RECEIVED: June 6, 2019

REVISED: July 13, 2019

ACCEPTED: August 4, 2019

PUBLISHED: August 20, 2019

The direct CP violation in a general two Higgs doublet model

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ABSTRACT: In this paper, we study the CP violating processes in a general two-Higgs-doublet model (2HDM) with tree-level flavor changing neutral currents. In this model, sizable Yukawa couplings involving top and charm quarks are still allowed by the collider and flavor experiments, while the other couplings are strongly constrained experimentally. The sizable couplings, in general, have imaginary parts and could largely contribute to the CP violating observables concerned with the B and K mesons. In particular, the contribution may be so large that it affects the direct CP violating K meson decay, where the discrepancy between the experimental result and the Standard Model prediction is reported. We discuss how well the anomaly is resolved in the 2HDM, based on study of the other flavor observables. We also propose the way to test our 2HDM at the LHC.

KEYWORDS: Beyond Standard Model, CP violation, Higgs Physics, Kaon Physics

ARXIV EPRINT: [1905.11778](https://arxiv.org/abs/1905.11778)

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1 Introduction

The Higgs field is the only fundamental scalar field in the Standard Model (SM). It has a negative mass squared and spontaneously breaks the electroweak (EW) gauge symmetry, according to the non-vanishing vacuum expectation value (VEV). The VEV realizes the masses of the SM fermions and the gauge bosons that mediate the weak interaction. This scenario can explain almost all of the experimental results, so that we finally succeed in constructing the model that describes our nature below the EW scale. The next task is to find out why the SM is so successful in the experiments. For instance, we do not know the origin of the negative mass squared. The Higgs mass squared is unstable against the radiative correction and the quartic coupling of the Higgs fields might be driven to the negative value at the high energy by the radiative correction. The origin of the Yukawa couplings between the Higgs field and the SM fermions should be also elucidated. It is known that the CP phase in the SM is not enough to explain the baryon asymmetry in our universe, so that there would be new physics related to the Higgs mechanism, the Yukawa structure and the CP violation in our universe.

There are many possibilities of the new physics to solve the issues concerned with the Higgs field. Introducing extra symmetry, e.g. supersymmetry and global symmetry, could make our vacuum stable against the radiative correction. Extending or unifying the SM gauge symmetry may provide a natural answer to the question why the mass hierarchy of the down-type quarks is similar to the one of the charged leptons. Such a unified theory also reveals the origin of the SM gauge symmetry [1–3] and could lead the suppressed strong CP phase as well [4]. We note that extra Higgs fields, that contribute to the EW symmetry

breaking, are predicted at low energy in those scenarios, so that it would be interesting and important to study the phenomenology relevant to the extra Higgs doublets. In fact, there are many works on the extended SM with some extra Higgs fields, motivated by the unified theories.¹ Interestingly, the Higgs fields flavor-dependently couple to quarks and leptons in some effective models, so that we can test the unified theories indirectly using the physical observables in flavor-violating processes, even if the scale, where the extended gauge symmetry is broken, is very high [10].

From the phenomenological point of view, it is also very attractive to introduce extra Higgs fields to the SM. In such a extended SM, we find a rich phenomenology: Higgs physics at the collider experiment, flavor physics, dark matter physics and so on. In particular, it has been suggested that the simple extension may solve the anomalies in flavor physics, reported by the LHCb, Belle and BaBar collaborations [11–23]. The authors in refs. [24–36] have studied the lepton universality of the semileptonic B decay, $B \rightarrow D^{(*)} \ell \nu$ ($\ell = e, \mu, \tau$), where the excesses are reported in the Belle and the BaBar experiments especially, in a general two-Higgs-doublet model (2HDM). In refs. [37–40], the anomaly in $B \rightarrow K^* \mu^+ \mu^-$ is discussed and the consistency with the other flavor-violating processes is investigated. In such a general 2HDM, there are large tree-level flavor changing neutral currents (FCNCs) involving the two Higgs doublets, so that it is not easy to avoid the constraints from flavor physics. This general 2HDM can, however, relax the discrepancy between the experimental results and the SM predictions, in not only the observables mentioned above but also the anomalous magnetic moment of muon [40–43], controlling the tree-level FCNCs by hand.² There may be new frameworks behind such a phenomenological 2HDM, but, in any case, it will be very important to investigate the consistency with the latest experimental results and to survey the way to test the explanation. In fact, the direct search for the extra charged scalar at the LHC has begun to exclude the explanation of the anomaly concerned with the lepton universality of the semileptonic B decay [36]. There are many possible underlying theories of a general 2HDM, but it is certain that the 2HDM with FCNCs can be tested by not only flavor physics but also the direct search for new physics at the LHC even if additional scalars especially couple to fermions in the 3rd generation.

Based on the background and our idea, we investigate the possibility that the 2HDM can be tested in the CP violation of $K \rightarrow \pi\pi$. The observables concerned with the CP violation in the K decay have been established. The one measurement is referred to as the indirect CP violation and it is induced by the $K - \bar{K}$ mixing. The size of the mixing is given by ϵ . The other is referred to as the direct CP violation, and the size is given by ϵ' . The CP violations have been observed and the parameters are measured in the experiments with high accuracy: $(\epsilon'/\epsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$ [46–48]. On the other hand, it is not easy to obtain the SM predictions because of the strong interaction among the quarks in the hadrons. Recently, the lattice QCD calculation of the matrix elements that contribute to the hadronic K decay has been done by the RBC-UKQCD collaboration. Then, we can obtain the prediction for the direct CP violation. The SM prediction [49, 50] with

¹See, for instance, refs. [5–10].

²We do not assume the specific ansatz for the Yukawa structure [44, 45].

