Bounding the flavor-violating Hbs vertex from the $B \to X_s\gamma$ decay

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Abstract. The nondiagonal Hbs coupling within the context of an effective Yukawa sector that comprises $SU_L(2) \times U_Y(1)$-invariant operators of up to dimension six is studied. The recent experimental result on $B \to X_s\gamma$ with hard photons is employed to constrain the Hbs vertex, with which the branching ratio for the $B_s \to \gamma\gamma$ decay is estimated. It is found that the $B_s \to \gamma\gamma$ decay can reach a branching ratio of the order of 4×10^{-8}.

1. Introduction

Suppressed observables such as $B \to X_s\gamma$, has been measured with good accuracy, showing no deviations from the standard model (SM) [1]. This means that this observable can provide stringent constraints on physics beyond the electroweak scale. We are interested in studying the flavor violating transitions $b \to s\gamma$ and $b \to s\gamma\gamma$ mediated by a SM-like Higgs boson within the context of extended Yukawa sectors that incorporates $SU_L(2) \times U_Y(1)$ invariants of up to dimension six, wich is enough to induce, in a model independent-manner, the presence of flavor and CP violation. Our main goal is to use the experimental data on the $B \to X_s\gamma$ decay to constrain the flavor violating Hbs vertex. Then we will use these results to predict the branching ratio for the $B_s \to \gamma\gamma$ transition.

2. The effective Yukawa sector

An effective Yukawa sector that generates flavor violating effects in the quark sector is:

$$\mathcal{L}^Y_{eff} = -Y^d_{ij}(\bar{Q}_i\Phi d_j) - \frac{\alpha^d_{ij}}{\Lambda^2}(\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_j) - Y^u_{ij}(\bar{Q}_i\tilde{\Phi}u_j) - \frac{\alpha^u_{ij}}{\Lambda^2}(\Phi^\dagger\Phi)(\bar{Q}_i\tilde{\Phi}u_j) + H.c., \quad (1)$$

where Y_{ij}, Q_i, Φ, d_i and u_i stand for the components of the Yukawa matrix, the left-handed quark doublet, the Higgs doublet and the right-handed quark singlets of down and up type, respectively. The α_{ij} are the components of a 3×3 general matrix, which parametrize the details of the underlying physics and Λ is the new physics scale.

After spontaneous symmetry breaking, in the unitary gauge, the diagonalized Lagrangian is:

$$\mathcal{L}^{Y}_{eff} = -\left(1+\frac{g}{2m_W}H\right)\left(\bar{D}M_d D+\bar{U}M_u U\right) - H\left(1+\frac{g}{4m_W}H\left(3+\frac{g}{2m_W}H\right)\right) \times \left(\bar{D}\Omega^d P_R D+\bar{U}\Omega^u P_R U + H.c.\right), \tag{2}$$

where the M_a $(a = d, u)$ are the diagonal mass matrix and $\bar{D} = (\bar{d}, \bar{s}, \bar{b})$ and $\bar{U} = (\bar{u}, \bar{c}, \bar{t})$ are vectors in the flavor space. The Ω^a are matrices defined in the flavor space through the relation: $\Omega^a = (1/\sqrt{2})(v/\Lambda)^2 V^a_L \alpha^a V^{a\dagger}_R$. In general, $\Omega^{a\dagger} \neq \Omega^a$ and the Higgs boson couples to fermions through both scalar and pseudoscalar components. As a consequence, the flavor violating coupling $H\bar{q}_i q_j$ has the most general renormalizable structure of scalar and pseudoscalar type given by $-i(\Omega_{ij}P_R + \Omega^*_{ij}P_L)$.

3. Constraint on Hbs from $B \to X_s\gamma$

The leading contribution to $B \to X_s\gamma$ decay with a hard photon is dominated by the $b \to s\gamma$ process [1, 2]. We calculate the contribution of the flavor violating Hbs coupling to the $b \to s\gamma$ and $b \to sg$ decays (see Fig. 1) and study their implications for the $B \to X_s\gamma$ process.

