

Bounding the flavor-violating Hbs vertex from the $B \rightarrow X_s\gamma$ 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 $B \rightarrow X_s\gamma$ with hard photons is employed to constrain the Hbs vertex, with which the branching ratio for the $B_s \rightarrow \gamma\gamma$ decay is estimated. It is found that the $B_s \rightarrow \gamma\gamma$ decay can reach a branching ratio of the order of 4×10^{-8} .

1. Introduction

Suppressed observables such as $B \rightarrow X_s\gamma$, 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 $b \rightarrow s\gamma$ and $b \rightarrow s\gamma\gamma$ 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, which 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 $B \rightarrow X_s\gamma$ decay to constrain the flavor violating Hbs vertex. Then we will use these results to predict the branching ratio for the $B_s \rightarrow \gamma\gamma$ transition.

2. The effective Yukawa sector

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

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

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:

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

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: $\Omega^a = (1/\sqrt{2})(v/\Lambda)^2 V_L^a \alpha^a V_R^{a\dagger}$. 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 $B \rightarrow X_s \gamma$

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

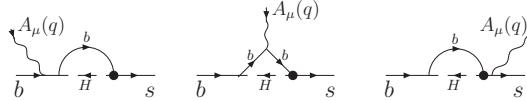


Figure 1. Diagrams contributing to the $b \rightarrow s \gamma$ transition. The $b \rightarrow sg$ process occurs via the same type of diagrams.

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]:

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

where Γ_{EXP} is the experimental decay width of the $B \rightarrow X_s \gamma$ 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:

$$\mathcal{M}_{SM}(b \rightarrow s \gamma) = -V_{tb} V_{ts}^* \frac{\alpha^{\frac{3}{2}}}{4\sqrt{\pi} s_W^2 m_W^2} C_7^{eff}(m_b) \bar{s}(p_s) \sigma_{\mu\nu} \epsilon^{*\mu}(q, \lambda) q^\nu (m_s P_L + m_b P_R) b(p_b), \quad (4)$$

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

The new physics contribution is:

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

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 $\mathcal{F} = \frac{3}{2} + x \sqrt{x^2 - 4x} \operatorname{sech}^{-1} \left(\frac{2}{\sqrt{x}} \right) + \frac{(2(2-3x+x^2)+(3x^2-x^3) \ln(x))}{2(x-1)}$, where $x = m_H^2/m_b^2$.

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 $|\mathcal{A}_{SM}|^2 > |\mathcal{A}_{NP}|^2$ condition, which implies that $|\Omega_{bs}|^2 < (0.7 - 6.8) \times 10^{-3}$ for a Higgs mass in the range $115 \text{ GeV} < m_H < 200 \text{ GeV}$ [1].

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

The Hbs effective vertex induces the flavor violating process $b \rightarrow s\gamma\gamma$ at the one-loop level (see Fig. 2). The contribution to $b \rightarrow s\gamma\gamma$ 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 $b \rightarrow s\gamma\gamma$ decay is:

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

with

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

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 $N_{ct} = 3$ is the color factor.

According to the static quark approximation [4], we can compute the decay width $\Gamma(B_s \rightarrow \gamma\gamma)$ starting from $\Gamma(b \rightarrow s\gamma\gamma)$, 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 $B_s \rightarrow \gamma\gamma$ process arising from the new physics effects encoding in B_{NP} has the following form

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

where

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

We show in Fig. 3 the branching ratio for the $B_s \rightarrow \gamma\gamma$ 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 $B \rightarrow X_s\gamma$ 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 $B_s \rightarrow \gamma\gamma$ 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.