RBC-UKQCD lattice collaboration [51, 52] and the Dual QCD approach (DQCD) [53, 54] is given as

$$(\epsilon'/\epsilon)_{SM} = ((1 - 2) \pm 5) \times 10^{-4}. \quad (1.1)$$

There is a discrepancy between this result and the experimental result. The authors of [55], on the other hand, obtain $(\epsilon'/\epsilon)_{SM} = (15 \pm 7) \times 10^{-4}$ with ideas from the chiral perturbation theory, that agrees with the experimental value. It would be too early to conclude that the discrepancy is from new physics, but it would be important to summarize the new physics possibilities taking into consideration the consistency with the other observables in the new physics. We can actually find some new physics candidates [57–66]. In this paper, we investigate how well a general 2HDM can fit the experimental result of the direct CP violation. In a general 2HDM, there are many experimental constraints since sizable flavor-violating Yukawa couplings between the SM fermions and the extra scalars are allowed. The couplings that can be sizable from the phenomenological point of view are the ones involving charm and top quarks [67]. Then, we concentrate on the contribution of the sizable couplings to the direct CP violation, and discuss the consistency with not only the other flavor observables but also the measurements at the LHC. Compared to the previous work [68], we also take into account the constraint from the CP violation in B meson mixing and survey the heavy mass region and CP phases in the Yukawa coupling as well. We also discuss signals at the LHC to test our model.

In section 2, we introduce our general 2HDM. In section 3, we discuss our prediction for the direct CP violation and summarize the relevant experimental constraints. Based on the result in section 3.4, we propose the way to test our model at the LHC in section 3.5. Section 4 is devoted to the summary.

2 General two Higgs doublet model

First of all, we introduce our 2HDM with tree-level FCNCs. There are two Higgs fields charged under the EW symmetry, $SU(2)_L \times U(1)_Y$, and both fields generally contribute to the EW symmetry breaking. To see the mass eigenstates of the scalars clearly, let us define the two Higgs fields in the base where only one of the Higgs doublets develops the VEV. This base is known as a Higgs basis or Georgi basis [69, 70], and those two Higgs doublets in this base are written as

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+\phi_1+iG}{\sqrt{2}} \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{\phi_2+iA}{\sqrt{2}} \end{pmatrix}, \quad (2.1)$$

where G^+ and G are Nambu-Goldstone bosons, and H^+ and A are physical mass eigenstates called a charged Higgs boson and a CP-odd Higgs boson, respectively. v is the non-vanishing VEV and satisfies $v \simeq 246$ GeV. The CP-even neutral Higgs bosons, ϕ_1 and ϕ_2 , mix each other and lead mass eigenstates, h and H as follows:

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\beta\alpha} & \sin \theta_{\beta\alpha} \\ -\sin \theta_{\beta\alpha} & \cos \theta_{\beta\alpha} \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}. \quad (2.2)$$

Here $\theta_{\beta\alpha}$ is the mixing angle and we identify h as the scalar with 125 GeV mass and assume that H is heavier than h . Then, the coupling of h becomes identical to the SM one in the limit, $\sin\theta_{\beta\alpha} \rightarrow 1$.

In our model, we do not assign any symmetry to distinguish the two Higgs fields, so both Higgs doublets can couple to all fermions. Then, the Yukawa interactions between the mass eigenstates of the SM fermions and the Higgs fields are given by

$$\begin{aligned}\mathcal{L} = & -\bar{Q}_L^i H_1 y_d^i d_R^i - \bar{Q}_L^i H_2 \rho_d^{ij} d_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \widetilde{H}_1 y_u^j u_R^j - \bar{Q}_L^i (V^\dagger)^{ij} \widetilde{H}_2 \rho_u^{jk} u_R^k \\ & - \bar{L}_L^i H_1 y_e^i e_R^i - \bar{L}_L^i H_2 \rho_e^{ij} e_R^j.\end{aligned}\quad (2.3)$$

Here the indices, i, j and k , represent flavor. $\widetilde{H}_{1,2} = i\tau_2 H_2^*$ is defined using the Pauli matrix, τ_2 . The $SU(2)_L$ doublet quarks and leptons are defined as $Q = (V^\dagger u_L, d_L)^T$ and $L = (V_{\text{MNS}} \nu_L, e_L)^T$, using the CKM matrix, V , and the MNS matrix, V_{MNS} . Note that Yukawa couplings y_f^i are expressed by the fermion masses m_{fi} as $y_f^i = \sqrt{2}m_{fi}/v$ ($f = d, u, e$), that are the same as the SM Yukawa couplings. On the other hand, Yukawa couplings ρ_f are unknown general 3×3 complex matrices and sources of the Higgs-mediated flavor violation.

In mass eigenstates of Higgs bosons, the Yukawa interactions are given by

$$\begin{aligned}\mathcal{L} = & - \sum_{f=u,d,e} \sum_{\phi=h,H,A} y_{\phi ij}^f \bar{f}_{Li} \phi f_{Rj} + \text{h.c.} \\ & - \bar{\nu}_{Li} (V_{\text{MNS}}^\dagger \rho_e)^{ij} H^+ e_{Rj} - \bar{u}_i (V \rho_d P_R - \rho_u^\dagger V P_L)^{ij} H^+ d_j + \text{h.c.},\end{aligned}\quad (2.4)$$

where

$$\begin{aligned}y_{hij}^f &= \frac{m_f^i}{v} s_{\beta\alpha} \delta_{ij} + \frac{\rho_f^{ij}}{\sqrt{2}} c_{\beta\alpha}, & y_{Hij}^f &= \frac{m_f^i}{v} c_{\beta\alpha} \delta_{ij} - \frac{\rho_f^{ij}}{\sqrt{2}} s_{\beta\alpha}, \\ y_{Aij}^f &= \begin{cases} -\frac{i\rho_f^{ij}}{\sqrt{2}} & (\text{for } f = u), \\ \frac{i\rho_f^{ij}}{\sqrt{2}} & (\text{for } f = d, e), \end{cases}\end{aligned}\quad (2.5)$$