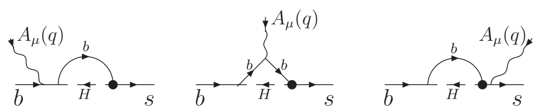

Figure 1. Diagrams contributing to the $b \to s\gamma$ transition. The $b \to sg$ process occurs via the same type of diagrams.

The total theoretical contribution to the $b - s$ transition is given by the sum of the SM contribution and the new physics effect induced by the Hbs vertex: $\mathcal{M}_T = \mathcal{M}_{SM} + \mathcal{M}_{NP}$. To get a bound for the Ω_{bs} parameter, we use the discrepancy between the theoretical prediction within the SM and the experimental measurement [3]:

$$R_{EXP-SM} \equiv \frac{\Gamma_{EXP} - \Gamma_{SM}}{\Gamma_{SM}} = \frac{Br_{EXP}(B \to X_s\gamma)}{Br_{SM}(B \to X_s\gamma)} - 1, \tag{3}$$

where Γ_{EXP} is the experimental decay width of the $B \to X_s\gamma$ transition and Γ_{SM} is the theoretical prediction of the SM. Explicitly, $R_{EXP-SM} = 0.117 \pm 0.113$. To constrain the Hbs vertex, we will assume that the SM prediction plus the Hbs contribution, coincides with the experimental value. Working out at leading order, the SM contribution is:

$$\mathcal{M}_{SM}(b \to s\gamma) = -V_{tb}V^*_{ts}\frac{\alpha^{\frac{3}{2}}}{4\sqrt{\pi}s^2_W m^2_W}C^{eff}_7(m_b)\,\bar{s}(p_s)\sigma_{\mu\nu}\epsilon^{*\mu}(q,\lambda)q^\nu(m_s P_L + m_b P_R)b(p_b), \tag{4}$$

with an effective Wilson coefficient $C^{eff}_7(m_b) = 0.689C_7(m_W) + 0.087C_8(m_W)$, which already contains the QCD contribution at the m_b scale [2].

The new physics contribution is:

$$\mathcal{M}_{NP}(b \to s\gamma) = -\frac{Q_b\,\alpha\,\mathcal{F}}{16\pi s_W m_W}\left(0.689 + \frac{0.087}{Q_b}\right)\bar{s}(p_s)\sigma_{\mu\nu}\epsilon^{*\mu}(q,\lambda)q^\nu(\Omega^*_{bs}P_L + \Omega_{bs}P_R)b(p_b), \tag{5}$$

where Q_b is the electric charge of b, s_W is the sine of the weak angle and $\mathcal{F}$ is the loop function given by $\mathcal{F} = \frac{3}{2} + x\sqrt{x^2-4x}\,\mathrm{sech}^{-1}\left(\frac{2}{\sqrt{x}}\right) + \frac{\left(2\left(2-3x+x^2\right)+\left(3x^2-x^3\right)\ln(x)\right)}{2(x-1)}$, where $x = m^2_H/m^2_b$.

The problem of finding a bound for the Ω_{bs} parameter reduces now to solve a quadratic equation. The physical solution corresponds to that for which the allowed values for Ω_{bs} satisfy the $|A_{SM}|^2 > |A_{NP}|^2$ condition, which implies that $|\Omega_{bs}|^2 < (0.7 - 6.8) \times 10^{-3}$ for a Higgs mass in the range 115 GeV$< m_H <$ 200 GeV [1].

4. The $B_s \to \gamma\gamma$ decay

The Hbs effective vertex induces the flavor violating process $b \to s\gamma\gamma$ at the one-loop level (see Fig. 2). The contribution to $b \to s\gamma\gamma$ occurs through two sets of Feynman diagrams, each given a finite and gauge invariant contribution. The first set of diagrams (see Fig. 2-a) includes box diagrams, reducible diagrams characterized by the one-loop $bs\gamma$ coupling and reducible diagrams composed by the one-loop $b-s$ bilinear coupling. Henceforth we will refer to this set of graphs as box-reducible diagrams. The second set of diagrams is characterized by the SM one-loop $H^*\gamma\gamma$ coupling, where H^* represents a virtual Higgs boson (see Fig. 2-b). These type of graphs will be named Higgs-reducible diagrams.

