

$h \rightarrow \Upsilon\gamma$ decay: Smoking gun signature of a wrong-sign $hb\bar{b}$ couplingAditya Batra^{1,2,*} Sanjoy Mandal^{3,†} and Rahul Srivastava^{1,‡}¹*Department of Physics, Indian Institute of Science Education and Research–Bhopal, Bhopal Bypass Road, Bhauri, Bhopal, India*²*Departamento de Física and CFTP, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal*³*Korea Institute for Advanced Study, Seoul 02455, Korea*

(Received 27 January 2026; accepted 13 August 2026; published 21 September 2026)

We perform a model-independent study of new physics effects in the Higgs decay $h \rightarrow \Upsilon\gamma$, focusing on scenarios that spoil the accidental cancellation between the direct and indirect amplitudes. After imposing all existing constraints from Higgs production and decay measurements, we find that a wrong-sign $hb\bar{b}$ coupling is the only viable scenario capable of enhancing the $h \rightarrow \Upsilon\gamma$ decay width by nearly 2 orders of magnitude. Therefore, an observation of a significantly enhanced $h \rightarrow \Upsilon\gamma$ rate at the LHC or future colliders would provide unambiguous evidence for a wrong-sign $hb\bar{b}$ coupling, directly pointing to the presence of an extended Higgs sector.

DOI: [10.1103/jndm-5wnt](https://doi.org/10.1103/jndm-5wnt)**I. INTRODUCTION**

The Standard Model (SM) of particle physics is a theory that describes electromagnetic, weak, and strong interactions using symmetry groups $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. It also consists of a framework that classifies all known fundamental particles with specific charges under these groups. Although it is an extremely successful theory with most of its predictions confirmed by experiments, it still remains a flawed theory with severe shortcomings. For example, it does not contain any particles that could be viable candidates for dark matter, as expected by observational cosmology [1]. It also does not incorporate masses for neutrinos deduced from neutrino oscillation experiments [2–5]. In addition, the SM also has several other shortcomings such as Higgs vacuum stability, the hierarchy problem, and baryon-antibaryon asymmetry, to name a few. In order to overcome these limitations, one has to extend the particle content of the SM. The new particles and interactions present in such Beyond Standard Model (BSM) proposals can then be tested directly or indirectly in various currently running experiments such as at the LHC.

On the experimental front, in 2012, the LHC discovered a new spin-0 particle [6,7]. So far the experimental data (see Table IV) on decay channels and branching ratios (BRs) are consistent with the predictions of the SM Higgs (h) boson. However, one must now do precision measurements of its couplings to other SM particles and verify whether there are any deviations from the predictions for the SM Higgs boson. Therefore, measuring the yet unmeasured couplings and improving the precision of the measured ones is one of the main physics goals of not only Run 3 of the LHC but also of various proposed future colliders [8–13].

Among the various Higgs couplings, measuring the Yukawa coupling of Higgs to fermions of the SM is especially challenging. This is because in the SM as well as in many simple BSM models, the Yukawa coupling strength is directly proportional to the mass of the fermion with which the Higgs couples. Since the light quarks (u , d , s) and charged leptons (e , μ) have very small masses, measuring their Yukawa couplings through Higgs decay to them becomes very challenging as the branching ratios are very small (see Fig. 12 and Table IV). The branching ratios of Higgs decay to b and c quarks as well as to the charged lepton τ are not small, but measuring them is still challenging due to complications arising from background events as well as difficulties in correctly tagging the resulting jets. As a result, only a few such decay modes have been measured at the LHC, as shown in Table IV. Thus, before one can conclude that the 125 GeV scalar particle observed at the LHC is the SM Higgs boson, one needs to measure and compare these Higgs fermionic decay modes to the SM predictions.

*Contact author: aditya.batra@tecnico.ulisboa.pt†Contact author: smandal@kias.re.kr‡Contact author: rahul@iiserb.ac.in

Among all the Yukawas, perhaps the Higgs coupling to b -quark is of particular interest. In the SM, the $h \rightarrow b\bar{b}$ decay has the largest branching ratio and has also been measured at the LHC [14,15]. Despite having the largest branching ratio, the observation of the $h \rightarrow b\bar{b}$ decay mode was very challenging and took quite some time. The current measured value is consistent with the SM prediction but has large error bars, leaving considerable room for deviations from the SM value due to presence of new physics. Even if the uncertainty in measurement is reduced substantially in the future, the $hb\bar{b}$ coupling can still have BSM imprints on it. One such simple but interesting scenario is the possibility of the $hb\bar{b}$ coupling being of the “wrong-sign”.

The wrong-sign $hb\bar{b}$ coupling can in fact arise in some of the natural and popular BSM extensions with extended scalar sectors. For example, the two-Higgs doublet model (2HDM) [16,17] is one of the simplest conceivable scalar extensions of the Standard Model. The 2HDMs arise in various contexts, with the scalar sector of many models being of the 2HDM form. For instance, the minimal versions of supersymmetry such as the Minimal Supersymmetric Standard Model have a specific (type II) 2HDM scalar sector and such is also the case in the scotogenic model for neutrino mass and dark matter [18]. Furthermore, 2HDMs can generate baryon asymmetry of substantial size in the Universe due to new sources of CP -violation through the complex parameters in the potential. There also exist 2HDMs that contain viable dark matter candidates, such as inert 2HDMs. Needless to say, 2HDMs are not only popular but also ubiquitous among BSM models. Even among the simplest 2HDM scenarios with an additional $\mathbb{Z}_2$ symmetry, the wrong-sign solution exists in the type II and flipped 2HDMs where the sign of the $hb\bar{b}$ coupling can be opposite to that of the SM.