where $c_{\beta\alpha}$ and $s_{\beta\alpha}$ are short for $\cos\theta_{\beta\alpha}$ and $\sin\theta_{\beta\alpha}$ respectively. Note that the Yukawa interactions of h become SM-like when $c_{\beta\alpha}$ is small, but there are small flavor-violating interactions ρ_f^{ij} suppressed by $c_{\beta\alpha}$. On the other hand, the Yukawa interactions of heavy Higgs bosons (H , A , and H^+) are mainly controlled by the ρ_f couplings, so that they can be sizable as far as the experimental constraints are not so tight. We consider the case $c_{\beta\alpha} = 0$ for simplicity. It is known that the elements of ρ_u involving charm and top quarks can be sizable since they are not strongly constrained by the flavor physics. Besides, it is pointed out that the sizable ρ_u^{tc} can improve the discrepancies in the $b \rightarrow sll$ and $b \rightarrow cl\nu$ processes [32, 40]. Based on these previous works on the 2HDM, we consider the following simple textures of ρ_f from the phenomenological point of view:

$$\rho_u \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_u^{cc} & \rho_u^{ct} \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}, \quad |\rho_d^{ij}| \ll \mathcal{O}(0.1), \quad |\rho_e^{ij}| \ll \mathcal{O}(0.1). \quad (2.6)$$

The other elements of ρ_u are assumed to be less than $\mathcal{O}(0.01)$, so that the physics involving ρ_u^{ct} , ρ_u^{tc} , and ρ_u^{tt} is mainly discussed in this paper.

Before our study of the phenomenology, let us summarize the masses of the heavy scalars. They are evaluated as

$$m_H^2 \simeq m_A^2 + \lambda_5 v^2, \quad (2.7)$$

$$m_{H^\pm}^2 \simeq m_A^2 - \frac{\lambda_4 - \lambda_5}{2} v^2. \quad (2.8)$$

m_H , m_A and $m_{H^\pm}$ denote the masses of the heavy CP-even, CP-odd and charged Higgs scalars, and λ_4 and λ_5 are the dimensionless couplings in the Higgs potential: $V(H_i) = \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \dots$. In order to evade the stringent bound from the EW precision observables (EWPOs) [71], we assume that the scalar masses are degenerate: $m_H = m_A = m_{H^\pm}$.³

3 Phenomenology

In this section, we discuss phenomenology: flavor physics and the signals at the LHC. First, we study the direct CP violation in the K meson decay.

3.1 The direct CP violation in $K \rightarrow \pi\pi$

3.1.1 Model-independent analysis

The K decay, $K \rightarrow \pi\pi$, has been well studied motivated by the CP violation. There are two types of the CP violation: one is indirect and the other is direct. The latter contribution is described by the $|\Delta S| = 1$ effective Hamiltonian expressed as [50]

$$\mathcal{H}_{\text{eff}}^{|\Delta S|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1}^{10} Q_i(\mu) s_i(\mu) + h.c., \quad (3.1)$$

where the effective operators are defined as [72]

Current-current

$$Q_1 = (\bar{s}_\alpha u_\beta)_{V-A} (\bar{u}_\beta d_\alpha)_{V-A}, \quad Q_2 = (\bar{s}u)_{V-A} (\bar{u}d)_{V-A},$$

QCD penguin

$$\begin{aligned} Q_3 &= (\bar{s}d)_{V-A} \sum_q (\bar{q}q)_{V-A}, & Q_4 &= (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V-A}, \\ Q_5 &= (\bar{s}d)_{V-A} \sum_q (\bar{q}q)_{V+A}, & Q_6 &= (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V+A}, \end{aligned}$$

³We note that our result of the flavor physics does not change even if the mass difference is sizable, since the charged scalar only contributes to the flavor physics in our analysis.

EW penguin

$$\begin{aligned}
 Q_7 &= \frac{3}{2}(\bar{s}d)_{V-A} \sum_q e_q(\bar{q}q)_{V+A}, & Q_8 &= \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A} \sum_q e_q(\bar{q}_\beta q_\alpha)_{V+A}, \\
 Q_9 &= \frac{3}{2}(\bar{s}d)_{V-A} \sum_q e_q(\bar{q}q)_{V-A}, & Q_{10} &= \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A} \sum_q e_q(\bar{q}_\beta q_\alpha)_{V-A}.
 \end{aligned} \tag{3.2}$$

We note that $V \pm A = \gamma_\mu(1 \pm \gamma_5)$, α and β are color indices, and e_q is a electric charge of q quark.

The mass eigenstates of the neutral K mesons are given by the linear combination of K and $\bar{K}$. One is a long-lived meson named K_L and the other is named K_S that has a short lifetime. K_L (K_S) is close to the CP-odd (CP-even) state, so that K_L dominantly decays to three π while K_S decays to two π . The measurement concerned with the CP violation is given by surveying the decay of $K_L \rightarrow 2\pi$.

The two π in the final state of $K \rightarrow 2\pi$ consist of the isospin-zero ($I=0$) state and the isospin-two ($I=2$) state. Taking the ratio of the amplitude of $K_L \rightarrow (\pi\pi)_{I=0}$ to the one of $K_S \rightarrow (\pi\pi)_{I=0}$, ϵ_K that is measurement of the indirect CP violation is obtained.

