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Bounding the $B_s \to \gamma\gamma$ decay from Higgs mediated flavor changing neutral current transitions

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The Higgs-mediated flavor violating bottom-strange quarks transitions induced at the one-loop level by a nondiagonal Hbs coupling are studied within the context of an effective Yukawa sector that comprises $SU_L(2) \times U_Y(1)$-invariant operators of up to dimension six. The most recent experimental result on $B \to X_s\gamma$ with hard photons is employed to constrain the Hbs vertex, which is used to estimate the branching ratio for the $B_s \to \gamma\gamma$ decay. It is found that the $B_s \to \gamma\gamma$ decay can reach a branching ratio of the order of 4×10^{-8}, which is 2 orders of magnitude smaller than the current experimental limit.

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I. INTRODUCTION

Radiative B decays have attracted considerable attention in the last years. The rich phenomenology of weak meson decays [1] provides an excellent laboratory to probe effects of physics beyond the standard model (SM). In particular, suppressed observables such as $B \to X_s\gamma$, potentially sensitive to new physics effects, has been measured with good accuracy, showing no deviations from the SM. This means that this observable can provide stringent constraints on physics beyond the electroweak scale. In fact, the rare $b \to s\gamma$ decay has been shown to be very sensitive to possible new physics effects in diverse scenarios [2]. It results that the leading contribution to $B \to X_s\gamma$ decay with a hard photon is dominated by the $b \to s\gamma$ process. The current experimental value, which is given by the Heavy Flavor Averaging Group [3] along with the *BABAR*, Belle, and CLEO Collaborations, is $\text{Br}(B \to X_s\gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$ for a photon energy $E_\gamma > 1.6$ GeV. On the theoretical side, the SM prediction at the next to next leading order is $\text{Br}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ for $E_\gamma \gtrsim 1.6$ GeV [4]. This high level of coincidence between experimental and theoretical results leaves a very small room for physics beyond the SM, which means that this process can lead to strong constraints on new physics effects.

In this paper, 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, which are always present within the SM with additional $SU_L(2)$-Higgs multiplets or in larger gauge groups. Some processes naturally associated with flavor violation could be significantly impacted by extended Yukawa sectors, as it is expected that more complicated Higgs sectors tend to favor this class of new physics effects. We will assume that the flavor violating decays $b \to s\gamma$ and $b \to s\gamma\gamma$ are mediated by a virtual neutral Higgs boson with a mass of the order of magnitude of the Fermi scale $v \approx 246$ GeV. However, instead of tackling the problem in a specific model, we will adopt a model-independent approach by using the effective Lagrangian technique [5], which is an appropriate scheme to study those processes that are suppressed or forbidden in the SM. As it has been shown in Refs. [6–10], it is not necessary to introduce new degrees of freedom in order to generate flavor violation at the level of classical action; the introduction of operators of dimension higher than four will be enough. We will see below that an effective Yukawa sector that incorporates $SU_L(2) \times U_Y(1)$ invariants of up to dimension six is enough to reproduce, in a model-independent manner, the main features that are common to extended Yukawa sectors, such as the presence of flavor and CP violation. Although theories beyond the SM require more complicated Higgs sectors that include new physical scalars, we stress that our approach for studying flavor violation mediated by a relatively light scalar particle is sufficiently general to incorporate the most relevant aspects of extended theories. As in most cases, it is always possible to identify in an appropriate limit a SM-like Higgs boson whose couplings to pairs of W and Z bosons coincide with those given in the minimal SM. This is the case of the most general version of the two-Higgs doublet model (THDM-III) [11] and multi-Higgs models that comprise additional multiplets of $SU_L(2) \times U_Y(1)$ or scalar representations of larger gauge groups. Our approach also covers more exotic formulations of flavor violation, such as the so-called familons models [12] or theories that involve an Abelian flavor symmetry [13]. In this way, our results will be applicable to a wide variety of models that predict scalar-mediated flavor changing neutral currents. Besides its model independence, our framework has the advantage that it involves an equal or even lesser number of unknown parameters than those usually appearing in specific extended Yukawa sectors.

