) scheme, by using the input parameters as given in Eqs. (3) and setting $\mu=2.5$ GeV, we find that

$$C_1=1.1245,\ C_2=-0.2662,\ C_3=0.0186,\ C_4=-0.0458,$$

$$C_5=0.0113,\ C_6=-0.0587,\ C_7=0.0006,\ C_8=0.0007,$$

$$C_9=-0.0096,\ C_{10}=0.0026,\ C_g^{eff}=0.3364, \tag{4}$$

where $C_g^{eff}=C_{8G}+C_5$.

For the $B\to PP$ decay modes considered here, the decay amplitudes as given in Ref. [8] will be used without further discussion about details. We focus on estimating the new physics effects on those seven well measured decay modes. In the NDR scheme and for $SU(3)_C$, the effective Wilson coefficients can be written as [9]

$$C_i^{eff}=\left[1+\frac{\alpha_s}{4\pi}\left(\hat{r}_V^T+\gamma_V^T\log\frac{m_b}{\mu}\right)\right]_{ij}\times C_j+\frac{\alpha_s}{24\pi}A_i'(C_t+C_p+C_g)+\frac{\alpha_{ew}}{8\pi}B_i'C_e, \tag{5}$$

where $A_i'=(0,0,-1,3,-1,3,0,0,0,0)^T$, $B_i'=(0,0,0,0,0,0,1,0,1,0)^T$, and the matrices $\hat{r}_V$ and γ_V contain the process independent contributions from the vertex diagrams [9,14]. The functions C_t, C_p, and C_g describe the contributions arising from the penguin diagrams of the current-current $Q_{1,2}$, the QCD operators Q_3-Q_6, and the tree-level diagram of the magnetic dipole operator Q_{8G}, respectively. The explicit expressions of the functions C_t, C_p, and C_g can be found for example in Ref. [14].

In the generalized factorization approach, the effective Wilson coefficients C_i^{eff} will appear in the decay amplitudes in the combinations,

$$a_{2i-1}\equiv C_{2i-1}^{eff}+\frac{C_{2i}^{eff}}{N_c^{eff}},$$

$$a_{2i}\equiv C_{2i}^{eff}+\frac{C_{2i-1}^{eff}}{N_c^{eff}}\quad(i=1,\ldots,5), \tag{6}$$

where the effective number of colors N_c^{eff} is treated as a free parameter varying in the range of $2\leqslant N_c^{eff}\leqslant\infty$, in order to model the nonfactorizable contribution to the hadronic matrix elements.

In the B rest frame, the branching ratios $\mathcal{B}(B\to PP)$ can be written as

$$\mathcal{B}(B\to XY)=\tau_B\frac{|p|}{8\pi M_B^2}|M(B\to XY)|^2, \tag{7}$$

where $\tau_B=1.653ps$ and $1.548ps$ for $B=B_u^-$ and B_d^0 [24], respectively. p_B is the four-momentum of the B meson and $M_B=5.279$ GeV is the mass of B_u or B_d meson. In the numerical calculations we use the same input parameters (the masses, gauge couplings, decay constants, form factors, etc.) as in Ref. [14]. Particularly, the elements of Cabibbo-Kobayashi-Maskawa (CKM) matrix in the Wolfenstein parametrization are $A=0.81$, $\lambda=0.2205$, $\rho=0.12$, $\eta=0.34$, which corresponds to $\gamma=71°$ and $\sin2\beta=0.79$ favored by the global fit and the new measurements [25].

For the seven well measured $B\to PP$ decay modes, currently available measurements as reported by the CLEO, BaBar, and Belle Collaborations [3–5] and their averages are listed in Table I. The data have been changed greatly when compared with those in the year 2000:

(i) For ratio $\mathcal{B}(B\to\pi^+\pi^-)$, the new BaBar result is $(4.1\pm1.0\pm0.7)\times10^{-6}$ instead of the old $(9.3^{+2.8+1.2}_{-2.1-1.4})\times10^{-6}$. The average therefore decreased to $(4.4\pm0.9)\times10^{-6}$.

(ii) The BaBar measurement of $\mathcal{B}(B\to K^0\pi^0)$ is only $\sim8\times10^{-6}$. The average therefore becomes much smaller than two years ago.