The measurement of the direct CP violation is given by taking into account the decay to the $I=2$ state: $K_L \rightarrow (\pi\pi)_{I=2}$ and $K_S \rightarrow (\pi\pi)_{I=2}$. When we define the amplitudes of $K \rightarrow (\pi\pi)_{I=0,2}$ as $A_{0,2}$, the parameter, ϵ'/ϵ , to measure the direct CP violating decay is given by [74]

$$\frac{\epsilon'}{\epsilon} = -\frac{\omega}{\sqrt{2}|\epsilon_K|} \left[\frac{\text{Im}A_0}{\text{Re}A_0}(1 - \Omega_{\text{eff}}) - \frac{1}{a} \frac{\text{Im}A_2}{\text{Re}A_2} \right]. \tag{3.3}$$

In our study, we approximately evaluate ϵ'/ϵ as follows. The parameter relevant to the indirect CP violation is fixed at the well measured experimental value: $|\epsilon_K| = (2.228(11)) \times 10^{-3}$. a and Ω_{eff} describe the isospin breaking effects: $a = 1.017$ and $\Omega_{\text{eff}} = (14.8 \pm 8.0) \times 10^{-2}$ [49, 75]. ω is the ratio of $\text{Re}A_2$ to $\text{Re}A_0$ and fixed at $\omega = (4.53 \pm 0.02) \times 10^{-2}$ in our analysis. Following the analysis in ref. [50], we obtain the evaluation of ϵ'/ϵ as

$$\frac{\epsilon'}{\epsilon} = \left(\frac{\epsilon'}{\epsilon} \right)_{\text{SM}} + \left(\frac{\epsilon'}{\epsilon} \right)_{\text{H}}, \tag{3.4}$$

$$\left(\frac{\epsilon'}{\epsilon} \right)_{\text{H}} \simeq \frac{G_F \omega}{2|\epsilon_K| \text{Re}A_0} \times \left\{ \sum_{i,j} \langle Q_i(\mu) \rangle U_{ij}(\mu, \mu_{NP}) \text{Im } s_j(\mu_{NP}) \right\}. \tag{3.5}$$

$(\epsilon'/\epsilon)_{\text{SM}}$ and $(\epsilon'/\epsilon)_{\text{H}}$ denote the SM contribution and the extra Higgs contribution, respectively. U_{ij} takes into account the renormalization-group (RG) correction to s_i , which is a short-distance correction, and $\langle Q_i(\mu) \rangle$ corresponds to the hadronic matrix element. We use the result of the RBC-UKQCD lattice collaboration [51, 52] for the evaluation of the matrix elements and obtain the numerical values for $F_j(\mu_{NP}) = \langle Q_i(\mu) \rangle U_{ij}(\mu, \mu_{NP})$, based on ref. [50]. When we fix the new physics scale at $\mu_{NP} = 1\text{TeV}$, we find the numerical evaluation as

$$\begin{aligned}
 F_3(1\text{TeV}) &= 0.045, & F_4(1\text{TeV}) &= -0.193, & F_5(1\text{TeV}) &= 0.081, & F_6(1\text{TeV}) &= 0.305, \\
 F_7(1\text{TeV}) &= 26.16, & F_8(1\text{TeV}) &= 88.61, & F_9(1\text{TeV}) &= 0.117, & F_{10}(1\text{TeV}) &= -0.084.
 \end{aligned} \tag{3.6}$$

We use these values to study the new physics effect to the direct CP violation.

Figure 1. The one-loop penguin diagrams relevant to ϵ'/ϵ .

3.1.2 Prediction of the general 2HDM for ϵ'/ϵ

We study the contribution of the heavy charged scalar to ϵ'/ϵ . We note that the diagram involving neutral heavy scalars is suppressed as far as ρ_d is vanishing. If the off-diagonal elements of ρ_d are sizable, we suffer from the tree-level FCNCs so that we consider the case that the off-diagonal elements of ρ_u involving heavy quarks are only sizable, assuming the Yukawa alignment as in eq. (2.6). The one-loop penguin diagrams involving charged heavy scalar are shown in figure 1. These diagrams dominantly contributes to ϵ'/ϵ , while the box diagram is subdominant numerically and can be neglected.⁴ Then the coefficients in eq. (3.1) are given by the photon-penguin, Z -penguin, and gluon-penguin diagrams that are defined as s_i^γ , s_i^Z and s_i^g , respectively:

$$s_i = s_i^\gamma + s_i^Z + s_i^g. \quad (3.7)$$

The each contribution is described as

$$s_7^\gamma = s_9^\gamma = -\frac{\alpha}{6\pi} C_\gamma, \quad (3.8)$$

$$s_3^g = s_5^g = \frac{\alpha_s}{24\pi} C_g, \quad (3.9)$$

$$s_4^g = s_6^g = -\frac{\alpha_s}{8\pi} C_g, \quad (3.10)$$

$$s_3^Z = \frac{1}{48\pi^2} C_Z, \quad (3.11)$$

$$s_7^Z = \frac{s_w^2}{12\pi^2} C_Z, \quad (3.12)$$

$$s_9^Z = -\frac{1 - s_w^2}{12\pi^2} C_Z, \quad (3.13)$$

⁴The box diagram is induced by the charged scalar and W boson exchanging, but it is suppressed by up-type quark masses and the CKM matrix.