Our main goal in this work is to use the experimental data on the $B \to X_s\gamma$ decay to constrain the flavor violating

Hbs vertex induced by the effective Yukawa sector described above and to establish the amplitude for the $b \to s\gamma\gamma$ decay within this context. Then we will use these results to predict the branching ratio for the $B_s \to \gamma\gamma$ transition. The amplitude for the $b \to s\gamma\gamma$ transition has already been calculated within the context of the SM and used to estimate the branching ratio for the $B_s \to \gamma\gamma$ decay, which, without QCD corrections, was found to be of the order of 10^{-7} [14,15]. Subsequent studies showed that the next order QCD corrections increase the branching ratio up to a value of $\sim(1.0 - 1 - 2) \times 10^{-6}$ [16]. Long-distance effects, where the two photons are emitted from intermediate states, such as $B_s \to \phi\gamma \to \gamma\gamma$ [17], $B_s \to \Psi\phi \to \gamma\gamma$ [18], or $B_s \to D^{(*)+}D^{(*)-} \to \gamma\gamma$ [19], have also been considered. It was found that these processes lead to corrections of 20%, at best. In our case for the $B_s \to \gamma\gamma$ process, as we will see, the main contribution comes from the so-called Higgs-reducible diagram, since the contribution of the so-called box-reducible diagrams is marginal. In the leading contribution, the two photons are emitted from a virtual Higgs boson through the $B_s \to H^* \to \gamma\gamma$ process, in which the SM one-loop vertex $H^*\gamma\gamma$ play a crucial role. Beyond the SM, the $B_s \to \gamma\gamma$ decay has been studied in softly broken supersymmetry [20], in the two-Higgs doublet model [21], in the presence of a four generation [22], and in supersymmetry with broken R parity [23]. In general terms, the branching ratio for the $B_s \to \gamma\gamma$ decay calculated in the SM and other of its extensions is located in the range $(0.4\text{–}1.0) \times 10^{-6}$, which is 1 order of magnitude lower than the upper limit $\mathrm{Br}(B_s \to \gamma\gamma) < 8.7 \times 10^{-6}$ obtained by the Belle experiment [24]. It is expected in the near future at the KEKB e^+e^- asymmetric-energy collider that the luminosity will be increased around 50 fb^{-1} at energies near to the resonance $\Upsilon(5S)$, which could improve the current experimental limit on the branching ratio for the $B_s \to \gamma\gamma$ decay process [25].

The rest of the paper has been organized as follows. In Sec. II, the main features of the effective Yukawa sector that induce the flavor violating Hbs coupling are briefly discussed. Section III is devoted to deriving a constraint on the Hbs vertex from the experimental data on the $B \to X_s\gamma$ decay. In Sec. IV, the amplitude for the $b \to s\gamma\gamma$ transition induced by the flavor violating Hbs vertex is introduced and its implications for the $B_s \to \gamma\gamma$ decay are discussed. Finally, in Sec. V the conclusions are presented.

II. THE EFFECTIVE YUKAWA SECTOR

As is shown in Refs. [6–10], it is not necessary to introduce explicitly additional degrees of freedom to generate Higgs-mediated flavor changing neutral current effects within the SM, but only their virtual effects through an effective Lagrangian that includes $SU_L(2) \times U_Y(1)$-invariant Yukawa-like interactions of dimensions higher than four. An appropriate effective Yukawa sector that generates flavor violating effects in the quark sector is given by [6–10]

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

where Y_{ij}, Q_i, Φ, d_i, and u_i stand for the usual 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} numbers are the components of a 3×3 general matrix, which parametrize the details of the underlying physics, whereas Λ is the typical scale of these new physics effects.

After spontaneous symmetry breaking, this extended Yukawa sector can be diagonalized in the usual manner via the unitary matrices $V^{d,u}_L$ and $V^{d,u}_R$, which correlate gauge states to mass eigenstates. In the unitary gauge, the diagonalized Lagrangian can be written as follows:

$$\begin{aligned}\mathcal{L}^Y_{\rm eff} = &-\left(1 + \frac{g}{2m_W}H\right)(\bar{D}M_dD + \bar{U}M_uU)\\ &- H\left(1 + \frac{g}{4m_W}H\left(3 + \frac{g}{2m_W}H\right)\right)\\ &\times (\bar{D}\Omega^dP_RD + \bar{U}\Omega^uP_RU + \mathrm{H.c.}),\end{aligned} \tag{2}$$

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. In addition, Ω^a are matrices defined in the flavor space through the relation

$$\Omega^a = \frac{1}{\sqrt{2}}\left(\frac{v}{\Lambda}\right)^2 V^a_L\alpha^aV^{a\dagger}_R. \tag{3}$$