Given the possibility of the wrong-sign solution among BSM physics, how can we look for its phenomenological signatures? The effect of the wrong sign must be examined indirectly because a sign change has no influence on the $h \rightarrow b\bar{b}$ rate. This means that the ideal place to look for wrong-sign solutions is in processes where two or more Feynman diagrams contribute. In such processes, the interference term will preserve some information about any anomalous and/or wrong-sign $hb\bar{b}$ coupling [19–22]. The aim of this work is to conclusively show that the rare Higgs decay $h \rightarrow \Upsilon\gamma$ is the ideal place to look for it¹ and observation of such a decay by the LHC or any future collider with a branching ratio substantially larger than the SM expectation will be a smoking gun signature of wrong-sign $hb\bar{b}$ coupling.

¹Throughout this work, we will mostly concentrate on the decay mode $h \rightarrow \Upsilon(1S)\gamma$; however, the results and the conclusion of this work can be easily generalized and applied to $h \rightarrow \Upsilon(2S)\gamma$ and $h \rightarrow \Upsilon(3S)\gamma$ decay modes as well. For the sake of brevity, we have also dropped the (1S) label and will simply denote it as $h \rightarrow \Upsilon\gamma$ decay.

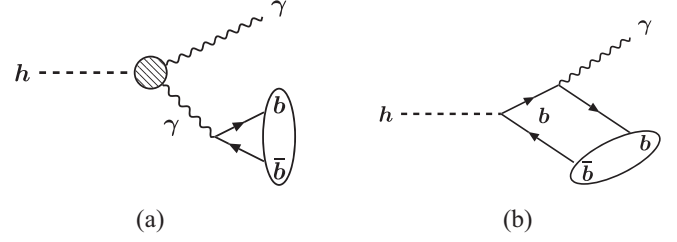


FIG. 1. Indirect (a) and direct (b) Feynman diagrams of the $h \rightarrow \Upsilon\gamma$ process.

In the SM, the decay $h \rightarrow \Upsilon\gamma$ comprises two types of Feynman diagrams called the direct and indirect diagrams; see Fig. 1. In the SM, the direct and indirect diagrams are of about equal magnitude but interfere destructively. Due to the cancellation between the two diagrams [23–26], the decay width of $h \rightarrow \Upsilon\gamma$ in the SM is greatly reduced when compared, for example, to $h \rightarrow J/\psi\gamma$; see Table V in Appendix A. This accidental cancellation in $h \rightarrow \Upsilon\gamma$ in the SM makes it an ideal channel to look for BSM physics. Any new physics contribution which can disrupt the accidental cancellation can potentially enhance the $h \rightarrow \Upsilon\gamma$ branching ratio significantly. Indeed, it was shown in Refs. [27,28] that the wrong-sign $hb\bar{b}$ coupling can enhance the $h \rightarrow \Upsilon\gamma$ branching ratio by about 2 orders of magnitude. Therefore, $h \rightarrow \Upsilon\gamma$ is the cleanest decay mode for probing the wrong-sign solution [27].

However, the reverse question still remains, i.e., if one observes the $h \rightarrow \Upsilon\gamma$ branching ratio to be significantly enhanced compared to the SM prediction, can one conclusively say that it is indeed due to the wrong-sign $hb\bar{b}$ coupling? The answer is not so straightforward as there is also the possibility of the cancellation being broken due to changes in the sign or magnitude of the indirect contribution. Therefore, one must thoroughly and systematically analyze all possible types of new physics contributions that can disrupt this accidental cancellation by changing the contribution coming from indirect diagram(s). In this work, we perform such a model-independent analysis, taking into account all possible contributions that can change either the sign or the magnitude of the direct or indirect contribution and thus break the accidental cancellation of the SM. After considering all such possibilities, we show that the wrong-sign $hb\bar{b}$ coupling is the only way one can change the branching ratio of the $h \rightarrow \Upsilon\gamma$ decay significantly. We can thus conclusively say that if the LHC or any future collider observes $h \rightarrow \Upsilon\gamma$ to be much larger than the SM expectation, then this is not only a conclusive signature of new physics but also that this new physics has to be related with the wrong-sign $hb\bar{b}$ coupling.

This paper is organized as follows: in Sec. II, we introduce the rare Higgs decay to $\Upsilon\gamma$. In Secs. III and IV, we discuss the modifications to the direct and indirect contributions of the $h \rightarrow \Upsilon\gamma$ decay respectively, looking in a model-independent way, at all possible new particle

contributions to the indirect mode in detail. Finally, we summarize our results in Sec. V. Further details on the Higgs boson couplings and decay channels, including their current experimental status, as well as the formulas relevant to our calculations, are provided in the Appendixes.

II. HIGGS DECAY TO $\Upsilon\gamma$

The $h \rightarrow \Upsilon(1S, 2S, 3S)\gamma$ decay process has two leading contributions from the so called direct and indirect Feynman diagrams shown in Fig. 1. In the indirect mode, h decays to $\gamma\gamma$ via a loop and one photon then morphs into an Υ , as shown in Fig. 1(a). In the SM, the primary contribution to the $h \rightarrow \gamma\gamma$ loop comes from the W boson followed by the top quark, which interferes destructively. In the direct mode, h decays to $b\bar{b}$ and either b or $\bar{b}$ emits a photon, as shown in Fig. 1(b). Note that in the SM, there is another indirect diagram in which the virtual γ is replaced by a virtual Z boson which morphs into an Υ . However its contribution is negligible due to the large mass of the Z boson.