where s_w is short for the sine of the Weinberg angle and the functions in the right-hand side are defined with $x_i = m_{u_i}^2/m_H^2$ as

$$C_\gamma = \frac{1}{2\sqrt{2}G_F m_{H^+}^2} \sum_i (V^\dagger \rho_u)^{si} (\rho_u^\dagger V)^{id} \left[\frac{2}{3} G_{\gamma 1}(x_i) + G_{\gamma 2}(x_i) \right], \quad (3.14)$$

$$C_g = \frac{1}{2\sqrt{2}G_F m_{H^+}^2} \sum_i (V^\dagger \rho_u)^{si} (\rho_u^\dagger V)^{id} [G_{\gamma 1}(x_i)], \quad (3.15)$$

$$C_Z = \sum_i (V^\dagger \rho_u)^{si} (\rho_u^\dagger V)^{id} G_Z(x_i). \quad (3.16)$$

Here the functions are defined as

$$G_{\gamma 1}(x) = -\frac{16 - 45x + 36x^2 - 7x^3 + 6(2 - 3x) \log x}{36(1 - x)^4}, \quad (3.17)$$

$$G_{\gamma 2}(x) = -\frac{2 - 9x + 18x^2 - 11x^3 + 6x^3 \log x}{36(1 - x)^4}, \quad (3.18)$$

$$G_Z(x) = \frac{x(1 - x + \log x)}{2(1 - x)^2}. \quad (3.19)$$

We note that there are dipole operators that contribute to the $\Delta S = 1$ processes, but they are very much suppressed by our ρ_u alignment. Therefore, we focus on the penguin-diagram contribution discussed above in our analysis.

3.2 The other constraints from flavor physics

In this subsection, we summarize the constraints from other flavor-violating processes in our model. The sizable Yukawa couplings between the heavy quarks, c and t , and the heavy (charged) scalars significantly contribute to $b \rightarrow s\gamma$, $B_{d(s)} - \overline{B}_{d(s)}$ mixing and $|\epsilon_K|$. The constraints on our model from those observables have been studied by the authors in refs. [10, 40, 68, 76]. In addition to the results of the previous works, we take into account the constraint from the CP violation in the $B_{d(s)} - \overline{B}_{d(s)}$ mixing. When we define the relevant parameters as

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\text{eff}}^{\text{full}} | \overline{B}_q \rangle}{\langle B_q | H_{\text{eff}}^{\text{SM}} | \overline{B}_q \rangle}, \quad (3.20)$$

the parameters to fit the experimental results are introduced by the UTfit collaboration [77]:⁵

$$C_{B_d} = 1.05 \pm 0.11, \quad \phi_{B_d} = -2.0 \pm 1.7, \quad (3.21)$$

$$C_{B_s} = 1.110 \pm 0.090. \quad (3.22)$$

Using those values, we draw the exclusion lines allowing the 95% CL interval from the central values. ϕ_{B_d} is referred to as a golden mode and can be measured precisely, while ϕ_{B_s} is not measured as accurately as ϕ_{B_d} [79]. Then, we do not include ϕ_{B_s} in our analysis.

Besides, we consider the constraint from ϵ_K . We require that the prediction is within the SM prediction with 2σ errors of $\eta_{1,2,3}$. We also checked that the constraints from $b \rightarrow s\gamma$ is less stringent. In addition, we found that the bound from $BR(K_L \rightarrow \mu\bar{\mu})$ is less stringent [80, 81].

⁵See ref. [78] for update.

3.3 Predictions for $BR(K \rightarrow \pi\nu\bar{\nu})$ and $BR(B_s \rightarrow \mu\bar{\mu})$

Before showing our numerical results, let us discuss our predictions for $BR(K \rightarrow \pi\nu\bar{\nu})$ and $BR(B_s \rightarrow \mu\bar{\mu})$. Those observables are expected to be measured with high accuracy in the near future, so that they may play a crucial role in testing our model.

In the rare K meson decay, there are two processes: $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\nu\bar{\nu}$. They are investigated in the NA62 and KOTO experiments, respectively [82], so that we look into some explicit correlations between $BR(K \rightarrow \pi\nu\bar{\nu})$ and the direct CP violation in our model. The $K \rightarrow \pi\nu\bar{\nu}$ decay is given by the following four-fermi operator [83],

$$\mathcal{H}_{\text{eff}}^\nu = \frac{G_F\alpha}{2\sqrt{2}\pi s_w^2} V_{ts}^* V_{td} X (\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A} + h.c.. \quad (3.23)$$

X includes both the SM and the 2HDM contributions. In our general 2HDM, the following operator is effectively generated by the penguin diagram involving the charged scalar:

$$\Delta\mathcal{H}_{\text{eff}}^\nu = -\frac{G_F}{2\sqrt{2}} \frac{C_Z}{16\pi^2} (\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A} + h.c., \quad (3.24)$$

where C_Z is given in eq. (25). Then, the contribution of the 2HDM to X is described as

$$X = X_{SM} + \Delta X, \quad (3.25)$$

$$\Delta X = -\frac{s_w^2 C_Z}{16\pi\alpha V_{td} V_{ts}^*}, \quad (3.26)$$

where X_{SM} denotes the SM contribution. $BR(K \rightarrow \pi\nu\bar{\nu})$ is calculated with X as

$$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = k_+(1 + \Delta_{EM}) \left[\left(\frac{\text{Im}[\lambda_t X]}{\lambda^5} \right)^2 + \left(\frac{\text{Re}[\lambda_c]}{\lambda} P_c + \frac{\text{Re}[\lambda_t X]}{\lambda^5} \right)^2 \right], \quad (3.27)$$

$$BR(K_L \rightarrow \pi^0\nu\bar{\nu}) = k_L \left(\frac{\text{Im}[\lambda_t X]}{\lambda^5} \right)^2. \quad (3.28)$$

To evaluate our prediction, we use $k_+ = (5.173 \pm 0.025) \times 10^{-11} \left(\frac{\lambda}{0.225} \right)^8$, $k_L = (2.231 \pm 0.013) \times 10^{-10} \left(\frac{\lambda}{0.225} \right)^8$, $P_c = 0.404 \pm 0.024$, $\Delta_{EM} = -0.003$, $X_{SM} = 1.481 \pm 0.009$, $m_c(m_c) = 1.275 \text{ GeV}$ and $m_t(m_t) = 160 \text{ GeV}$ [84].