(iii) For the ratio $\mathcal{B}(B\to K^0\eta')$, both the BaBar and Belle results are much smaller than CLEO's measurement; the average is only $(56\pm10)\times10^{-6}$ and clearly smaller than the branching ratio of $B\to K^+\eta'$ decay.

In the SM and GF approach, the decay $B\to\pi^+\pi^-$ is very simple and receives contributions from the dominated tree diagram, the QCD, and electroweak penguin diagrams, and depend on one form factor $F_0^{B\pi}(0)$ only, as can be seen from the decay amplitude [8],

$$\mathcal{M}(\overline{B}^0\to\pi^+\pi^-)=-i\frac{G_F}{\sqrt{2}}f_\pi F_0^{B\pi}(m_\pi^2)(m_B^2-m_\pi^2)\times\left\{V_{ub}V_{ud}^*a_1-V_{tb}V_{td}^*\left[a_4+a_{10}+2(a_6+a_8)\frac{m_\pi^2}{(m_b-m_u)(m_u+m_d)}\right]\right\}. \quad (8)$$

The new physics contribution to this decay in the model III is only 2.5% and thus can be neglected. In the SM, there is no other contribution to this decay mode and therefore it seems to be a clean decay mode to determine the form factor $F_0^{B\pi}(0)$. For $\gamma\approx 71°$ as indicated by the global fit, the interference between the tree and penguin diagrams is constructive, and the measured branching ratio of this decay leads to a small $F_0^{B\pi}(0)$,

$$F_0^{B\pi}(0)=0.21\pm0.03, \quad (9)$$

which is clearly smaller than the values from lattice-QCD or light-cone QCD sum rules: $F_0^{B\pi}(0)=0.30\pm0.04$, or 0.28 ± 0.05 as given in Ref. [26] and Ref. [27], respectively. For $F_0^{B\pi}(0)=0.3$ and $\gamma=71°$, however, the SM prediction for the branching ratio is $(7.5–10.7)\times10^{-6}$ for $N_c^{eff}=2-\infty$ in the GF approach and about 9×10^{-6} in the BBNS approach [28], which is clearly too large to be consistent with the data. We thus believe that the form factor $F_0^{B\pi}(0)$ should be apparently smaller than 0.3.

On the other hand, the QCD-penguin-dominated $B\to K^-\pi^+$ and $K^0\pi^+$ decays also depend on the form factor $F_0^{B\pi}(0)$, as can be seen from the decay amplitudes as given in Ref. [8]. But one should be very careful to extract the form factor $F_0^{B\pi}(0)$ from these two decay modes because of (a) the neglected rescattering and other nonfactorized contributions to these two decays may be large, and (b) the new physics contributions in the model III are also large, $\sim$50% with respect to the SM predictions. In the GF approach, the measured branching ratios of these two decays prefer a larger $F_0^{B\pi}(0)$: $F_0^{B\pi}(0)=0.30\pm0.03$ if the new physics contributions to these two decay modes are not included. But,

$$F_0^{B\pi}(0)=0.24\pm0.03 \quad (10)$$

if the measured branching ratios of $B\to\pi^+\pi^-$, $K^-\pi^+$, $K^0\pi^+$ decays and the new physics enhancements are all taken into account. Although the central value of the form factor in Eq. (10) is still smaller than $F_0^{B\pi}(0)=0.28\pm0.05$ as given in Refs. [26,27], they are compatible within errors. In the numerical calculations, we will use $F_0^{B\pi}(0)=0.24\pm0.03$.

Furthermore, the form factor $F_0^{BK}(0)$ cannot deviate too much from $F_0^{B\pi}(0)$, otherwise the SU(3) flavor symmetry will be broken badly. As indicated by the data and theoretical considerations, it is a good approximation to take $F_0^{BK}(0)/F_0^{B\pi}(0)=f_k/f_\pi$ as a measure of SU(3) symmetry breaking. We then find that

$$F_0^{BK}(0)=0.29\pm0.04 \quad (11)$$

for $F_0^{B\pi}(0)=0.24\pm0.03$.