The $h \rightarrow \Upsilon(1S)\gamma$ decay width in the SM is given as [23–26]

$$\Gamma[h \rightarrow \Upsilon\gamma] = \frac{1}{8\pi} \frac{m_h^2 - m_\Upsilon^2}{m_h^2} |\mathcal{A}_{\text{direct}} + \mathcal{A}_{\text{indirect}}|^2, \quad (1)$$

where the direct and indirect decay amplitudes are as given in Ref. [23], as follows:

$$\begin{aligned} \mathcal{A}_{\text{direct}} &= -K \frac{2}{\sqrt{3}} e \left(\sqrt{2} G_F \frac{m_\Upsilon}{m_h} \right)^{1/2} \frac{m_h^2 - m_\Upsilon^2}{(m_h^2 - m_\Upsilon^2/2 - 2m_b^2)} \\ &\quad \times \phi_0(\Upsilon), \\ \mathcal{A}_{\text{indirect}} &= -\frac{eg_{\Upsilon\gamma}}{m_\Upsilon^2} (\sqrt{2} G_F)^{1/2} \frac{\alpha}{\pi} \frac{m_h^2 - m_\Upsilon^2}{\sqrt{m_h}} \zeta, \end{aligned} \quad (2)$$

where G_F is the Fermi constant, e is the absolute charge of the electron, m_Υ and m_b are the Υ and b -quark masses, α is the fine-structure constant, $\phi_0^2(\Upsilon) \sim 0.512 \text{ GeV}^3$ is the wave function of Υ at the origin, $g_{\Upsilon\gamma} = \frac{2}{\sqrt{3}} \sqrt{m_\Upsilon} \phi_0(\Upsilon)$, ζ is the effective $h\gamma\gamma$ coupling at one-loop, and $K = 0.689$ is an added factor that comes from next-to-leading order corrections [23]. Note that the sign of ζ is negative which implies that the overall sign of the indirect amplitude is positive and that of the direct amplitude is negative. This means that the direct and indirect contributions in the SM interfere destructively. Moreover, in the SM it so happens that the contributions of the direct and indirect diagrams are almost of the same magnitude. Thus, there is an almost complete cancellation of the two contributions, leading to a much smaller decay width compared to other Higgs quarkonium decays listed in Table V. Before moving on, note that due to the close nature of the cancellation, the SM branching ratio of $h \rightarrow \Upsilon\gamma$ is extremely sensitive to the values of the input parameters and different groups have

reported slightly different values of the SM branching ratios [23–26]. However, since in our work we are interested in new physics effects which can change the branching ratio by orders of magnitude, the high sensitivity to input parameters will not have any appreciable effect on our results and conclusions.

The accidental cancellation between the direct and indirect diagrams for $h \rightarrow \Upsilon\gamma$ in the SM makes this decay channel an excellent hunting ground for BSM models. Any new physics which disrupts this accidental cancellation will increase the branching ratio of $h \rightarrow \Upsilon\gamma$, potentially by orders of magnitude. This disruption can happen primarily because of either (a) modifications in the direct diagram or (b) modification in the indirect diagram. In the next sections, we will look at these possible modifications.

III. POSSIBLE MODIFICATIONS TO THE DIRECT DIAGRAM

We begin with first looking at the possible modifications to the direct diagram. The only way the direct diagram of $h \rightarrow \Upsilon\gamma$ can be modified is if the $hb\bar{b}$ vertex is modified. The other vertex $b\bar{b}\gamma$, being a QED vertex is highly constrained, with no scope for any significant modification. The $hb\bar{b}$ coupling can be modified from its SM value in many new physics scenarios. Such modifications can lead to an “anomalous” $hb\bar{b}$ coupling. More interestingly, in certain extensions of the SM with additional scalar fields, the sign of the $hb\bar{b}$ coupling is opposite to that of the SM. This is called the wrong-sign solution. As shown in Ref. [27], this effect produces a very significant modification to the direct diagram of $h \rightarrow \Upsilon\gamma$. The simplest models in which this occurs are the type II and flipped versions of the 2HDM. In the following subsections, we will briefly look at the 2HDM and its wrong-sign solution. The final analysis we present for the impact of the wrong-sign solution on the direct diagram of $h \rightarrow \Upsilon\gamma$ will be general and is applicable to any theory with a wrong-sign $hb\bar{b}$ coupling.

A. The two Higgs doublet model

In the 2HDM, the most general potential can be written as [17,29]

$$\begin{aligned} V &= -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - [\mu_{12}^2(\Phi_1^\dagger\Phi_2) + \text{H.c.}] \\ &\quad + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &\quad + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\lambda_5(\Phi_1^\dagger\Phi_2)^2 \\ &\quad + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{H.c.}]. \end{aligned} \quad (3)$$

The Higgs doublet fields can be parametrized as [30]

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i - i\eta_i) \end{pmatrix}, \quad i = 1, 2,$$

TABLE I. Scalar doublets coupling to up-type quarks (u), down-type quarks (d), and leptons (l) in the 2HDM models.