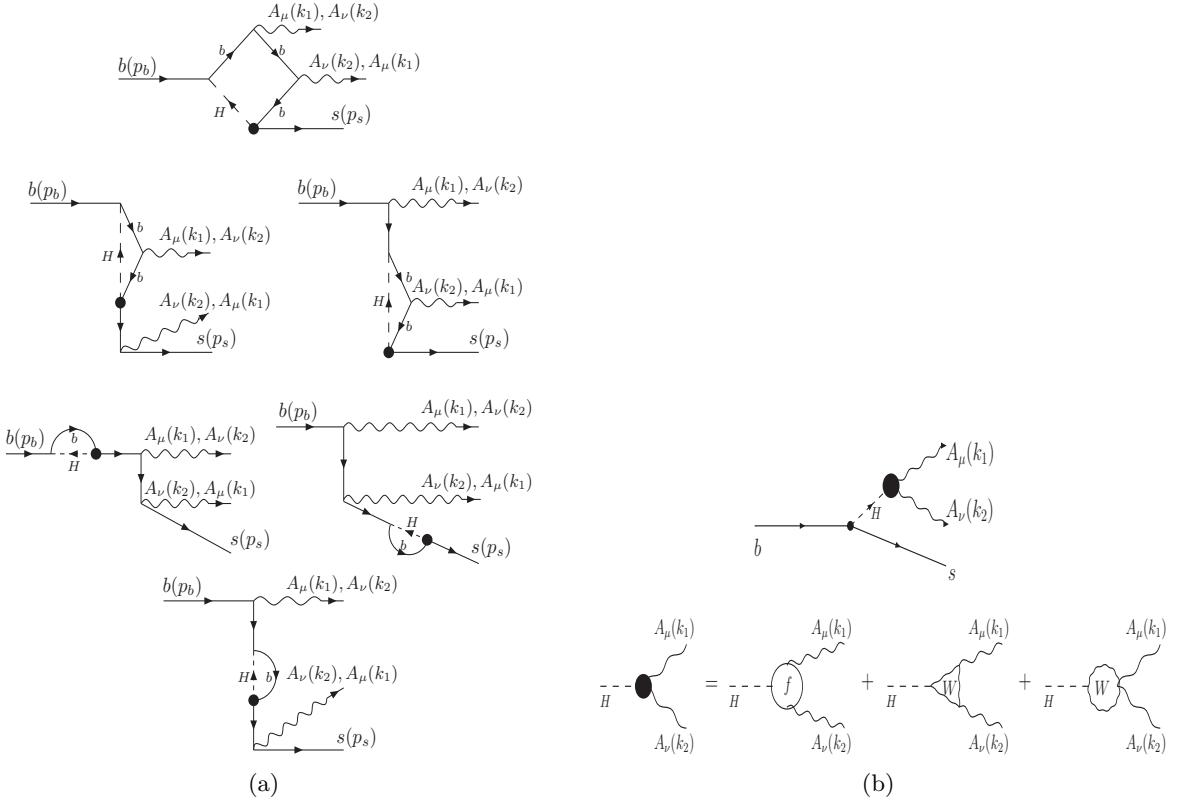


Figure 2. (a) Contribution of the box and reducible diagrams to the $b \rightarrow s\gamma\gamma$ decay. (b) Contribution of the SM one-loop induced $H^* \gamma\gamma$ vertex to the $b \rightarrow s\gamma\gamma$ decay.

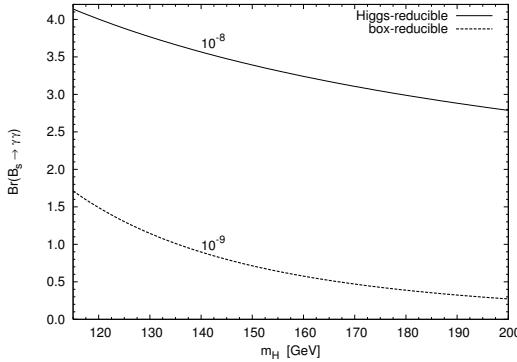


Figure 3. The branching ratio of the $B_s \rightarrow \gamma\gamma$ decay for the Higgs-reducible contribution (solid line) and box-reducible contribution (dashed line) as a function of the Higgs mass.

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