The amplitude for the $b \to s\gamma\gamma$ decay is:

$$\mathcal{M}^{\mu\nu} = \frac{\alpha\, g}{8\pi m_W}\, F_0\, \bar{u}_s(p_s)(\Omega_{bs} P_R + \Omega^*_{bs} P_L)\frac{k_2^\mu k_1^\nu - k_1\cdot k_2 g^{\mu\nu}}{2k_1\cdot k_2 - m_H^2 + i m_H \Gamma_H} u_b(p_b), \tag{6}$$

with

$$\begin{aligned} F_0 =& \frac{8\, m_W^2}{2\, k_1\cdot k_2}\left(3 + \frac{2\, k_1\cdot k_2}{2\, m_W^2} + 6\, m_W^2\left(1 - \frac{2\, k_1\cdot k_2}{2\, m_W^2}\right) C_0(1)\right) \\ & - Q_t^2\, N_{c_t}\, \frac{8\, m_t^2}{2\, k_1\cdot k_2}\left(2 + (4\, m_t^2 - 2\, k_1\cdot k_2)\, C_0(2)\right), \end{aligned} \tag{7}$$

where $C_0(1) = C_0(0, 0, 2\, k_1\cdot k_2, m_W^2, m_W^2, m_W^2)$ and $C_0(2) = C_0(0, 0, 2\, k_1\cdot k_2, m_t^2, m_t^2, m_t^2)$ are the Passarino-Veltman scalar functions, m_t is the top quark mass, Q_t is the top quark charge and $N_{c_t} = 3$ is the color factor.

According to the static quark approximation [4], we can compute the decay width $\Gamma(B_s \to \gamma\gamma)$ starting from $\Gamma(b \to s\gamma\gamma)$, where it is assumed that the three-momenta of the b and s quarks vanish in the rest frame of the B_s meson. In this approximation, the B_s meson decays into two photons emitted with energies $m_{B_s}/2$ and the product $k_1 \cdot k_2 = m_{B_s}^2/2$, where $m_{B_s} = m_b + m_s$ [1] is the B_s-meson mass. The decay width for the $B_s \to \gamma\gamma$ process arising from the new physics effects encoding in B_{NP} has the following form

$$\Gamma(B_s \to \gamma\gamma) = f_{B_s}^2 \frac{m_{B_s}^3}{16\pi}|B_{NP}|^2, \tag{8}$$

where

$$B_{NP} = \frac{\alpha^{\frac{3}{2}}\Omega_{bs}}{4\pi^{\frac{1}{2}} s_W}\frac{m_{B_s}}{m_W m_H^2}\, F_0. \tag{9}$$

We show in Fig. 3 the branching ratio for the $B_s \to \gamma\gamma$ process. From this figure, it can be appreciated that the contribution induced by the Higgs-reducible graphs is approximately 2 orders of magnitude larger than those generated by the box-reducible graphs in the range of a Higgs mass of 115 GeV$< m_H <$ 200 GeV.

5. Conclusions

We have estimated the Hbs coupling strength from the branching ratio for the $B \to X_s\gamma$ process. The effective parameter Ω_{bs} was bounded by using the discrepancy between the respective theoretical and experimental central values of the branching ratios. This constraint was used to bound the Higgs-mediated flavor violating $B_s \to \gamma\gamma$ decay and we found that its branching ratio is less than 10^{-8} in the Higgs mass interval ranging from 115 GeV to 200 GeV. Our results for the branching ratio are 2 orders of magnitude smaller than the current experimental bound imposed by the Belle Collaboration.

[1] As in Refs. [4], we will use the constituent mass for the strange quark $m_s = m_K = 0.497$ GeV.

