Implications of CP violating 2HDM in B physics

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Abstract. The charged fermion mass matrices are invariant under $U(1)^3$ symmetry linked to the fermion number transformation. Under the condition that the definition of this symmetry in arbitrary weak basis does not depend upon Higgs parameters such as ratio of vacuum expectation values, a class of two Higgs doublet models (2HDM) can be identified in which tree level flavor changing neutral currents normally present in 2HDM are absent. However unlike the type I or type II Higgs doublet models, the charged Higgs couplings in these models contain additional flavor dependent CP violating phases. These phases can account for the recent hints of the beyond standard model CP violation in the $B_d$ and $B_s$ mixing. In particular, there is a range of parameters in which new phases do not contribute to the $K$ meson CP violation but give identical new physics phases in the $B_d$ and $B_s$ meson mixing.

1. Introduction

Cabibbo Kobayashi Maskawa (CKM) mechanism of CP violation has been established as the dominant source of CP violation by observations at B-factories and Tevatron. These experiments have also shown some hints of physics beyond standard model [1–5]. One of them is CP violating observable $S_{J/\psi K_s}$ of $B^0_d - \bar{B}^0_d$ mixing which is measured in time dependent CP asymmetry of $B^0_d \to J/\psi K_s$ by BABAR experiment at the Stanford linear accelerator center (SLAC) and by Belle experiment at KEK [6, 7]. Value of $S_{J/\psi K_s}$ obtained from fit using $\epsilon_K, \Delta m_q, |V_{cb}|, \alpha, \gamma$ as inputs shows deviations from experimentally determined value at about 2σ [8]. Another hint for new physics comes from determination of CP violating phase $\phi_s$ of $B^0_s - \bar{B}^0_s$ mixing. $\phi_s$ is determined from analysis of time dependent angular distribution of decay products in flavor tagged decay $B^0_s \to J/\psi \phi$ by CDF and D0 experiments at Fermilab Tevatron collider through decay chain $B^0_s \to J/\psi \phi, J/\psi \to \mu^+\mu^-, \phi \to K^+K^-$ [9, 10]. SM predicted value for $\phi_s$ is much small compared to the experimentally determined value. UTfit group has combined all the available experimental constraints on $B_s$ mixing and performed a model independent analysis of NP contribution to $B^0_s - \bar{B}^0_s$ mixing. From this analysis UTfit group has concluded that phase $\phi_s$ of $B^0_s - \bar{B}^0_s$ mixing determined from their analysis deviates from the SM prediction by about 3σ [1, 11]. A similar analysis performed by CKMfitter group shows that the deviation from SM prediction is about 2.5σ [12].

Inconsistencies between SM prediction and the experimental determination in $B^0_d - \bar{B}^0_d$ and $B^0_s - \bar{B}^0_s$ mixing discussed here can be resolved if there is some new physics beyond SM which can give extra contribution to above mentioned CP violating observables. Here we explore the possibility of explaining these deviations in two Higgs doublet model (2HDM). The most general 2HDM generates large flavor changing neutral currents (FCNC) for moderate Higgs mass. To avoid FCNC an additional discrete symmetry is imposed which results in type-I or type II
2HDM. In these models the charged Higgs couplings do not provide any additional source of CP violation. Therefore they cannot explain possibly large CP violating phases in the neutral $B$ mixings if confirmed in future. Hence we need to go beyond the type-I and type-II 2HDM to explain new CP violating phases. One way is to restrict the structure of FCNC couplings using flavor symmetries rather than eliminating them altogether [13–17]. This leads to models with suppressed FCNC and additional phases whose phenomenological consequences have been studied in [18–20]. A different approach based on shared flavour symmetry is given in [21]. An interesting possibility is to have models without tree level FCNC but containing additional phases in the charged Higgs couplings. Here we wish to discuss such models motivated by the studies of flavor symmetries of mass matrix in 2HDM.