To generate Higgs-mediated flavor changing neutral current effects at the level of classical action, it is assumed that neither $Y^{d,u}$ nor $\alpha^{d,u}$ are diagonalized by the $V^a_{L,R}$ rotation matrices, which should only diagonalize the sum $Y^{d,u} + \alpha^{d,u}$. As a consequence, mass and interactions terms would not be simultaneously diagonalized as occurs in the dimension-four theory. In addition, if $\Omega^{a\dagger} \neq \Omega^a$, the Higgs boson couples to fermions through both scalar and pseudoscalar components, which in turn could lead to CP violation in some processes. As a consequence, the flavor violating coupling $H\bar{q}_iq_j$ has the most general renormalizable structure of scalar and pseudoscalar type given by $-i(\Omega_{ij}P_R + \Omega^*_{ij}P_L)$. Notice also that the Lagrangian in Eq. (2) gives not only couplings of the type $H\bar{q}_iq_j$ but also couplings of the type $HH\bar{q}_iq_j, \ldots$, etc., which are of no interest for our analysis.

III. CONSTRAINT ON Hbs FROM $B \to X_s\gamma$

The sensitivity of the $b \to s\gamma$ transition to new physics effects has been studied in diverse approaches beyond the SM, as supersymmetric models [26], the two-Higgs doublet model [27], left-right symmetric models [28], technicolor models [29], models with a fourth generation [30], supergravity models [31], effective field theories [32], the littlest Higgs model [33], unparticle interactions [34], 331 models [35], and extra dimensions [36]. In this section, we calculate the contribution of the flavor violating Hbs coupling to the $b \to s\gamma$ and $b \to sg$ decays and study their implications for the $B \to X_s\gamma$ process. At the leading order in QCD, the $b \to s$ transition is described via an operator product expansion based on the effective Hamiltonian [37]

$$H_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu) O_i(\mu), \qquad (4)$$

where the Wilson coefficients $C_i(\mu)$ are evolved from the electroweak scale down to $\mu = m_b$ by the renormalization group equations. The O_i is a set of eight renormalized dimension-six operators. From these, the O_{1-6} represent interactions among four light quarks and are not of interest for our purposes. The remainder O_7 and O_8 parametrize the electromagnetic dipolar transition and the analogous strong dipolar transition, whose contributions to the $b \to s\gamma$ and $b \to sg$ transitions are dominated by one-loop effects of the t quark and the W gauge boson. The corresponding amplitudes can be written as follows:

$$\mathcal{M}_{\rm SM}(b \to s\gamma) = -V_{tb}V_{ts}^* \frac{\alpha^{3/2}}{8\sqrt{\pi} s_W^2 m_W^2} \times C_7(\mu)\bar{s}(p_s)\sigma_{\mu\nu}\epsilon^{*\mu}(q,\lambda)q^\nu \times (m_s P_L + m_b P_R) b(p_b), \qquad (5)$$

$$\mathcal{M}_{\rm SM}(b \to sg) = -V_{tb}V_{ts}^* \frac{\sqrt{\alpha_s}\alpha}{8\sqrt{\pi} s_W^2 m_W^2} \times C_8(\mu)\bar{s}(p_s)\sigma_{\mu\nu}\epsilon_a^{*\mu}(q,\lambda)q^\nu T^a \times (m_s P_L + m_b P_R) b(p_b), \qquad (6)$$

where $\epsilon^\mu(q,\lambda)$ and $\epsilon_a^\mu(q,\lambda)$ are the polarization vectors of the photon and gluon, respectively. Here, T^a are the generators of the $SU_C(3)$ group, which are normalized as ${\rm Tr}(T^aT^b) = \delta^{ab}/2$, and α_s is the strong coupling constant.