	Type I	Type II	Lepton-specific	Flipped
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
l	Φ_2	Φ_1	Φ_1	Φ_2

where v_i is the vacuum expectation value (VEV) of Φ_i ; $\sqrt{v_1^2 + v_2^2} = v = (\sqrt{2}G_F)^{-1/2} \simeq 246$ GeV; h_i and η_i are real scalars; and ϕ_i^+ is a complex scalar. The mass eigenstates are defined by

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = R(\beta) \begin{pmatrix} G^0 \\ A \end{pmatrix},$$

$$\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = R(\beta) \begin{pmatrix} G^+ \\ H^+ \end{pmatrix},$$

where $R(\theta)$ is the rotation matrix

$$R(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}. \quad (4)$$

There are five physical scalar particles: two CP -even scalars h and H , one CP -odd scalar A , and a pair of charged scalars $H^\pm$. G^0 and $G^\pm$ are the Goldstone bosons. α and β are mixing angles ($\tan \beta = v_2/v_1$). Here we take the lightest scalar (h) to be the 125 GeV scalar particle found at the LHC and will simply refer to it as the Higgs boson. The coupling of h with gauge bosons are

$$\mathcal{L}_{hVV} = \sin(\beta - \alpha)h \left[\frac{m_Z^2}{v} Z^\mu Z_\mu + 2 \frac{m_W^2}{v} W^{+\mu} W_\mu^- \right]. \quad (5)$$

If one takes the limit $\sin(\beta - \alpha) = 1$, then the coupling of h with the gauge bosons will be same as the SM Higgs coupling. This limit is often called the ‘‘alignment’’ limit in literature.

Since fermions can couple to any of the two scalar doublets, 2HDMs allow tree-level flavor changing neutral currents (FCNCs), which are restricted experimentally. These interactions can be forbidden by introducing discrete symmetries such as $\mathbb{Z}_2$. If both doublets have different $\mathbb{Z}_2$ charges, then fermions couple to only one doublet depending on their own $\mathbb{Z}_2$ charges. Imposing the $\mathbb{Z}_2$ symmetry forbids the $\lambda_6(\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2)$ and $\lambda_7(\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2)$ terms in the potential. The μ_{12} , which also breaks the $\mathbb{Z}_2$, is usually allowed in the potential, thus breaking the $\mathbb{Z}_2$ symmetry softly.

Depending on the $\mathbb{Z}_2$ charges of the fermions, there are four types of 2HDMs without tree-level FCNCs: type I, type II, lepton-specific, and flipped, as shown in Table I. In the type I 2HDM, all quarks and leptons couple to Φ_2 .

TABLE II. Yukawa couplings of various fermions with the physical Higgs boson h in the four different types of 2HDM [17].

	Type I	Type II	Lepton-specific	Flipped
ξ_u	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$	$\cos \alpha / \sin \beta$
ξ_d	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$
ξ_ℓ	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$-\sin \alpha / \cos \beta$	$\cos \alpha / \sin \beta$

In the type II 2HDM, up-type quarks couple to Φ_2 , while down-type quarks and leptons couple to Φ_1 . In the lepton-specific 2HDM, all quarks couple to Φ_2 , while leptons couple to Φ_1 ; while in the flipped 2HDM, up-type quarks and leptons couple to Φ_2 , while down-type quarks couple to Φ_1 .

The couplings of h to fermions are given by

$$\mathcal{L}_{\text{yukawa}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \xi_f \bar{f} f h, \quad (6)$$

where the factors $\xi_{u,d,\ell}$ are given in Table II.

B. Wrong-sign $h\bar{b}b$ coupling

As mentioned before, the wrong-sign solution occurs in the type II and flipped 2HDMs. Let us look at its origin in a bit of detail. As shown in Table II, in the type II and flipped 2HDMs, the coupling of h to quarks are given by

$$\xi_u = \frac{\cos \alpha}{\sin \beta}, \quad \xi_d = -\frac{\sin \alpha}{\cos \beta}. \quad (7)$$

The coupling of the leptons differs between the type II and flipped models, and are

$$\xi_\ell = \xi_d(\text{type II}), \quad \xi_\ell = \xi_u(\text{flipped}). \quad (8)$$

The limit where the couplings become the same as the SM couplings is $\xi_u = \xi_d = \xi_\ell = 1$. Taking the ratio of the up-type and down-type quark couplings, we get

$$-\frac{\xi_u}{\xi_d} = \frac{1}{\tan \alpha \tan \beta} = \frac{\cos(\beta - \alpha) + \cos(\beta + \alpha)}{\cos(\beta - \alpha) - \cos(\beta + \alpha)}. \quad (9)$$

Now $|\xi_u/\xi_d| \sim 1$ for two cases, i.e., either $\beta - \alpha = \pi/2$ or $\beta + \alpha = \pi/2$, as follows:

- (i) $\beta - \alpha = \pi/2$ implies $\xi_d = +1$ which is called the right-sign solution.
- (ii) $\beta + \alpha = \pi/2$ implies $\xi_d = -1$ which is the wrong-sign solution.