Flavor symmetries are often applied to restrict the structure of Yukawa couplings all of which cannot be directly determined from experiments. The relation between the structures of mass matrices and symmetries was studied in [22–25]. It was shown by Lam that a symmetry can always be found under which an arbitrary neutrino mass matrix $M_\nu$ remains invariant [25]. Grimus, Lavoura and Ludl [22] showed that any Hermitian mass matrix $M_fM_f^\dagger$ obtained form a fermion mass matrix $M_f$ always possesses a symmetry $G_f = U(1) \times U(1) \times U(1)$ and the corresponding $G$ for the mass matrix of the Majorana neutrinos is $Z_2 \times Z_2 \times Z_2$. Here we generalize this study to the non hermitian mass matrices in 2HDM.

In the next section we will describe general 2HDM and the structure of FCNC and charged higgs interaction. Study of the symmetries of mass matrices in 2HDM and their consequences on FCNC and charged higgs interaction will also be given. In section 3, phenomenology of this model in neutral mesons mixing will be given. In section 4, we will obtain constraints on NP parameters in present case from the numerical analysis of $B_s^0 - \bar{B}_s^0$ mixing and charge asymmetry of like sign dimuon events. Last section will present a summary.

2. Mass matrix symmetries and 2HDM

Yukawa couplings for 2HDM are given as

$$-\mathcal{L}_Y = \bar{Q}_L^i (\Gamma_{1q} \phi_1 + \Gamma_{2q} \phi_2) d_R^i + \bar{Q}_L^i (\Gamma_{1\bar{q}} \tilde{\phi}_1 + \Gamma_{2\bar{q}} \tilde{\phi}_2) u_R^i + \text{H.c.} , \quad (1)$$

where $\Gamma_{iq}$ ($i = 1, 2; q = u, d$) are matrices in the generation space. $\phi_{1,2}$ denote Higgs doublets and $\tilde{\phi}_i = i \gamma_2 \phi_i^*$. $Q^i_L$ refer to three generations of doublet quarks and primed fields in the above equation refer to various quark fields in the weak basis. The neutral component of a specific linear combination of the Higgs fields $\phi \equiv \cos \beta \phi_1 + \sin \beta e^{-i\theta} \phi_2$ is responsible for the mass generation

$$M_q = v \cos \beta \Gamma_{1q} + \sin \beta \Gamma_{2q} e^{i\theta} = V_{qL} D_q V_{qR}^\dagger , \quad (2)$$

where $\langle \phi_1^0 \rangle = v \cos \beta$; $\langle \phi_2^0 \rangle = v \sin \beta e^{-i\theta}$ with $v \sim 174$ GeV and $\theta_d = -\theta_u = \theta$. The matrices $V_{qL,R}$ diagonalize $M_q$. We define the matrices $S_{qL,R}$ as

$$S_{qL,R} = V_{qL,R} P_q V_{qL,R}^\dagger , \quad (3)$$

It can be seen that the mass matrices have invariance given by following equation.

$$S_{qL}^\dagger M_q S_{qR} = M_q . \quad (4)$$

Where $P_q = \text{diag.}(e^{i\alpha_1}, e^{i\alpha_2}, e^{i\alpha_3})$. Here $S_{qL,R}$ define two different $U(1) \times U(1) \times U(1)$ symmetries $G_u$ and $G_d$ for up and down quarks. We put a mild requirement on possible $S_{qL,R}$ namely that the form of $S_{qL,R}$ be independent of the parameters $\tan \beta$ and $\theta$ which are determined entirely in the Higgs sector. With this requirement and from eq.(2) of mass matrices, we get

$$S_{qL}^\dagger \Gamma_{iq} S_{qR} = \Gamma_{iq} \quad i = 1, 2 . \quad (5)$$
This shows that individual Yukawa couplings should also respect the symmetry. Let us parametrize $\Gamma_{iq}$ as

$$\Gamma_{iq} \equiv V_{qL} \tilde{\Gamma}_{iq} V_{qR}^\dagger \ .$$  

(6)

Eqs. (3,5) then imply

$$P_{q}^\dagger \tilde{\Gamma}_{iq} P_{q} = \tilde{\Gamma}_{iq} \ .$$  

(7)