As for new physics effects induced by the flavor violating Hbs vertex, the contribution to the $b \to s\gamma$ and $b \to sg$ transitions is given through the loop diagrams shown in Fig. 1. A direct calculation leads to amplitudes of the dipolar type, free of ultraviolet divergences, given by

$$\mathcal{M}_{\rm NP}(b \to s\gamma) = -\frac{Q_b \alpha}{16\pi s_W m_W} \mathcal{F} \bar{s}(p_s)\sigma_{\mu\nu}\epsilon^{*\mu}(q,\lambda)q^\nu \times (\Omega_{bs}^* P_L + \Omega_{bs} P_R) b(p_b), \qquad (7)$$

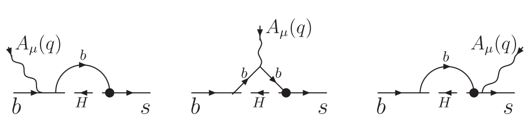

FIG. 1. Diagrams contributing to the $b \to s\gamma$ transition. The $b \to sg$ process occurs via the same type of diagrams.

$$\mathcal{M}_{\rm NP}(b \to sg) = -\frac{\sqrt{\alpha_s \alpha}}{16\pi s_W m_W} \mathcal{F} \bar{s}(p_s)\sigma_{\mu\nu}\epsilon_a^{*\mu}(q,\lambda)q^\nu T^a \times (\Omega_{bs}^* P_L + \Omega_{bs} P_R) b(p_b), \qquad (8)$$

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

$$\begin{aligned}\mathcal{F} &= \frac{3}{2} - 2(B_0(3) - B_0(2)) - \frac{m_H^2}{m_b^2}(2B_0(1) - B_0(3) - B_0(4) + 2) \\ &= \frac{3}{2} + x\sqrt{x^2 - 4x}\,{\rm sech}^{-1}\left(\frac{2}{\sqrt{x}}\right) + \frac{(2(2 - 3x + x^2) + (3x^2 - x^3)\ln(x))}{2(x-1)},\end{aligned} \qquad (9)$$

where $x = m_H^2/m_b^2$ and, in second line, the explicit form of Passarino-Veltman scalar functions $B_0(i)$ [10] were used: $B_0(1) = B_0(0, m_H^2, m_H^2)$, $B_0(2) = B_0(0, m_b^2, m_b^2)$, $B_0(3) = B_0(0, m_H^2, m_b^2)$, and $B_0(4) = B_0(m_b^2, m_H^2, m_b^2)$. Let us mention that we are tacitly assuming that Ω_{bs} is purely imaginary; otherwise the CP-violation condition is not satisfied as it is required for the B_s meson.

In the context of the effective theory that we are considering, 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:

$$\mathcal{M}_T = \mathcal{M}_{\rm SM} + \mathcal{M}_{\rm NP}. \qquad (10)$$

Our main objective in this section is to get a bound for the Ω_{bs} parameter. We will follow closely the analysis given in Ref. [34]. The discrepancy between the theoretical prediction within the SM and the experimental measurement can be quantified via the following ratio:

$$R_{\rm EXP-SM} \equiv \frac{\Gamma_{\rm EXP} - \Gamma_{\rm SM}}{\Gamma_{\rm SM}} = \frac{{\rm Br}_{\rm EXP}(B \to X_s\gamma)}{{\rm Br}_{\rm SM}(B \to X_s\gamma)} - 1, \qquad (11)$$

where $\Gamma_{\rm EXP}$ is the experimental decay width of the $B \to X_s\gamma$ transition and $\Gamma_{\rm SM}$ is the corresponding theoretical prediction of the SM. In addition, ${\rm Br}_{\rm EXP}$ and ${\rm Br}_{\rm SM}$ are the respective branching ratios. Using the experimental and theoretical values presented at the beginning of the introduction, it is found that the discrepancy between theory and experiment is given by $R_{\rm EXP-SM} = 0.117 \pm 0.113$. To constrain the Hbs vertex, we will assume that the total theoretical prediction, i.e., the SM prediction plus the Hbs contribution, coincides with the experimental value. Thus, we define the ratio

$$R_{\rm TOT-SM} \equiv \frac{\Gamma_{\rm SM+NP} - \Gamma_{\rm SM}}{\Gamma_{\rm SM}} = \frac{{\rm Br}_{\rm SM+NP}}{{\rm Br}_{\rm SM}} - 1, \qquad (12)$$

which quantifies the theoretical discrepancy between the effective theory prediction (SM plus new physics effects) and the SM prediction. We now demand that $R_{\rm TOT-SM} \approx R_{\rm EXP-SM}$, which allows us to obtain a bound for the Ω_{bs}

parameter. Before doing this, some additional considerations must be taken into account. Working out at leading order, which is sufficient for our purposes, the SM contribution can be written as follows:

$$\mathcal{M}_{\rm SM}(b \to s\gamma) = \bar{s}(p_s)\sigma_{\mu\nu}\epsilon^{*\mu}(q,\lambda)q^{\nu} \times (A^L_{\rm SM}P_L + A^R_{\rm SM}P_R)b(p_b), \quad (13)$$

where the $A^{L,R}_{\rm SM}$ form factors are given by

$$\begin{aligned} A^L_{\rm SM} &= -V_{tb}V^*_{ts}\frac{\alpha^{3/2}}{8\sqrt{\pi}s^2_W m^2_W}C^{\rm eff}_7(m_b)m_s, \\ A^R_{\rm SM} &= -V_{tb}V^*_{ts}\frac{\alpha^{3/2}}{8\sqrt{\pi}s^2_W m^2_W}C^{\rm eff}_7(m_b)m_b, \end{aligned} \quad (14)$$

with an effective Wilson coefficient $C^{\rm eff}_7(m_b) = 0.689C_7(m_W) + 0.087C_8(m_W)$ [37], which already contains the QCD contribution at the m_b scale. In a similar way, the corresponding new physics contribution can be written as follows:

$$\mathcal{M}_{\rm NP}(b \to s\gamma) = \bar{s}(p_s)\sigma_{\mu\nu}\epsilon^{*\mu}(q,\lambda)q^{\nu} \times (A^L_{\rm NP}P_L + A^R_{\rm NP}P_R)b(p_b), \quad (15)$$

where

$$\begin{aligned} A^L_{\rm NP} &= -\frac{Q_b\alpha}{16\pi s_W m_W}\Omega^*_{bs}\mathcal{F}\left(0.689 + \frac{0.087}{Q_b}\right), \\ A^R_{\rm NP} &= -\frac{Q_b\alpha}{16\pi s_W m_W}\Omega_{bs}\mathcal{F}\left(0.689 + \frac{0.087}{Q_b}\right). \end{aligned} \quad (16)$$

From expression (12) and the assumption $R_{\rm TOT-SM} \approx R_{\rm EXP-SM}$, one obtains

$$R_{\rm EXP-SM} = \frac{|A^L_{\rm SM} + A^L_{\rm NP}|^2 + |A^R_{\rm SM} + A^R_{\rm NP}|^2}{|A^L_{\rm SM}|^2 + |A^R_{\rm SM}|^2} - 1. \quad (17)$$

The problem of finding a bound for the Ω_{bs} parameter reduces now to solve a quadratic equation, which has two solutions.[1] The physical solution corresponds to that for which the allowed values for Ω_{bs} satisfy the $|A_{\rm SM}|^2 > |A_{\rm NP}|^2$ condition, which is a reasonable requirement. In Fig. 2, the behavior of $|\Omega_{bs}|^2$ as a function of the Higgs mass in the range 100 GeV $< m_H <$ 200 GeV is shown. From this figure, it can be appreciated that $|\Omega_{bs}|^2 < (0.7 - 6.8) \times 10^{-3}$ for a Higgs mass in the range 115 GeV $< m_H <$ 200 GeV. Within the context of the minimal supersymmetric standard model in the uplifted region, a similar result for Ω_{bs} was recently obtained in Ref. [38] coming from the $B_s - \bar{B}_s$ mixing system for a Higgs mass of 650 GeV. On the other hand, we would like to mention that in Ref. [8] experimental results from $D^0 - \bar{D}^0$ mixing were used to get a constraint on the Htc coupling, where the parameter Ω_{tc} was bounded to be $\Omega^2_{tc} < 10^{-2}$, which represents the strength of the Htc interaction.

[1]In the numerical evaluation, the central value for $R_{\rm EXP-SM}$ was used.

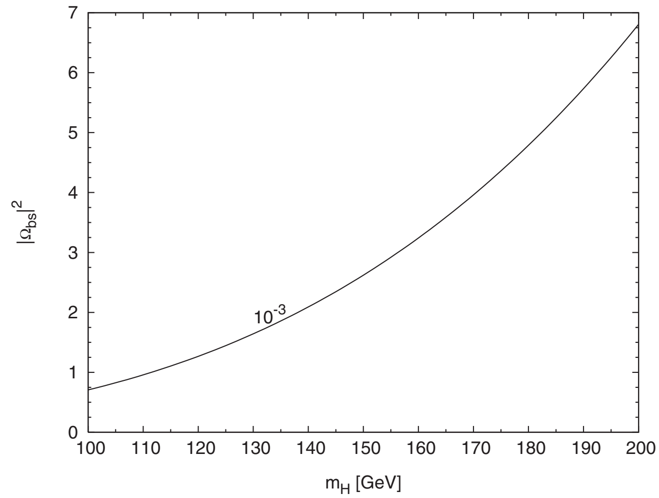

FIG. 2. $|\Omega_{bs}|^2$ as a function of the Higgs mass.