Moreover, one can further simplify things by noting that

$$\frac{\sin(\beta - \alpha)}{\sin(\beta + \alpha)} = \frac{1 - \frac{t_\alpha}{t_\beta}}{1 + \frac{t_\alpha}{t_\beta}} = \frac{1 + \frac{1}{t_\beta} \frac{\xi_d}{\xi_u}}{1 - \frac{1}{t_\beta} \frac{\xi_d}{\xi_u}}. \quad (10)$$

Thus, for large values of t_β and $|\xi_u/\xi_d| \sim 1$, one can write

$$\sin(\beta - \alpha) \sim \sin(\beta + \alpha) \left(1 + \frac{2\xi_d}{t_\beta^2 \xi_u} \right). \quad (11)$$

For somewhat large values of $\tan\beta$, $\sin(\beta - \alpha) \sim \sin(\beta + \alpha)$. Thus, for all values of $\tan\beta$, the SM limit corresponds to $\sin(\beta - \alpha) \sim 1$ ($\xi_d = 1$), and for large values of $\tan\beta$, it also corresponds to $\sin(\beta + \alpha) \sim 1$ ($\xi_d = -1$). Therefore, even when the quark couplings are of the same magnitude as the SM values, one can have a wrong-sign solution where the magnitude of the couplings will be SM-like but the overall sign will be opposite. Such wrong-sign solutions cannot be constrained from just measuring the $h \rightarrow b\bar{b}$ decay more precisely.

However, the situation is very different for the $h \rightarrow \Upsilon\gamma$ decay. The wrong-sign solution modifies the direct diagram of $h \rightarrow \Upsilon\gamma$ by changing the overall sign of the amplitude of the process. Hence, the previously discussed near complete cancellation between direct and indirect diagram in SM will now be incomplete.

It should be noted that although we have so far discussed the possible modifications and wrong-sign solution of the $hb\bar{b}$ coupling in the context of 2HDMs as prototype models, the discussion applies to all models with a modified $hb\bar{b}$ coupling. In any BSM model, the modification to the $h \rightarrow \Upsilon\gamma$ decay width due to any variation in the $hb\bar{b}$ coupling can be calculated as

$$\Gamma[h \rightarrow \Upsilon\gamma] = \frac{1}{8\pi} \frac{m_h^2 - m_\Upsilon^2}{m_h^2} |\xi_b \mathcal{A}_{\text{direct}} + \mathcal{A}_{\text{indirect}}|^2, \quad (12)$$

where the factor ξ_b takes into account any deviation, of magnitude or sign, from the SM value of the $hb\bar{b}$ coupling. In particular, for the case of the wrong-sign solution with $|\xi_b| = 1$, we have

$$\Gamma[h \rightarrow \Upsilon\gamma] = \frac{1}{8\pi} \frac{m_h^2 - m_\Upsilon^2}{m_h^2} |-\mathcal{A}_{\text{direct}} + \mathcal{A}_{\text{indirect}}|^2. \quad (13)$$

Note that in Eq. (13), if there is a sign change in the contribution from the direct diagram ($\xi_b < 0$), there will be constructive interference between the direct and indirect diagrams instead of destructive interference like in the SM.

The modification in the $h \rightarrow \Upsilon\gamma$ decay width due to either a magnitude or a sign change in the value of the $hb\bar{b}$ coupling ξ_b is shown in Fig. 2. Figure 2 shows the effect on $h \rightarrow \Upsilon\gamma$ branching ratio due to modifications in the $hb\bar{b}$ coupling parametrized by the ξ_b parameter. As one can see, large modifications from the SM value in the magnitude of the $hb\bar{b}$ coupling are ruled out by the various $h \rightarrow XX$ measurements at the LHC [31,32], where X represents a possible decay product of h . The gray-shaded region is excluded by the LHC constraint $\text{BR}(h \rightarrow \Upsilon\gamma) < 2.5 \times 10^{-4}$ [33]. Thus, a large change in the $h \rightarrow \Upsilon\gamma$ branching ratio due to a large change in the magnitude of the $hb\bar{b}$

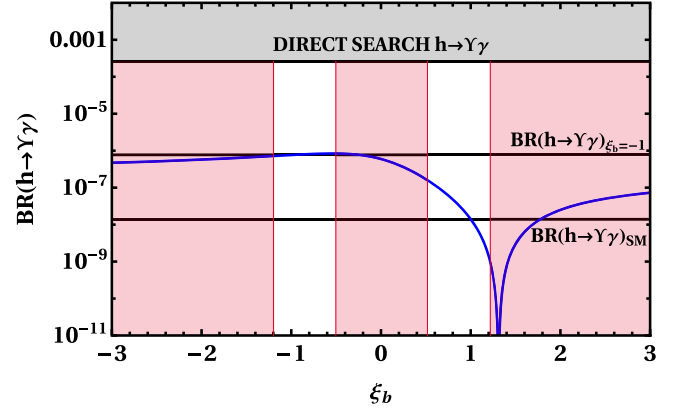


FIG. 2. Branching ratio of $h \rightarrow \Upsilon\gamma$ as a function of ξ_b with $\xi_b = 1$ corresponding to the SM case. The black lines show the wrong-sign and right-sign predictions for $|\xi_b| = 1$. The horizontal gray region depicts the region excluded by direct search of $h \rightarrow \Upsilon\gamma$ [33], while the red regions are ruled out from $h \rightarrow XX$ measurements listed in Table IV [31,32].

coupling is not possible. This leaves us with a wrong-sign solution with $|\xi_b| \sim 1$ as the only possibility which can result in an order of magnitude change in the $h \rightarrow \Upsilon\gamma$ branching ratio.

As shown in Fig. 2, the right-sign solution $\xi_b = 1$ leads to a very small $h \rightarrow \Upsilon\gamma$ branching ratio,²

$$9.70 \times 10^{-9} \lesssim \text{BR}(h \rightarrow \Upsilon\gamma) \lesssim 1.41 \times 10^{-8}, \quad (14)$$

whereas the wrong-sign solution $\xi_b = -1$ leads to a branching ratio of

$$\text{BR}(h \rightarrow \Upsilon\gamma) = 7.66 \times 10^{-7}, \quad (15)$$

which is larger by almost 2 orders of magnitude. Thus, we can conclude with very high confidence that the wrong-sign solution $\xi_b \approx -1$ is the only possibility that appreciably modifies the $h \rightarrow \Upsilon\gamma$ branching ratio through changes in the direct diagram.