If $G_u, G_d$ refer to the full $U(1) \times U(1) \times U(1)$ symmetry with totally independent $\alpha_{iq}$ then the only non-trivial solution of eq.(7) is a diagonal $\tilde{\Gamma}_{iq}$ for every $i$ and $q$. Yukawa couplings are then given as

$$\Gamma_{iq} = V_{qL} \gamma_{iq} V_{qR}^\dagger \ ,$$  

(8)

where $\gamma_{iq}$ are diagonal matrices with complex entries. More general forms for $\tilde{\Gamma}_{iq}$ are allowed if one demands invariance with respect to subgroups of $G_u \times G_d$. All the flavor violations are induced by Higgs combination $\phi_F \equiv -\sin \beta \phi_1 + \cos \beta \phi_2 e^{-i\theta}$. The couplings of the neutral component $\phi_0^F$ are given as

$$-\mathcal{L}_Y^0 = \bar{q}_L F_q q_R \phi_0^F + \text{H.c.}$$  

(9)

with

$$F_q \equiv V_{qL}^\dagger \left(-\sin \beta \Gamma_{1q} + \cos \beta \Gamma_{2q} e^{i\theta_q}\right) V_{qR} \ = \ \left(-\sin \gamma_{1q} + \cos \beta \gamma_{2q} e^{i\theta_q}\right) ,$$  

(10)

where we have used eq.(8) to obtain the second line. It is seen that the FCNC matrix $F_q$ become diagonal along with the mass matrices and the tree level FCNC are absent. But the phases of $(F_q)_{ii}$ cannot be removed in the process of making the quark masses real and remain as physical parameters. The charged component $H^+$ of $\phi_F$ correspond to the physical charged Higgs field and its couplings in our case are given by

$$-\mathcal{L}_{H^+} = H^+ V_{ij} (F_d)_{jj} d_{jR} - \bar{u}_{iL} V_{ij} \left(F_u^*\right)_{ii} d_{jL} + \text{H.c.}$$  

(11)

The above couplings are similar to the charged Higgs couplings in 2HDM of type-I and II. In those models, $(F_q)_{ii}$ are proportional to the corresponding quark masses $m_{iq}$ and are real. Here $(F_q)_{ii}$ are general complex numbers which can provide new phases in the $B_{d,s} - \bar{B}_{d,s}$ mixing.

An interesting class of 2HDM without the tree level FCNC have been obtained from general 2HDM by assuming that two Yukawa couplings $\Gamma_{1q}$ and $\Gamma_{2q}$ are proportional to each other [26]. In the present case, the two Yukawa coupling matrices are not proportional to each other but the tree level FCNC are still absent. The phases of $(F_q)_{ii}$ in the charged Higgs couplings are dependent on the flavour index $i$ unlike in models of [26] which are characterized by universal phases one for the up and the other for the down quarks. If the diagonal matrices $\gamma_{1q}$ and $\gamma_{2q}$ in eq.(8) are proportional to each other then the present class of models reduce to the one in [26].

If $S_{uL} \neq S_{dL}$ then neither the Yukawa interactions given in eq.(1) nor the charged current weak interactions remain invariant under symmetries of the mass matrices. This means that radiative corrections will not preserve [27] the structure implied by eq.(8). However as in case of the 2HDM of type-I and type-II as well as the aligned models of [26], the full Lagrangian of the present model is formally invariant under the fermion number transformation $q_{L,R} \rightarrow e^{i\alpha_{qL}} q_{L,R}$ accompanied by the change in the CKM matrix elements $V_{ij} \rightarrow e^{i\alpha_{ij}} V_{ij} e^{-i\alpha_{jL}}$. As a consequence of this all the radiative corrections in the model would display structure similar to the one obtained in the Minimal Flavor Violating [28] models.
3. Neutral Mesons mixings

In this section we discuss phenomenological application of the model in new contribution to neutral meson mixing induced by the charged Higgs couplings in eq.(11). The \((F_d)_{ii}\) and \((F_u)_{ii}\) entering the \(H^+\) couplings are determined by the diagonal Yukawa couplings \(\gamma_{iq}\) which also determine corresponding quark masses, see eq.(8). We make a simplifying assumption that the first two generation quark masses and the corresponding \((F_q)_{ii}\) are small compared to the third generation masses and \((F_q)_{33}\). Hence eq.(11) reduces to

\[-\mathcal{L}_{H^+} \approx \frac{H^+}{v} (\bar{u}_i L V_{i3} (F_d)_{33} b_R - \bar{t}_R V_{3j} (F_u^*)_{33} d_{jL}) + \text{H.C.}\]  