IV. THE $B_s \to \gamma\gamma$ DECAY

As mentioned above, the Hbs effective vertex induces the flavor violating process $b \to s\gamma\gamma$ at the one-loop level (with kinematics defined in Fig. 3). The contribution to $b \to s\gamma\gamma$ occurs through two sets of Feynman diagrams, each given a finite and gauge invariant contribution [9]. The first set of diagrams (see Fig. 3) 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. 4). These type of graphs will be named Higgs-reducible diagrams. We find that the dominant Higgs-mediated flavor violating effect is given by the contribution of the Feynman diagrams shown in Fig. 4. The arising contributions from box-reducible graphs are marginal due to the bottom quark charge, which induces an extra factor equal to 1/9 at the one-loop level amplitude.

In order to make predictions, we will use our previous result for the flavor violating parameter $\Omega_{bs}(m_H)$ as a function of the Higgs mass. We find that the amplitude for the $b \to s\gamma\gamma$ decay can be written as [9]

$$\mathcal{M}^{\mu\nu} = \frac{\alpha g}{8\pi m_W}F_0\bar{u}_s(p_s)(\Omega_{bs}P_R + \Omega^*_{bs}P_L) \times \frac{k^{\mu}_2 k^{\nu}_1 - k_1\cdot k_2 g^{\mu\nu}}{2k_1\cdot k_2 - m^2_H + im_H\Gamma_H}u_b(p_b), \quad (18)$$

with

$$
\begin{aligned}
F_0 &= \frac{8m_W^2}{2k_1\cdot k_2}\left(3+\frac{2k_1\cdot k_2}{2m_W^2}+6m_W^2\left(1-\frac{2k_1\cdot k_2}{2m_W^2}\right)C_0(1)\right)-Q_t^2N_{c_t}\frac{8m_t^2}{2k_1\cdot k_2}(2+(4m_t^2-2k_1\cdot k_2)C_0(2)),\\
&=\frac{8m_W^2}{2k_1\cdot k_2}\left\{3+\frac{k_1\cdot k_2}{m_W^2}-\frac{3m_W^2}{2k_1\cdot k_2}\left(1-\frac{k_1\cdot k_2}{m_W^2}\right)\left[\pi^2-4\pi\cot^{-1}\left(\frac{\sqrt{k_1\cdot k_2}}{\sqrt{2m_W^2-k_1\cdot k_2}}\right)\right.\right.\\
&\quad\left.\left.+8\left[\cot^{-1}\left(\frac{\sqrt{k_1\cdot k_2}}{\sqrt{2m_W^2-k_1\cdot k_2}}\right)\right]^2+\left[\ln\left(\frac{k_1\cdot k_2-m_W^2+i\sqrt{k_1\cdot k_2(2m_W^2-k_1\cdot k_2)}}{m_W^2}\right)\right]^2\right]\right\}\\
&\quad-Q_t^2N_{c_t}\frac{8m_t^2}{2k_1\cdot k_2}\left\{2+\frac{(4m_t^2-2k_1\cdot k_2)}{4k_1\cdot k_2}\left[\pi^2-4\pi\cot^{-1}\left(\frac{\sqrt{k_1\cdot k_2}}{\sqrt{2m_t^2-k_1\cdot k_2}}\right)+8\left[\cot^{-1}\left(\frac{\sqrt{k_1\cdot k_2}}{\sqrt{2m_t^2-k_1\cdot k_2}}\right)\right]^2\right.\right.\\
&\quad\left.\left.+\left[\ln\left(\frac{k_1\cdot k_2-m_t^2+i\sqrt{k_1\cdot k_2(2m_t^2-k_1\cdot k_2)}}{m_t^2}\right)\right]^2\right]\right\},
\end{aligned}
\tag{19}
$$

where the Passarino-Veltman scalar functions $C_0(1) = C_0(0, 0, 2k_1 \cdot k_2, m_W^2, m_W^2, m_W^2)$ and $C_0(2) = C_0(0, 0, 2k_1 \cdot k_2, m_t^2, m_t^2, m_t^2)$ [10] were used, m_t is the top quark mass, Q_t is the top quark charge, and $N_{c_t} = 3$ is the color factor.