IV. POSSIBLE MODIFICATIONS TO THE INDIRECT DIAGRAM

Having looked at all possible modifications in the direct diagram, now let us look at the possible modifications in the indirect diagram. The only way to significantly modify the contribution of the indirect decay diagram of $h \rightarrow \Upsilon\gamma$ is through possible modifications in the $h \rightarrow \gamma\gamma$ effective coupling. As shown schematically in Fig. 3, this can happen if any new particle runs in the $h \rightarrow \gamma\gamma$ loop. Here, $\mathbb{X}$ can be any electromagnetically charged particle so that the $\mathbb{X}\mathbb{X}\gamma$ vertex exists. Thus, there are many possibilities, as pictorially depicted in Fig. 4.

²This value is highly sensitive to the input parameters. The value 1.41×10^{-8} is taken from Ref. [23], while our own computation gives a slightly different value of 9.70×10^{-9} .

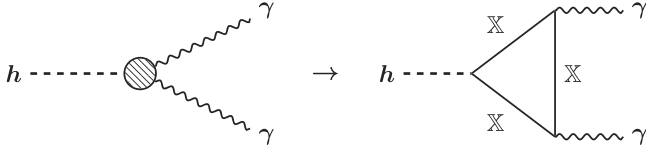


FIG. 3. Feynman diagram for the $h \rightarrow \gamma\gamma$ process with a new particle $\mathbb{X}$ running in the loop.

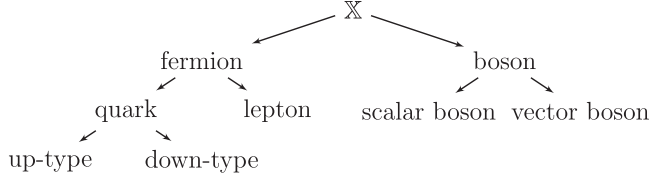


FIG. 4. Possible particle types for $\mathbb{X}$.

The modification to the $h \rightarrow \Upsilon\gamma$ decay width due to variation in the $h \rightarrow \gamma\gamma$ decay coming from the contribution of new particles to the indirect diagram can be parametrized as

$$\Gamma[h \rightarrow \Upsilon\gamma] = \frac{m_h^2 - m_\Upsilon^2}{8\pi m_h^2} \left| \mathcal{A}_{\text{direct}} + \sqrt{1 + \frac{\text{err}}{100}} \mathcal{A}_{\text{indirect}} \right|^2, \quad (16)$$

where

$$\text{err} = \frac{\Gamma_{\text{new}}[h \rightarrow \gamma\gamma] - \Gamma_{\text{SM}}[h \rightarrow \gamma\gamma]}{\Gamma_{\text{SM}}[h \rightarrow \gamma\gamma]} \times 100, \quad (17)$$

is the variation (in %) to the $h \rightarrow \gamma\gamma$ decay width due to new physics.

To estimate the modification induced by all these particles in the indirect decay diagram, one has to look at each possibility one by one. To calculate the modifications to the Higgs decay width and production cross section, new model files were written in SARAH [34] and FeynRules [35], the mass spectrum and effective vertices were calculated in SPheno [36,37], and collider simulations were done in MadGraph [38].

Among the various possibilities shown in Fig. 4, the fermion loops actually decrease the $\text{BR}(h \rightarrow \Upsilon\gamma)$. This is because the SM contribution is dominated by the W boson loop and the contribution of a new fermion will be opposite in sign to the bosonic loop, leading to destructive interference. New charged bosons interfere constructively with

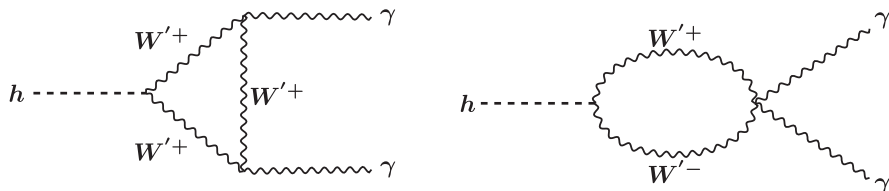


FIG. 5. Feynman diagrams for the $h \rightarrow \gamma\gamma$ process with the new charged vector boson running in the loop.

TABLE III. Charges of the new charged vector boson.

Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
W'^+	1	1	$(\mathbf{1}, \mathbf{1}, 1)$

the existing SM $h \rightarrow \gamma\gamma$ loops, since their contribution has the same sign as the SM bosonic loop. Among the bosons, we found that a new charged vector boson leads to the largest positive change in the $h \rightarrow \Upsilon\gamma$ decay width, which we discuss below. All other cases are given in detail in Appendix B.

