Neutral Higgs boson contributions to rare leptonic and semi-leptonic B decays in 2HDM and MSSM

Abstract We review the neutral Higgs boson (NHB) contributions to rare leptonic and semi-leptonic B decays in 2HDM and MSSM with large $\tan \beta$. We present relevant Wilson coefficients of NHB induced operators. We discuss branching ratios and other observables in those decays. Finally we present CP violation in rare leptonic B decays.

Keywords neutral Higgs bosons, supersymmetry, B decays, CP violation

PACS numbers 13.20.He, 13.25.Hw

1 Introduction

There are no flavor changing neutral currents (FCNC) at tree-level in the standard model (SM). FCNC appear at loop-level and consequently offer a good place to test quantum effects of the fundamental quantum field theory on which SM is based. Furthermore, they are very small at one loop-level due to the unitarity of the Cabbibo-Kobayashi- Maskawa (CKM) matrix. In models beyond SM new particles may appear in the loop and have significant contributions to flavor changing transitions. Therefore, FCNC interactions give an ideal place to search for new physics. Any positive observation of FCNC couplings deviated from those in SM would unambiguously signal the presence of new physics. Searching for FCNC is clearly one of important goals of the next generation of high energy colliders [1].

As one kind of FCNC processes, the rare leptonic and semi-leptonic B decays have less theoretical uncertainties, compared with rare hadronic B decays. In this brief review we shall present Higgs mediated FCNC interactions and their significant role to the rare leptonic and semi-leptonic B decays in two Higgs doublet models (2HDM) and supersymmetric (SUSY) models with emphasis on the latter.

We present relevant Wilson coefficients of NHB induced operators in a model II 2HDM and MSSM with large $\tan \beta$ in Section 2. We discuss branching ratios in rare leptonic B decays in Section 3. We discuss branching ratios and other observables in rare semi-leptonic B decays in Section 4. In Section 5 we present CP violation in rare leptonic B decays. Finally we draw conclusions and discussions in Section 6.

2 Higgs mediated FCNC interactions

In SM the couplings of neutral Higgs bosons (NHBs) to fermions are proportional to $\frac{m_f}{m_w}$ where $m_f$ are masses of fermions. So they are negligibly small except for the couplings to the third generation quarks. However, in a model II 2HDM or SUSY models the couplings of neutral Higgs bosons to down-type quarks or leptons are proportional to $\frac{m_f}{m_w} \tan \beta$, where $\tan \beta$ is the ratio of two Higgs vacuum expectation value $v_U$ and $v_D$, $\tan \beta = \frac{v_U}{v_D}$, which can be not small if $\tan \beta$ is large. In other words, they are enhanced by a factor of $\tan \beta$, compared with those in the SM, in the case of large $\tan \beta$. So we shall pay particular attention to the large $\tan \beta$ case in the review.

The FCNC $b \rightarrow D^{\pm}f(D = d, s)$ decays can be straightforward calculated by the Feynman diagrammatic approach. The neutral Higgs bosons mediated Feynman diagrams consist of the Higgs penguin which denotes $H$-$b$-$D$ loop induced flavor transitions and the vertex $H$-$f$-$\bar{f}$. Besides, there
are box diagrams with charged particles in the loop. It is necessary to include box diagrams in order to keep the gauge invariance [2]. Limited to diagrams which are related to Higgs mediated FCNC interactions and relevant box diagrams, to the one loop level, in addition to the SM diagrams, there are new diagrams shown in Fig. 1 for 2HDM, and in addition to those in SM and 2HDM, there are new diagrams shown in Fig. 2 for SUSY models. In the version of effective Hamiltonian for B decays the calculations of Feynman diagrams give the Wilson coefficients of corresponding operators at the scale $m_W$.

The $\Delta B = 1$ effective Hamiltonian for rare leptonic and semi-leptonic B decays in 2HDM and MSSM is [3, 4]:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \lambda_i \left[ \sum_{i=1}^{6} C_i(\mu) O_i(\mu) + \sum_{i=7}^{10} C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) + \sum_{i=1}^{8} Q_i(\mu) Q_i(\mu) + Q'_i(\mu) Q'_i(\mu) \right].$$  \hspace{1cm} (1)$$

where $\lambda_i = |V_{ib} V_{i\alpha}^*|$ (for specific, set $D = s$ from now on and the $D = d$ case can be obtained with explicit substitutions), $O_i(i = 1, \ldots, 10)$ are the operators in the SM and their explicit expressions can be found in Refs. [5, 6], $O'_i(i = 7, \ldots, 10)$, $Q_i$ and $Q'_i(i = 1, \ldots, 8)$ are the new physics operators and their explicit expressions can be found in Refs. [3, 4]. The primed operators, the counterpart of the unprimed operators, are obtained by replacing the chiralities in the corresponding unprimed operators with opposite ones. $Q_i$'s (and $Q'_i$'s) come from neutral Higgs mediated FCNC interactions. We call $Q_i$'s (and $Q'_i$'s) the neutral Higgs boson induced or neutral Higgs penguin operators. The explicit expressions of the operators governing $B \to X_s l^+ l^-$ and $B \to l^+ l^-$ are given by

$$O_7 = \frac{\epsilon}{16\pi^2} m_b (\bar{s} \sigma_{\mu\nu} P_L b) F_{\mu\nu}, \quad O'_7 = \frac{\epsilon}{16\pi^2} m_b (\bar{s} \sigma_{\mu\nu} P_L b) F_{\mu\nu},$$

$$O_8 = \frac{\epsilon^2}{16\pi^2} (\bar{s} g_{\mu\nu} P_L b) (\bar{t} \gamma^\mu t), \quad O'_8 = \frac{\epsilon^2}{16\pi^2} (\bar{s} g_{\mu\nu} P_L b) (\bar{t} \gamma^\mu t),$$

$$O_{10} = \frac{\epsilon^2}{16\pi^2} (\bar{s} g_{\mu\nu} P_L b) (\bar{t} \gamma^\mu \gamma^\nu t), \quad O'_{10} = \frac{\epsilon^2}{16\pi^2} (\bar{s} g_{\mu\nu} P_L b) (\bar{t} \gamma^\mu \gamma^\nu t),$$

$$Q_i = \frac{\epsilon^2}{16\pi^2} (\bar{t} P_L b) (\bar{b} t), \quad Q'_i = \frac{\epsilon^2}{16\pi^2} (\bar{t} P_L b) (\bar{b} t).$$  \hspace{1cm} (2)$$

where $P_L = (1 - \gamma_5)/2$ and $P_R = (1 + \gamma_5)/2$. We also consider the operators

$$O_8 = \frac{\epsilon^2}{16\pi^2} m_b (\bar{s} g_{\mu\nu} P_L b) G_{\mu\nu}, \quad O'_8 = \frac{\epsilon^2}{16\pi^2} m_b (\bar{s} g_{\mu\nu} P_L b) G_{\mu\nu}.$$  \hspace{1cm} (3)$$

\footnote{We follow the convention in Ref. [6] for the indices of operators as well as Wilson coefficients. In the convention of Ref. [5] $O_8 (O_{10})$ is changed into $O_{10} (O_8).$}

\footnote{Note that $O_{1,2} = \frac{\epsilon^2}{m_0 16\pi^2} O_{X_R}$ and $O_{3,4}$ are used in some papers (see, e.g., Ref. [2]).}