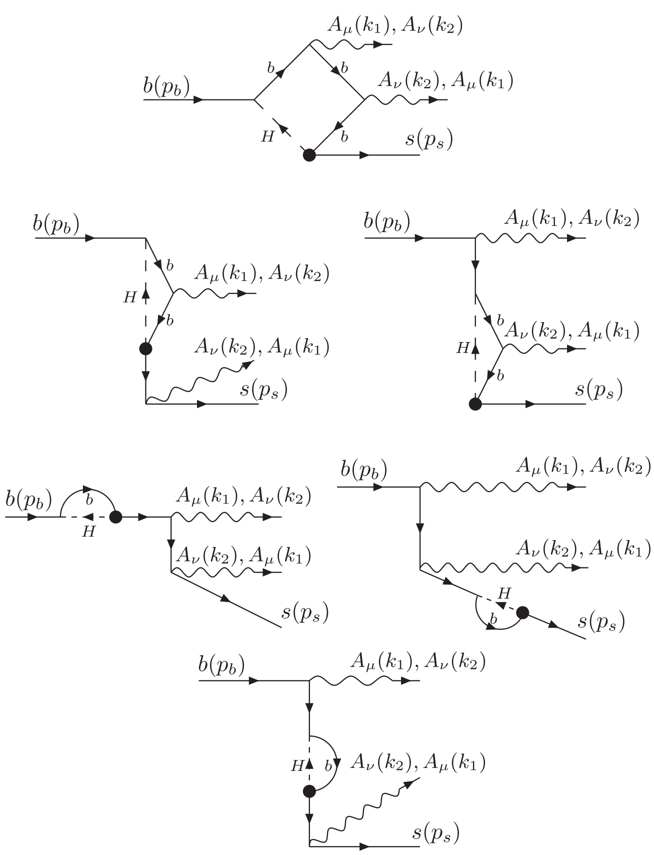

FIG. 3. Contribution of the box and reducible diagrams to the $b \to s\gamma\gamma$ decay.

According to the static quark approximation [15,23], 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 $m_{B_s} = m_b + m_s$[2] is the B_s-meson mass.

In order to get the amplitude for $B_s \to \gamma\gamma$ we resort to the following matrix elements [15,23]:

$$
\begin{aligned}
\langle 0|\bar{u}_s\gamma^5 u_b|B_s\rangle &= i f_{B_s} m_{B_s},\\
\langle 0|\bar{u}_s\gamma^\mu\gamma^5 u_b|B_s\rangle &= i f_{B_s} P^\mu,
\end{aligned}
\tag{20}
$$

where $P = p_b - p_s$ is the B_s-meson four-momentum and f_{B_s} is the B_s-meson decay constant. By using the above matrix elements the amplitude for $B_s \to \gamma\gamma$ can be written as follows:

$$
\mathcal{M}^{\mu\nu}(B_s \to \gamma\gamma) = f_{B_s} B_{\rm NP}\left(k_1^\nu k_2^\mu - \frac{m_{B_s}^2}{2} g^{\mu\nu}\right), \tag{21}
$$

where $B_{\rm NP}$ is the Higgs-mediated flavor violating form factor defined as

$$
B_{\rm NP} = \frac{\alpha^{3/2}\Omega_{bs}}{4\pi^{1/2} s_W}\frac{m_{B_s}}{m_W m_H^2} F_0. \tag{22}
$$

This implies that the decay width for the $B_s \to \gamma\gamma$ process arising from the new physics effects encoding in $B_{\rm NP}$ has the following form:

[2] As in Refs. [15,23], we will use the constituent mass for the strange quark $m_s = m_K = 0.497$ GeV.