In the GF approach, the QCD-penguin-dominated $B\to K\eta'$ decays depend on the form factors $F_0^{BK}(0)$ and $F_0^{B\eta'}(0)$,

$$F_0^{B\eta'}(0)=F_0^{B\pi}(0)\left[\frac{\sin\theta_8}{\sqrt{6}}+\frac{\cos\theta_0}{\sqrt{3}}\right]=0.10\pm0.02, \quad (12)$$

for $F_0^{B\pi}(0)=0.24\pm0.03$, $\theta_0=-9.1°$, and $\theta_8=-22.2°$ in the two-angle mixing scheme [29].

In Table II, we show the theoretical predictions for the branching ratios of seven studied decay modes. We use the form factors as given in Eqs. (10)–(12), and keep all other input parameters the same as those used in Ref. [14]. The branching ratios collected in Table II are the averages of the corresponding B and anti-B meson decay rates. The ratio $\delta\mathcal{B}$ describes the new physics correction on the decay rates and is defined as

$$\delta\mathcal{B}(B\to XY)=\frac{\mathcal{B}(B\to XY)^{III}-\mathcal{B}(B\to XY)^{SM}}{\mathcal{B}(B\to XY)^{SM}}. \quad (13)$$

From Table I and Table II, we find that (a) by using $F_0^{B\pi}(0)=0.24\pm0.03$, our predictions for $\mathcal{B}(B\to\pi^+\pi^-)$ in both the SM and model III are in agreement with the data. (b) For $B\to K\pi$ decays, the SM predictions seem smaller than the measurements. The results under the BBNS approach are similar [22]. For the $B\to K^0\pi^0$ decay, specifically, the SM prediction is about half of the measured decay rate, and the new physics enhancement is essential for the theoretical prediction to become consistent with the data. (c) By taking into account the uncertainties of those input parameters as given explicitly in Ref. [14], we find numerically that

$$\mathcal{B}(B\to K^+\eta')\approx\mathcal{B}(B\to K^0\eta')=\begin{cases}(10-40)\times10^{-6} & \text{in SM},\\ (17-57)\times10^{-6} & \text{in Model III},\end{cases} \quad (14)$$

where the uncertainties of those input parameters have been considered. It is easy to see that the SM predictions in the GF approach is about half of the measured value. In the BBNS approach, the theoretical predictions for the corresponding branching ratios are also much smaller than the experimental data [22]. The new physics enhancement can boost the theoretical predictions close to the lower part of the measured values, but still leaves a moderate space for additional contributions.

Since 1997, the unexpected large η' production has been widely discussed in the literature [10–15,20–22,28]. For the sake of completeness, we make a brief comment here on some typical interpretations in the framework of the SM.

Atwood and Soni [10] gave arguments for the need of enhanced $b\to sg^*$ decays followed by $g^*\to\eta' g$ via the QCD gluon anomaly. Taking a constant $gg\eta'$ vertex form

TABLE II. Branching ratios (in units of 10^{-6}) of seven $B\to PP$ decay modes in the SM and Model III by using $F_0^{B\pi}(0)=0.21$ (the first entries), 0.24 (the second entries), 0.27 (the third entries), and assuming $N_c^{eff}=2-\infty$, $\theta=0°$, and $M_{H^+}=200$ GeV. The last column lists the world average data.