A. New heavy charged vector bosons

We add a new heavy charged vector boson W'^+ to the SM particle content. We look at the simplest model-independent possibility of a new $SU(2)_L$ singlet vector boson without any connection to a gauge group. The conclusions drawn can be generalized to other cases. The charges of the new charged vector boson are given in Table III. The relevant new terms in the Lagrangian in this case are given by

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} W'_{\mu\nu} W'^{\mu\nu} + m_{W'}^2 W'_\mu W'^\mu + g_{hW'} h W'_\mu W'^{\mu} \\ & + \frac{e}{\sin\theta_W} \left[\frac{g_L}{\sqrt{2}} (\bar{\nu}_L \gamma^\mu C_L^e e_L + \bar{u}_L \gamma^\mu C_L^q d_L) W'_\mu \right. \\ & \left. + \frac{g_R}{\sqrt{2}} (\bar{u}_R \gamma^\mu C_R^q d_R) W'_\mu + \text{H.c.}, \right] \end{aligned} \quad (18)$$

where $W'_{\mu\nu} = (\partial_\mu W'_\nu - \partial_\nu W'_\mu)$, h is the SM Higgs boson, and ν_L , $e_{L,R}$, $u_{L,R}$, and $d_{L,R}$ denote the SM neutrinos, left- and right-handed charged leptons, and up- and down-type quarks, respectively. For the sake of simplicity, we take $C_L^{q,e}$ and C_R^q to be identity matrices, $g_L = 0$, and $g_R = 1$ such that W'^+ does not interfere with SM weak processes, thereby avoiding the consequent experimental bounds.

The Feynman diagrams for the process that contributes to the indirect diagram in $h \rightarrow \Upsilon\gamma$ decay in this case are shown in Fig. 5. The contribution to the $h \rightarrow \gamma\gamma$ decay amplitude in this case can be calculated from the formula given in Appendix C, as follows:

$$\mathcal{A}_{\text{new}}^{W'^\pm}(h \rightarrow \gamma\gamma) = -g_{hV} \frac{v}{2m_{W'}^2} A_1^h(\tau_{W'}), \quad (19)$$

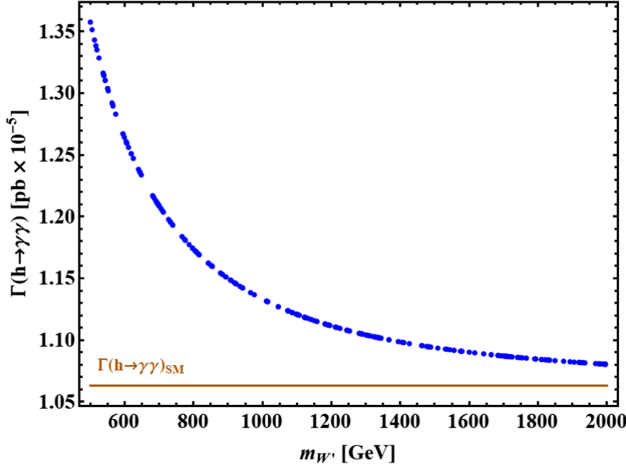


FIG. 6. $h \rightarrow \gamma\gamma$ decay width vs mass of the new charged vector boson for $g_{hW'} = 1$.

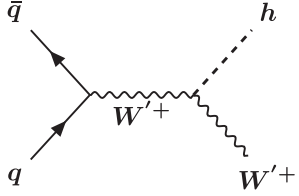


FIG. 7. Feynman diagram for $q\bar{q} \rightarrow W'^+ + h$ process involving the new charged vector boson.

where $m_{W'}$ is the mass of the new charged vector boson, $\tau_{W'} = m_h^2/4m_{W'}^2$ and $g_{hV} = v g_{hW'}$. The form factor A_1^h is given in Eq. (C4).

The modification in the $h \rightarrow \gamma\gamma$ decay width can be seen in Fig. 6. As we can see in Fig. 6, the new charged vector boson interferes constructively with the existing SM $h \rightarrow \gamma\gamma$ loops, since its contribution has the same sign as the SM bosonic loop.

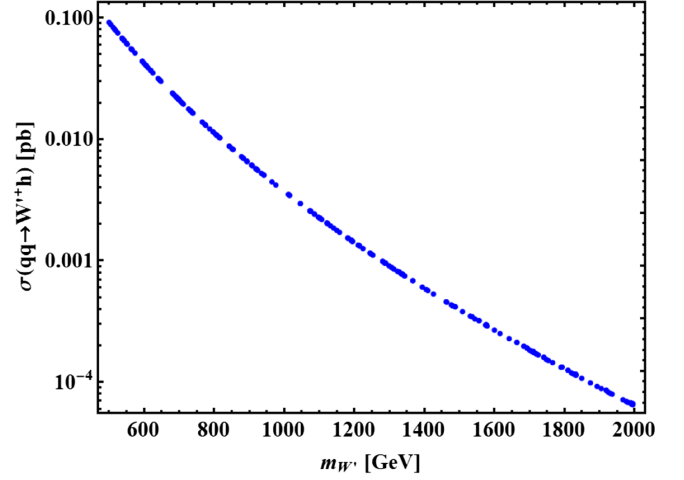


FIG. 8. $pp \rightarrow h$ production cross section vs mass of the new charged vector boson for $g_{hW'} = 1$.