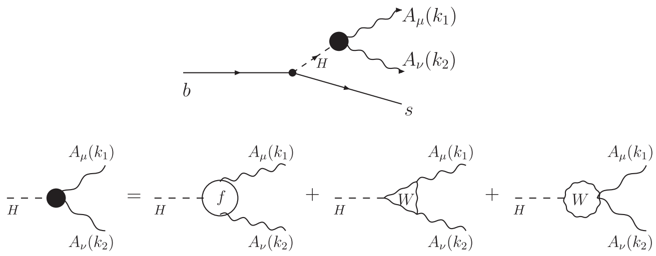

FIG. 4. Contribution of the SM one-loop induced $H^*\gamma\gamma$ vertex to the $b \to s\gamma\gamma$ decay.

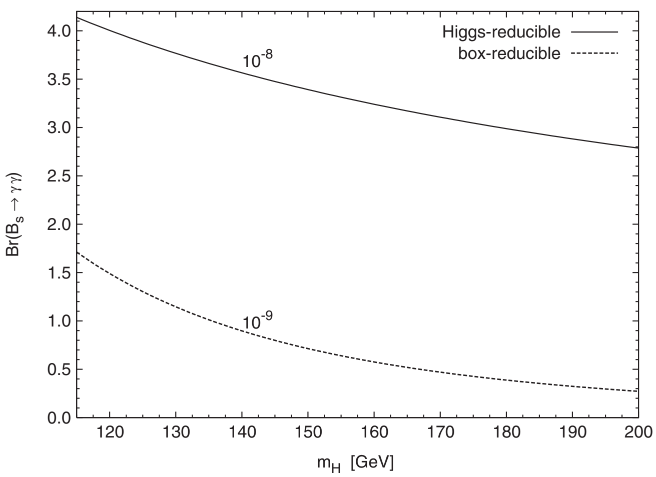

FIG. 5. The branching ratio of the $B_s \to \gamma\gamma$ decay for the Higgs-reducible contribution (solid line) and box-reducible contribution (dashed line) as a function of the Higgs mass.

$$\Gamma(B_s \to \gamma\gamma) = f_{B_s}^2 \frac{m_{B_s}^3}{16\pi} |B_{\rm NP}|^2. \tag{23}$$

Finally, we can compute the corresponding branching ratio for $B_s \to \gamma\gamma$ decay by means of

$$\mathrm{Br}\,(B_s \to \gamma\gamma) = \frac{\Gamma(B_s \to \gamma\gamma)}{\Gamma_T(B_s)}, \tag{24}$$

where $\Gamma_T(B_s)$ is the total B_s-meson width decay determined by its lifetime $\tau(B_s) = 1.43$ ps [39].

Hereafter, we shall present our results for $\mathrm{Br}(B_s \to \gamma\gamma)$ as a function of the Higgs mass. The results were obtained using the values $m_{B_s} = 5.37$ GeV, $m_K = 0.497$ GeV, and $f_{B_s} = 0.24$ GeV. We show in Fig. 5 the branching ratio for the $B_s \to \gamma\gamma$ process, where it has displayed separately the contributions coming from Higgs-reducible and box-reducible diagrams. 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. Moreover, we can see that $\mathrm{Br}(B_s \to \gamma\gamma)$ ranges from 4.14×10^{-8} to 2.79×10^{-8} for a Higgs mass in the same range. We note that the behavior of both curves in Fig. 5 is such that, essentially, the difference in order of magnitude is maintained along the Higgs mass range analyzed.

From the discussion presented in the introduction, we can appreciate that our prediction for the Higgs-mediated flavor violating $\mathrm{Br}(B_s \to \gamma\gamma)$ process is almost 2 orders of magnitude smaller than the current experimental limit and 1 order of magnitude lower than those derived from SM and its extensions.

V. CONCLUSIONS

Effective theories beyond the SM can encode new physics effects such as flavor violating transitions which is of current interest. In this work we have used dimension-six operators in the Yukawa sector to study these transitions mediated by a SM-like Higgs boson. In particular we have studied the resulting Hbs coupling and estimated its strength from the branching ratio for the $B \to X_s\gamma$ process; specifically, 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 on the branching ratio in question are 2 orders of magnitude smaller than the current experimental bound imposed by the Belle Collaboration. As expected we found that the box-reducible diagrams contribute marginally to the $B_s \to \gamma\gamma$ process, this being dominated by the contribution of the Higgs-reducible diagrams. Finally we would like to stress that our bound for this process is model-independent, with two free parameters, namely, the effective coupling strength Ω_{bs} which is fixed from experimental results for the branching ratio of the $B \to X_s\gamma$ process, and the mass of the Higgs boson.

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