	SM			Model III			$\delta\mathcal{B}$ [%]	Data
Decay mode	2	3	∞	2	3	∞	$N_c^{eff}=3$	
$B^0\to\pi^+\pi^-$	3.66	4.16	5.24	3.75	4.26	5.37	2.5	4.4 ± 0.9
	4.78	5.43	6.85	4.90	5.56	7.01	2.5	
	6.05	6.87	8.66	6.20	7.04	8.87	2.5	
$B^+\to K^+\pi^0$	4.93	5.53	6.85	7.12	8.01	9.98	44.9	12.1 ± 1.7
	6.44	7.22	8.95	9.29	10.5	13.0	44.9	
	8.15	9.14	11.3	11.8	13.2	16.5	44.9	
$B^0\to K^+\pi^-$	7.18	7.96	9.66	10.8	12.0	14.7	51.3	17.3 ± 1.3
	9.37	10.4	12.6	14.1	15.7	19.2	51.3	
	11.9	13.2	16.0	17.9	19.9	24.3	51.3	
$B^+\to K^0\pi^+$	8.12	9.46	12.5	12.1	14.1	18.4	48.9	17.4 ± 2.6
	10.6	12.4	16.3	15.9	18.4	24.1	48.9	
	13.4	15.6	20.6	20.1	23.3	30.5	48.9	
$B^0\to K^0\pi^0$	2.90	3.32	4.25	4.56	5.21	6.66	56.9	10.7 ± 2.7
	3.80	4.34	5.56	5.96	6.80	8.69	56.9	
	4.81	5.49	7.03	7.54	8.61	11.0	56.9	
$B^+\to K^+\eta'$	9.69	12.2	18.2	16.3	20.1	29.0	64.7	75 ± 7
	12.7	16.0	23.8	21.3	26.3	37.9	64.7	
	16.0	20.2	30.5	27.0	33.3	47.9	64.7	
$B^0\to K^0\eta'$	9.33	12.0	18.3	15.6	19.5	30.0	62.8	56 ± 10
	12.2	15.6	23.9	20.4	25.5	37.4	62.8	
	15.4	19.8	30.2	25.8	32.2	47.3	62.8	

factor $H(0,0,m^2_{\eta'})$, the observed large branching ratio $B\to\eta' X_s$ can be achieved. But as pointed out by Hou and Tseng [10] and Kagan and Petrov [15], if one considers the running of α_s, and the $m^2_{\eta'}/(q^2-m^2_{\eta'})$ dependence of the $gg\eta'$ coupling, the result presented in [10] will be reduced greatly.

Halperin and Zhitnitsky [13] argued that the dominant contribution to η' production is due to the Cabibbo favored $b\to(\bar{c}c)_1 s$ process followed by the transition $(\bar{c}c)_1\to\eta'$, i.e., the "intrinsic charm" component of η'. But according to the explicit calculations in Refs. [8,9], this mechanism cannot give a good explanation for the measured $B\to K\eta'$ decay rates.

Yuan and Chao [11] argued that the inclusive η' production in B decays may dominantly come from the Cabibbo favored $b\to(\bar{c}c)_8 s$ process where $\bar{c}c$ pair is in a color-octet configuration, and followed by the nonperturbative transition $(\bar{c}c)_8\to\eta' X$.

The authors of Ref. [12] proposed di-gluon fusion mechanism. It seems that this mechanism could enhance η' production. But because of our ignorance about the form factor of $g^*g^*\eta'$ vertex, there are large uncertainties in calculation.

Recently, M.Z. Yang and Y.D. Yang reconsidered the di-gluon mechanism and gave a calculation for $B\to\eta^{(\prime)}P$ in the BBNS approach. They computed the vertex $g^*g^*\eta'$ in PQCD, and found that the branching ratios of $B\to K\eta'$ are really enhanced and in agreement with the data. But, as pointed out in Ref. [22], the consistency of Yang's perturbative calculation is questionable due to the end point behavior.

From the above discussions, one can understand that it is still an open question for us to interpret the large branching ratios of $B\to K\eta'$ decays. Further investigations for various possible mechanisms are welcome.

Furthermore, because of the isospin symmetry between the u and d quarks, the decays $B\to K^+\eta'$ and $K^0\eta'$ should theoretically have similar branching ratios. The known new mechanisms in the SM or the new physics models also contribute to these two decay modes in very a similar way. The measurements of the BaBar and Belle Collaborations, however, show a clear difference between these two decay rates. We do not know how to interpret this difference. One may need something new to resolve this problem if it is confirmed by the forthcoming data.

In short, we reexamined the branching fractions of seven well measured $B\to PP$ decay modes in the SM and model III, and compared the theoretical predictions with the new data. Within the considered parameter space we found that: (a) the measurements of the branching ratios for $B\to\pi^+\pi^-$, $K^-\pi^+$, and $K^0\pi^+$ lead to a strong constraint on the form factor $F_0^{B\pi}(0)$: $F_0^{B\pi}(0)=0.24\pm0.03$ and (b) the new physics enhancements to the penguin-dominated $B\to K\pi$ and $K\eta'$ decays are significant in size, $\sim(40\text{–}65)\%$ with respect to the SM predictions, and play an important role in restoring the consistency between the data and the theory.

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