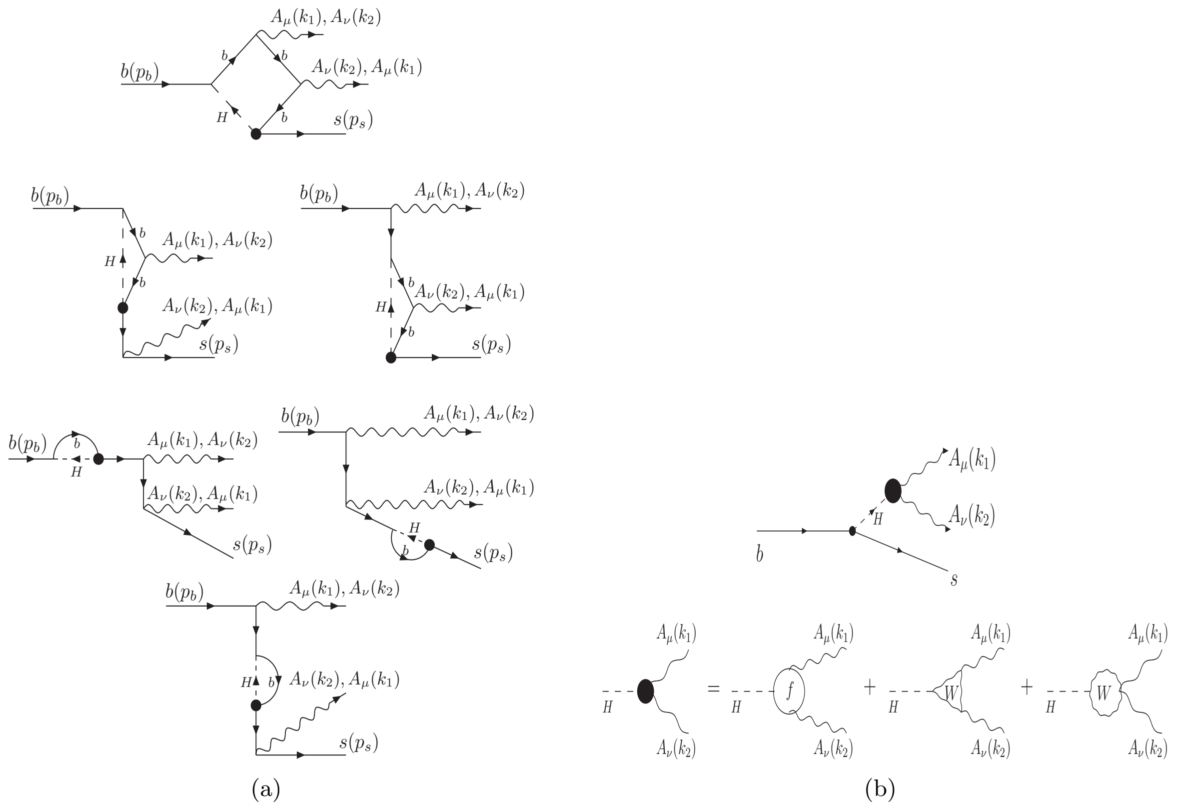

Figure 2. (a) Contribution of the box and reducible diagrams to the $b \to s\gamma\gamma$ decay. (b) Contribution of the SM one-loop induced $H^*\gamma\gamma$ vertex to the $b \to s\gamma\gamma$ decay.

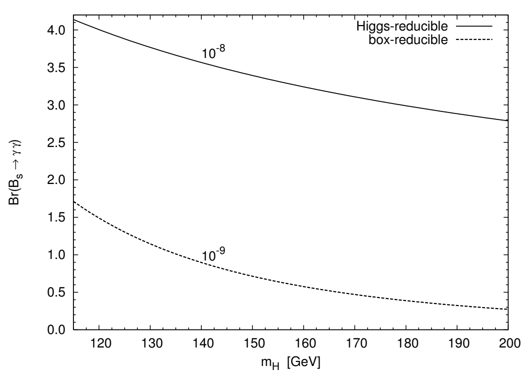

Figure 3. The branching ratio of the $B_s \to \gamma\gamma$ decay for the Higgs-reducible contribution (solid line) and box-reducible contribution (dashed line) as a function of the Higgs mass.

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