The rare leptonic B_s decay, $B_s \rightarrow \mu\bar{\mu}$, is one of the main targets of the LHC experiment. $BR(B_s \rightarrow \mu\bar{\mu})$ is measured as $BR(B_s \rightarrow \mu\bar{\mu})_{\text{exp}} = (2.7 \pm 0.6) \times 10^{-9}$ [79], and can be expected to be measured with high accuracy in the future. In our model, the Z-penguin diagram contributes to the decay as,

$$BR(B_s \rightarrow \mu\bar{\mu}) = BR(B_s \rightarrow \mu\bar{\mu})_{SM} \left| 1 + \frac{C_{10}^{G2HDM}}{C_{10}^{SM}} \right|^2. \quad (3.29)$$

We note that $BR(B_s \rightarrow \mu\bar{\mu})_{SM}$ is 3.32×10^{-9} in our study. Following ref. [32], we calculate our prediction for this leptonic B_s decay.

Figure 2. The prediction for $\epsilon'/\epsilon_H \times 10^4$ is expressed in dashed black lines in the case (I). In each figure, the exclusion lines explained in the text are shown: $|\epsilon_K|$ (magenta), C_{B_d} (cyan), C_{B_s} (light green) and ϕ_{B_d} (blue).

3.4 Numerical result

Based on the above discussion, we numerically analyze our model. We mainly focus on the contribution of ρ_u^{tt} , ρ_u^{tc} , ρ_u^{ct} and ρ_u^{cc} that are the Yukawa couplings involving heavy quarks. In particular, top and charm quarks only appear in the one-loop diagram relevant to B and K physics: the diagram induced by ρ_u^{ct} and ρ_u^{tt} involves top quarks in the loop, while the diagram induced by ρ_u^{tc} and ρ_u^{cc} involves charm quarks. In order to study the each contribution quantitatively, we consider the following two cases:

$$\begin{aligned} \text{(I)} \quad & |\rho_u^{tt}|, |\rho_u^{ct}| \gg |\rho_u^{tc}|, |\rho_u^{cc}|, \\ \text{(II)} \quad & |\rho_u^{tt}|, |\rho_u^{ct}| \ll |\rho_u^{tc}|, |\rho_u^{cc}|. \end{aligned}$$

In the case (I) (case (II)), top quark (charm quark) runs in the penguin diagram in figure 1.

First, we discuss the case (I). In this case, the dominant contribution to the direct CP violation comes from the one-loop diagram with top quark that is linear to $\rho_u^{tt} \times \rho_u^{ct}$. The relevant parameters are m_H , $|\rho_u^{ct}|$, $|\rho_u^{tt}|$ and a relative phase between ρ_u^{ct} and ρ_u^{tt} . In our presentation, we set ρ_u^{tt} to unit and look into the ρ_u^{ct} dependence on the flavor physics.

Figure 2 shows the prediction for $(\epsilon'/\epsilon)_H$ in the case (I). The prediction is depicted by the dashed black lines with the number that corresponds to $(\epsilon'/\epsilon)_H \times 10^4$. In the left panel, the vertical and horizontal axes denote the phase and the absolute value of ρ_u^{ct} respectively. We define the phase as $\rho_u^{ct} = |\rho_u^{ct}|e^{i\delta_{ct}}$ and charged scalar mass, m_H , is fixed at 1 TeV. In the right panel, the vertical and horizontal axes denote the heavy Higgs mass and the absolute value of ρ_u^{ct} respectively. The phase is fixed at $\delta_{ct} = 0.05\pi$ that drastically relaxes the bound from the B meson mixing. In the each panel, the exclusion lines of $|\epsilon_K|$, C_{B_d} , C_{B_s} and ϕ_{B_d} are drawn by the solid lines colored in magenta, cyan, light green and blue,

respectively. The shaded region is excluded by those constraints. We see that δ_{ct} is strongly constrained by the B meson mixing and the magnitude of δ_{ct} should be less than 0.2π . Now, we fix ρ_u^{tt} at unit, so that our prediction is deviated from the SM prediction even if ρ_u^{ct} is vanishing. Then, we find the allowed region for ρ_u^{ct} around 0.1. The right panel shows the m_H dependence on the flavor observables. If m_H is heavier than 1 TeV, $|\rho_u^{ct}|$ can be large. On the other hand, the constraint from the $B_{d(s)} - \overline{B_{d(s)}}$ mixing becomes severe if our charged scalar is light, as shown in the right panel of figure 2. If we consider the charged scalar whose mass is less than 800 GeV, the enhancement of ϵ'/ϵ becomes less than the one in the heavy scalar region in figure 2. Such a very light charged scalar case is actually discussed in ref. [68], but we find that the region to enhance ϵ'/ϵ is excluded by ϕ_{B_d} that is not analyzed in ref. [68].