(12)

The charged Higgs contribution to the \(K^0 - \bar{K}^0\) mixing arise only from the second term. The phase in \((F_d)_{33}\) can be absorbed in the definition of \(H^+\). As a result the above Lagrangian does not generate any new CP violating phases in the \(K\) meson mixing as long as \((F_q)_{jj}\) are neglected for \(j = 1, 2\). However it can lead to non-trivial phases in the \(B_q - \bar{B}_q\) mixing since the charged Higgs exchanges in this case involve both \((F_d)_{33}\) and \((F_u)_{33}\) and their phases can not be simultaneously removed. More interestingly, the interaction in eq.(12) distinguishes between the \(d\) and \(s\) quarks only through the CKM factor and not through additional phases. This results in strong correlations among the CP violation in \(B_s\) and \(B_d\) system. This can be seen as follows.

\[B_q^0 - \bar{B}_q^0 \ (q = d, s)\] 

mixing amplitude can be parameterized in the presence of new physics contribution as

\[\langle B_q | \mathcal{H}^{SM} + \mathcal{H}^{NP} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{SM} | \bar{B}_q \rangle (1 + \kappa_q e^{i\phi_q^{NP}}) \equiv |\langle B_q | \mathcal{H}^{SM} | \bar{B}_q \rangle | \rho_q e^{-2i(\beta_q + \phi_q^{NP})},\]  

(13)

where \(\beta_q\) represent the relevant phase in case of the SM and \(\phi_q\) are the charged Higgs induced phases. The box diagrams involving \(WH\) and \(HH\) lead to new physics contribution involving the charged Higgs \(H\). The interaction in eq.(12) lead to the following effective Hamiltonian at the weak scale:

\[\mathcal{H}^{NP} = C_1 q_L \gamma^\mu b_L \eta^\mu \gamma^\nu b_L + C_2 q_{H1} b_L \eta b_L,\]

where \(C_{1,2}\) are the Wilson coefficients. Taking matrix element of the above equation and comparing with the SM result leads to

\[\kappa_q e^{i\phi_q^{NP}} = \frac{4\pi^2}{G_F^2 M_W^2 \eta_B S_0(x_t)} \left[ C_1 - 5/24 C_2 \left( \frac{M_{B_a}}{m_b + m_q} \right)^2 B_{1q} \right], \]

(15)

where \(G_F, M_W\) respectively denote the Fermi coupling constant and the W boson mass. \(S_0(x_t) \approx 2.3\) for \(m_t \sim 161\) GeV. \(\eta_B \approx 0.55\) refers to the QCD correction to the Wilson operator in the SM, \(B_{1q,2q}\) are the bag factors which enter the operator matrix elements in eq.(14) and \(M_{B_q}, m_b, m_q\) respectively denote the masses for the \(B_q\) mesons for \(q = d, s, b\) quark and the \(d, s\) quarks. The Wilson coefficients \(C_{1,2}\) are independent of the flavour \(q = d, s\) of the light quark in \(B_q\). Mild dependence of \(\kappa_q\) on \(q\) arise from the operator matrix element multiplying \(C_2\) in eq.(15). This leads to two predictions: To a good approximation, (i) \(\kappa_d \approx \kappa_s\) and (ii) \(\phi_d^{NP} \approx \phi_s^{NP}\). This implies from eq.(13) that

\[\frac{\Delta M_d}{\Delta M_s} \approx \frac{\Delta M_d^{SM}}{\Delta M_s^{SM}},\]

(16)

where \(\Delta M_q\) denote the values of the mass difference between heavy and light mass eigenstates in \(B_q\) system in presence of new physics. Equality of \(\kappa_d\) and \(\kappa_s\) as well as \(\phi_d^{NP}\) and \(\phi_s^{NP}\) along with eq.(13) also imply

\[\phi_d \approx \phi_s,\]

