

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

**J. I. Aranda<sup>(a)</sup>, J. Montaña<sup>(b)</sup>, F. Ramírez-Zavaleta<sup>(a)</sup>, J. J. Toscano<sup>(c)</sup> and E. S. Tututi<sup>(a)</sup>**

<sup>(a)</sup>Facultad de Ciencias Físico Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Avenida Francisco J. Mújica S/N, 58060, Morelia, Michoacán, México.

<sup>(b)</sup>Departamento de Física, Universidad de Guanajuato, Campus Leon, C.P. 37150, León, Guanajuato, México.

<sup>(c)</sup>Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Apartado Postal 1152, Puebla, Puebla, México.

E-mail: feryuphy@fismat.umich.mx

**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  $4 \times 10^{-8}$ .

## 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  $Y_{ij}$ ,  $Q_i$ ,  $\Phi$ ,  $d_i$  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  $\alpha_{ij}$  are the components of a  $3 \times 3$  general matrix, which parametrize the details of the underlying physics and  $\Lambda$  is the new physics scale.

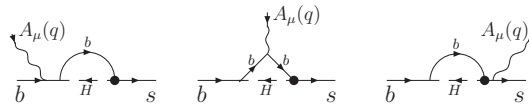
After spontaneous symmetry breaking, in the unitary gauge, the diagonalized Lagrangian is:

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

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  $\Omega^a$  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  $\Omega_{bs}$  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  $\Gamma_{EXP}$  is the experimental decay width of the  $B \rightarrow X_s \gamma$  transition and  $\Gamma_{SM}$  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  $\mathcal{F} = \frac{3}{2} + x \sqrt{x^2 - 4} \operatorname{sech}^{-1} \left( \frac{2}{\sqrt{x}} \right) + \frac{(2(2-3x+x^2) + (3x^2-x^3) \ln(x))}{2(x-1)}$ , where  $x = m_H^2/m_b^2$ .

The problem of finding a bound for the  $\Omega_{bs}$  parameter reduces now to solve a quadratic equation. The physical solution corresponds to that for which the allowed values for  $\Omega_{bs}$  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  $115 \text{ GeV} < m_H < 200 \text{ GeV}$  [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

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

where  $C_0(1) = C_0(0, 0, 2k_1 \cdot k_2, m_W^2, m_W^2, m_W^2)$  and  $C_0(2) = C_0(0, 0, 2k_1 \cdot k_2, m_t^2, m_t^2, m_t^2)$  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  $m_{B_s} = m_b + m_s$ <sup>1</sup> 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

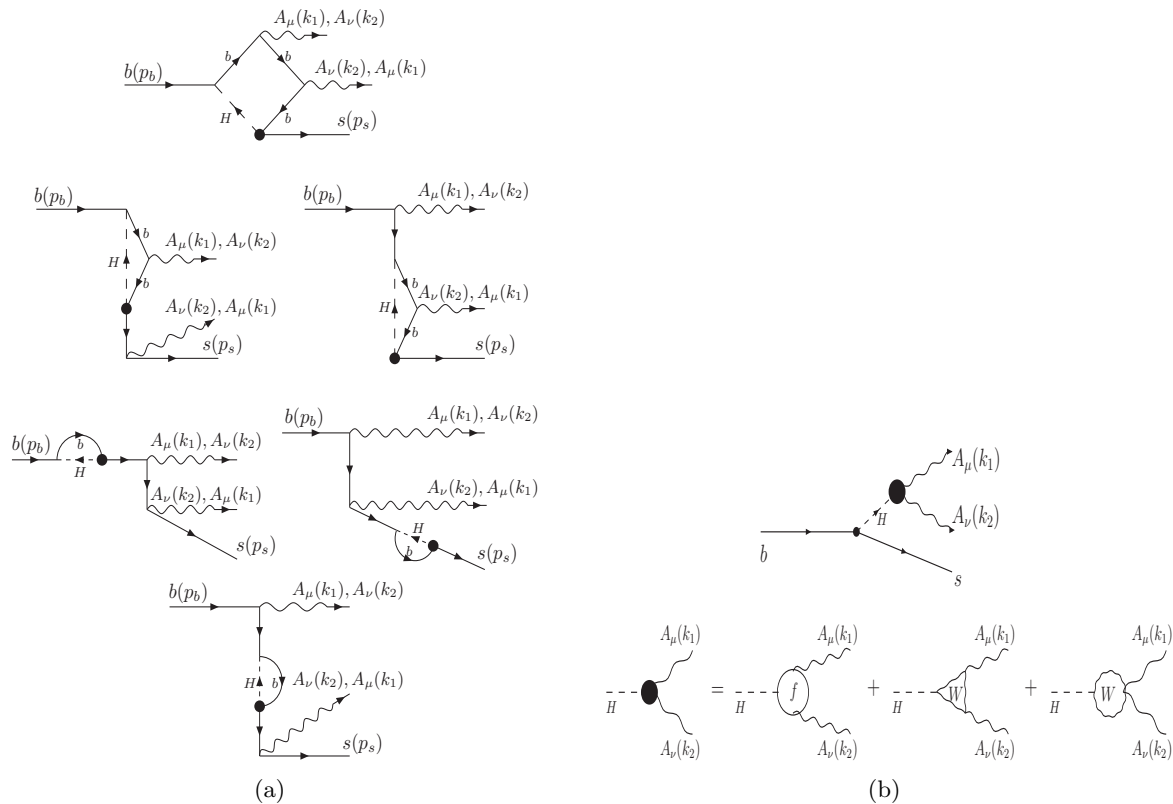
$$B_{NP} = \frac{\alpha^{\frac{3}{2}} \Omega_{bs}}{4\pi^{\frac{1}{2}} s_W} \frac{m_{B_s}}{m_W m_H^2} F_0. \quad (9)$$

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  $115 \text{ GeV} < m_H < 200 \text{ GeV}$ .

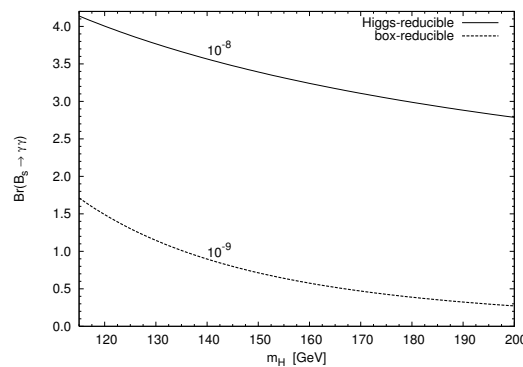
#### 5. Conclusions

We have estimated the  $Hbs$  coupling strength from the branching ratio for the  $B \rightarrow X_s\gamma$  process. The effective parameter  $\Omega_{bs}$  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.

<sup>1</sup> As in Refs. [4], we will use the constituent mass for the strange quark  $m_s = m_K = 0.497 \text{ GeV}$ .



**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.

- [1] J. I. Aranda, J. Montaño, F. Ramírez-Zavaleta, J. J. Toscano and E. S. Tututi, Phys. Rev. **D82**, 054002 (2010).
- [2] B. Grinstein, R. Springer and M. B. Wise, Nucl. Phys. **B339**, 269 (1990); A. J. Buras *et al.*, Nucl. Phys. **B424**, 374 (1994).
- [3] Xiao-Gang He and Lu-Hsing Tsai, JHEP **0806**, 074 (2008).
- [4] S. Herrlich and J. Kalinowski, Nucl. Phys. **B381**, 501 (1992); A. Gemintern, S. Bar-Shalom and G. Eilam, Phys. Rev. **D70**, 035008 (2004).