Finally, we find that those observables strongly limit the enhancement of (ϵ'/ϵ) . In addition to the CKM matrix, there is another source of the CP violation, that is the phase of ρ_u^{ct} . The phase should be tuned to be consistent with especially ϕ_{B_d} . Even if the phase is tuned, the enhancement of ϵ'/ϵ is at most 3×10^4 . The SM prediction has still ambiguity, so that we could not exclude our model but we conclude that our model cannot reach the 1σ region of the experimental result if we use the SM prediction in eq. (1.1). Note that our predictions of $BR(K \rightarrow \pi\nu\bar{\nu})$ and $BR(B_s \rightarrow \mu\bar{\mu})$ are deviated from the SM prediction in this case. Figure 3 summarizes our predictions on the same plane with the same dashed black lines as in the right panel of figure 2. The green solid lines correspond to our predictions for $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) \times 10^{11}$. The orange dotted lines denote our predictions for $BR(K_L \rightarrow \pi^0\nu\bar{\nu}) \times 10^{11}$. The blue dashed lines are for $BR(B_s \rightarrow \mu\bar{\mu}) \times 10^9$. Note that the SM predictions using our input parameters are $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) \times 10^{11} = 9.0$, $BR(K_L \rightarrow \pi^0\nu\bar{\nu}) \times 10^{11} = 3.1$ and $BR(B_s \rightarrow \mu\bar{\mu}) \times 10^9 = 3.3$. They are consistent with the results in refs. [85, 86] within 1σ error. The shaded region is excluded by the constraints. We find some correlations among the observables. We see that $BR(K_L \rightarrow \pi^0\nu\bar{\nu})$ and $BR(B_s \rightarrow \mu\bar{\mu})$ are suppressed if $(\epsilon'/\epsilon)_H$ is large, while $BR(K^- \rightarrow \pi^-\nu\bar{\nu})$ is enhanced. The deviation reaches about 10 % of the SM prediction when the enhancement of ϵ'/ϵ is maximum.

Next, we consider the case (II). In this case, the loop correction involving the charged scalar and charm quark is dominant and it is linear to $\rho_u^{tc} \times \rho_u^{cc}$. The relevant parameters are m_H , $|\rho_u^{tc}|$, $|\rho_u^{cc}|$ and a relative phase between ρ_u^{tc} and ρ_u^{cc} . Now we take ρ_u^{tc} to be real and ρ_u^{cc} to be complex without a loss of generality. This loop is enhanced by $\log(m_c/m_H)$ in eq. (26), but the loop correction is small unless the charged scalar is light. If $m_H < m_t$, ρ_u^{tc} generates a flavor changing top decay as $t \rightarrow Hc$ and $t \rightarrow Ac$, so that we fix m_H at $m_H = 200$ GeV. We plot our prediction of $(\epsilon'/\epsilon)_H \times 10^4$ with dashed black lines in figure 4. We fixed $\rho_u^{tc} = 1$ to draw the figure. The gray shaded region is excluded by the various constraints as discussed in the previous section. The vertical and horizontal axes correspond to the phase and the absolute value of ρ_u^{cc} . We define the phase as $\rho_u^{cc} = |\rho_u^{cc}|e^{i\delta_{cc}}$. In this case, δ_{cc} should be smaller than 0.2π and the enhancement of ϵ'/ϵ can be 3×10^4 . On the other hand, the dominant contribution to ϵ'/ϵ is from the photon penguin diagram in figure 1 in the case (II), while the contribution to $BR(K \rightarrow \pi\nu\bar{\nu})$ and $BR(B_s \rightarrow \mu\bar{\mu})$ comes from the Z-penguin diagram that is subdominant in $(\epsilon'/\epsilon)_H$. Thus the deviation from the SM predictions in $BR(K \rightarrow \pi\nu\bar{\nu})$ and $BR(B_s \rightarrow \mu\bar{\mu})$ is less than 1% in the case (II).

Figure 3. Predictions for $BR(K^- \rightarrow \pi^- \nu \bar{\nu})$, $BR(K^0 \rightarrow \pi^0 \nu \bar{\nu})$ and $BR(B_s \rightarrow \mu \bar{\mu})$. The green solid lines depict our predictions for $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \times 10^{11}$. The orange solid lines express our predictions for $BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) \times 10^{11}$. The blue dashed lines are for $BR(B_s \rightarrow \mu \bar{\mu}) \times 10^9$. The black dashed lines are the same as in the right panel in figure 2.

Figure 4. The prediction for $\epsilon'/\epsilon_H \times 10^4$ is expressed in the case (II) with the δ_{cc} and $|\rho_u^{cc}|$ plane setting $\rho_u^{tc} = 1$ and $m_H = 200$ GeV. The white region is allowed by constraints. The color code for the prediction and constraints is the same as in the left of figure 2.

Figure 5. Our prediction for 4 top in the final state at the LHC in the case (I). The vertical and horizontal axes denote the heavy Higgs mass and ρ_u^{tt} . The solid black lines are our prediction of the cross section including the SM contribution for the signal with $\sqrt{s} = 13$ TeV. The numbers attached to the black lines indicate the cross sections of $pp \rightarrow t\bar{t}t\bar{t}$ in fb. A magenta dashed line expresses the upper limit from the $t\bar{t}$ resonance search reported by the ATLAS. A purple (orange) dotted line is obtained from the constraint with the assumption, $\Gamma_{Z'} = 0.1(0.01)m_{Z'}$ by the CMS. See the main text for the further description.

3.5 The collider constraint and prediction

Before closing this paper, we propose processes to test our scenario at the LHC in both cases.

In the case (I), ρ_u^{tt} is large, so that we expect some signal associated with top quarks. There are several channel to test our model; for instance, $4t$ and $2t$ in the final states. We calculate our signal using Madgraph5 [87] with $\sqrt{s} = 13$ TeV. In this case, ρ_u^{tt} is much larger than ρ_u^{ct} so that we assume $BR(H \rightarrow t\bar{t}) = BR(A \rightarrow t\bar{t}) \sim 1$ for simplicity.