(17)
The detailed phenomenological consequences of this prediction are already discussed in [29] in a model independent manner. It appears to be in the right direction for explaining the CP violating anomalies. In case of $B_d$, the unitarity triangle angle $\beta$

$$\sin 2\beta = 0.84 \pm 0.09$$

as determined [8] using the information from $V_{cb}, \epsilon_K$ and $\frac{\Delta M_s}{\Delta M_d}$ is found to be higher than the value

$$\sin 2\beta = 0.681 \pm 0.025$$

obtained from the mixing induced asymmetry in $B \rightarrow J/\psi K_S$ decay. Since the latter measures $\beta + \phi_d$, the above information can be reconciled [29] with a negative $\phi_d \approx -10^\circ$. $\phi_d \approx \phi_s$ then implies a sizable asymmetry $S_{\phi\phi} = \sin 2(\beta_s - \phi_s) \sim 0.4$ in $B_s$ decay as indicated by the analysis of UTfit [11] or the CKMfitter [12] group.

In a recent study global fit to various observables was carried out in different scenarios [30]. One of the scenario has the relation $\kappa_d \equiv \kappa_s$ and $\phi_d^{NP} \equiv \phi_s^{NP}$. The resulting fit in this scenario is better than the SM fit. Results from this fit are a common NP phase $2\phi_d = 2\phi_s = -14.4^{+6.7}_{-4.2}$ and $\sin 2\beta = 0.83 \pm 0.05$ at $2\sigma$. These results agree with our results obtained here.

4. Numerical analysis

In this section we discuss our numerical analysis in which we obtain constraints on model parameters from study of $B^0_s - \bar{B}^0_s$ mixing. New physics contribution to $B^0_s - \bar{B}^0_s$ mixing is parametrized by UTfit group as [11]

$$C_{Bs} e^{-2i\phi_{Bs}} = \left(1 + \frac{\Delta M_{NP}^{s}}{\Delta M_{SM}^{s}}\right)$$

(18)

Also from eq.(13), $C_{Bs} = \left|1 + \kappa_s e^{-2i(\phi_s^{NP} - \beta_s)}\right|$ and $\phi_{Bs} = -\frac{1}{2} \text{Arg}[1 + \kappa_s e^{-2i(\phi_s^{NP} - \beta_s)}]$. UTfit collaboration has obtained the allowed range of the parameters $C_{Bs}$ and $\phi_{Bs}$ as [11]

$$C_{Bs} = [0.68, 1.51], \quad \phi_{Bs} = [-30.5, -9.9] \cup [-77.8, -58.2]$$

(19)

We calculate $C_{Bs}$ and $\phi_{Bs}$ in the present model neglecting first and second generation masses and corresponding $F_{qii}$. The Charged higgs mass $M_h$ is allowed to vary in the range $100 - 500$ GeV while $\beta$ and couplings $F_{q3}$ are varied in the allowed range. Values of $C_{Bs}$ and $\phi_{Bs}$ which can be obtained in this case is shown in Figure(1).

![Figure 1](image-url)  

**Figure 1.** Values of NP parameter $C_{Bs}$ and $\phi_{Bs}$ which can be obtained in limit when first two generation masses and $F_{qii}$, where $q = u, d$ and $i = 1, 2$, can be neglected
We have also checked that our model is compatible with the recent determination of like-sign dimuon charge asymmetry of semileptonic b-hadron decays by D0 collaboration [31]. The model discussed here can give extra contribution required to explain the deviation of the experimental value of like-sign dimuon charge asymmetry of semileptonic b-hadron decays from SM prediction.

5. Summary
Using the flavor symmetries which does not depend on the higgs parameter tan $\beta$ and $\theta$, we obtained a class of 2HDM in which FCNCs can be eliminated without imposing discrete symmetries. Unlike type - I and type-II 2HDM, charged higgs interaction in this model contains new phases which are flavor dependant. In the limit of vanishing first and second generation masses and corresponding couplings $F_{qii}$ where $q = u, d$ and $i = 1, 2$, $K^0 - \bar{K}^0$ mixing does not get any new CP phase while the $B^0_d - \bar{B}^0_d$ and $B^0_s - \bar{B}^0_s$ mixing gets new phases. New contribution to CP violation in this model in $B^0_d - \bar{B}^0_d$ and $B^0_s - \bar{B}^0_s$ mixing are correlated and it is possible to explain CP violating anomalies in $B_d$ and $B_s$ systems. The model parameters can also generate like sign dimuon charge asymmetry required by the experimental data.

6. References
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