We plot our prediction for the $4t$ signal in figure 5. The solid black lines are our prediction of the cross section including the SM contribution for the signal with 4 top in the final state. The numbers attached to the black lines indicate the cross sections of $pp \rightarrow t\bar{t}t\bar{t}$ in fb. The SM prediction is 9.2 fb. Currently a mild excess is reported by the ATLAS collaboration as $\mu_C = 3.1^{+1.3}_{-1.2}$ [88], where μ_C is defined by the ratio of cross sections as $\mu_C = \sigma_{exp}/\sigma_{SM}$. The CMS collaboration also announces the result as $\mu_C = 1.8^{+1.5}_{-1.3}$ [89].

We draw the bound from the $t\bar{t}$ resonance search. We apply the constraint for a heavy vector boson, namely Z' , assuming $m_A = m_H$. In figure 5 a magenta dashed line expresses the upper limit from the $t\bar{t}$ resonance search reported by the ATLAS at 95% CL. [90]. Note that the bound from a charged Higgs search: $H^- \rightarrow \bar{t}b$ search [91] is weaker than the one in ref. [90]. There is also a result on the $t\bar{t}$ heavy resonance search reported by the CMS collaboration [92]. A purple dotted line is obtained from the constraint with the assumption, $\Gamma_{Z'} = 0.1m_{Z'}$ at 95% CL. We also plot the orange dotted line that is from the constraint

with the assumption, $\Gamma_{Z'} = 0.01m_{Z'}$ at 95% CL. Note that when particles in decay of heavy scalars H and A is light enough in comparison with them, the decay width scalar is given as $\Gamma_{A(H)} \sim 0.06|\rho_u^{tt}|^2 m_{A(H)}$. Therefore, applying the bound of the orange line seems to be too aggressive. In figure 5, we see that μ_C could be about 2, and both 4 top search and $t\bar{t}$ resonance search with Run 2 full data may test our scenario e.g. $m_H = 1000\text{GeV}$ and $\rho_u^{tt} \simeq 1$.

The collider physics of the case (II) with sizable ρ_u^{tc} and ρ_u^{cc} needs a discussion. In this scenario, ρ_u^{tc} is much larger than ρ_u^{cc} . The analysis in ref. [40] can be applied to our model. The flavor inclusive dijet search result to look for the charged scalar that decays dominantly to bc is available for more than 450 GeV [93]. An additional b tagged jet can be helpful to look into the lighter mass resonance in the future. If CP even and odd scalars are not degenerated, a large ρ_u^{tc} would generate the same-sign top signal [94].

4 Summary

We have studied the phenomenology in a general 2HDM with tree-level FCNCs. In the bottom-up approach, there are many free parameters in the Yukawa couplings between the heavy scalars and the SM fermions. The parameters may be fixed by the underlying theory, but there are actually many candidates for the extended SM behind this kind of model. Then, it would be important to survey the experimental constraints on the each coupling in this model as well, not specifying the underlying theory.

Most of the parameters are strongly constrained by flavor physics. The only Yukawa couplings that can be sizable would be the ones involving heavy quarks: charm and top quarks. The bounds are not relatively tight, so that we can expect that the signals caused by the couplings and the heavy scalar are observed in the LHC and the flavor experiments. In this paper, we have focused on the physics caused by the couplings between the heavy scalar and heavy quarks.

One of the flavor observables attracting attention recently is ϵ'/ϵ related to the direct CP violation of $K \rightarrow \pi\pi$. Both of the direct and indirect CP violations in the $K \rightarrow \pi\pi$ process are experimentally measured with high accuracy. The SM prediction, on the other hand, suffers from the large theoretical uncertainty. Recently, the calculation of the hadronic process has been done by the RBC-UKQCD lattice collaboration and we find the discrepancy between the SM prediction and the experimental result. Motivated by the excess, some new physics possibilities have been discussed, and one good candidate is the extended SM with extra Higgs doublets that have large FCNCs involving heavy quarks [68, 76, 95]. We find that the couplings can enhance the direct CP violation, but the constraint from the CP violation in the B decay is so strong that the enhancement is at most $\epsilon'/\epsilon_H \approx 3 \times 10^{-4}$. This can explain the discrepancy of the direct CP violation at the 2σ level. We have considered the two cases: the top loop is dominant in the case (I) and the charm loop is dominant in the case (II). The favored mass region for the heavy scalar is different because of the quark mass dependence on loop functions. m_H should be about 1 TeV in the case (I), while m_H should be about 200 GeV in the case (II). In refs. [68, 76], the authors concluded that a general 2HDM can enhance the ϵ'/ϵ by considering the light charged scalar and the chromomagnetic operator with the large mass

difference between m_{H^-} and $m_H = m_A$. In our result, the light scalar region is excluded by the constraint from the CP violation of the B decay. We also confirm that the contribution of the chromomagnetic operator is very small in the allowed region. We also note that the parameter set to enhance ϵ'/ϵ , that is introduced in refs. [68, 76], is excluded in our analysis, taking into account the electroweak precision observables as well.

Finally, we have discussed how to test our scenario at the LHC. Our setup predicts the 4 top signal at the LHC, so that we have estimated the cross section of $pp \rightarrow t\bar{t}t\bar{t}$. The enhancement of the direct CP requires ρ_u^{tt} to be $\mathcal{O}(1)$ so we may be able to test our model if m_H is about 1 TeV, according to figure 5.

Acknowledgments

We would like to acknowledge Kei Yamamoto for a collaboration at the early stage. The work of S. I. is supported by Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Toyoaki scholarship foundation and the Japan Society for the Promotion of Science (JSPS) Research Fellowships for Young Scientists, No. 19J10980. The work of Y. O. is supported by Grant-in-Aid for Scientific research from the Ministry of Education, Science, Sports, and Culture (MEXT), Japan, No. 19H04614, No. 19H05101 and No. 19K03867.

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