Furthermore, there is a modification to the production of h in this case, since the existence of the new charged vector boson modifies the $q\bar{q} \rightarrow V + h$ and $qq \rightarrow qq + (V^*V^* \rightarrow h)$ processes. The most constraining production process out of these is $q\bar{q} \rightarrow W'^+ + h$. The Feynman diagram corresponding to this process is shown in Fig. 7. The modification to the production of h is shown in Fig. 8. As we can see in Fig. 8, there is an increase in the production of h because of the existence of new production processes. The overall modification to the μ parameter and the $h \rightarrow \Upsilon\gamma$ branching ratio as a result is shown in Fig. 9. The points in Fig. 9 are generated assuming the coupling $g_{hW'}$ to be in the perturbative range ($\leq \sqrt{4\pi}$). Since the new charged vector boson interferes constructively with the existing SM $h \rightarrow \gamma\gamma$ loops, the $h \rightarrow \Upsilon\gamma$ decay width is also increased. Thus, this case can lead to an enhancement in the $h \rightarrow \Upsilon\gamma$ branching ratio. Again, the 3σ constraints from

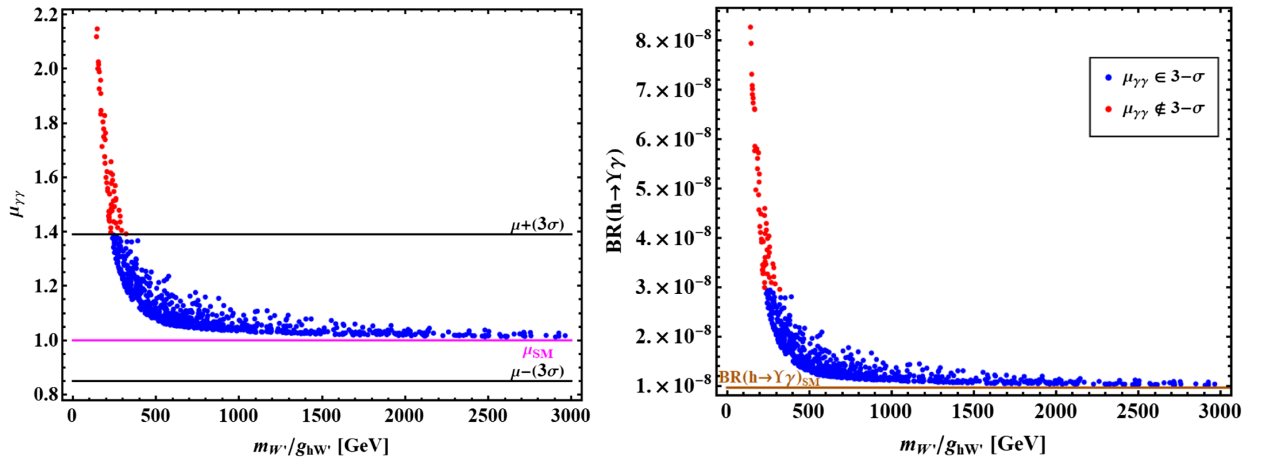


FIG. 9. Left: $\mu_{\gamma\gamma}$ vs ratio of mass of the new charged vector boson to $g_{hW'}$. The solid black lines are the experimentally measured $\mu_{\gamma\gamma}$ at $\pm 3\sigma$ uncertainty [31]. The magenta line is $\mu_{\gamma\gamma}$ in the SM. Right: Branching ratio of $h \rightarrow \Upsilon\gamma$ vs ratio of mass of the new charged vector boson to $g_{hW'}$, depicting the allowed values of $\mu_{\gamma\gamma}$ at each point.

$h \rightarrow \gamma\gamma$ limits it to be only a small enhancement, as shown in Fig. 9.

B. Summarizing the contribution of new particles to the indirect diagram

The variation to $\Gamma[h \rightarrow \gamma\gamma]$ that can bring about the largest positive change in the $h \rightarrow \Upsilon\gamma$ decay width within experimental constraints on $\mu_{\gamma\gamma}$ observed in the calculations is for the new charged vector boson at mass 753 GeV and coupling $g_{hW'} = 3.07$. For these mass and coupling values,

$$\text{err} = \frac{\Gamma_{\text{new}}^{W'^+}[h \rightarrow \gamma\gamma] - \Gamma_{\text{SM}}[h \rightarrow \gamma\gamma]}{\Gamma_{\text{SM}}[h \rightarrow \gamma\gamma]} \times 100 = 38.24\%, \quad (20)$$

for which the $h \rightarrow \Upsilon\gamma$ branching ratio is

$$\text{BR}(h \rightarrow \Upsilon\gamma) = 2.94 \times 10^{-8}, \quad (21)$$

which is still smaller by more than 1 order of magnitude than the branching ratio due to the wrong-sign solution [from Eq. (15)],

$$\text{BR}(h \rightarrow \Upsilon\gamma) = 7.66 \times 10^{-7}. \quad (22)$$

The variation to $\Gamma(h \rightarrow \gamma\gamma)$ that can bring about the largest negative change in the $h \rightarrow \Upsilon\gamma$ decay width within experimental constraints on $\mu_{\gamma\gamma}$ observed in the calculations in the sections above is in the case of a new up-type quark at mass 753 GeV and coupling $g_{hT} = 1.91$. For these mass and coupling values,

$$\text{err} = \frac{\Gamma_{\text{new}}^{T'}[h \rightarrow \gamma\gamma] - \Gamma_{\text{SM}}[h \rightarrow \gamma\gamma]}{\Gamma_{\text{SM}}[h \rightarrow \gamma\gamma]} \times 100 = -18.62\%, \quad (23)$$

for which the $h \rightarrow \Upsilon\gamma$ branching ratio is

$$\text{BR}(h \rightarrow \Upsilon\gamma) = 3.18 \times 10^{-9}. \quad (24)$$

The branching ratio in the SM is [from Eq. (14)]

$$\text{BR}(h \rightarrow \Upsilon\gamma) = 9.70 \times 10^{-9}. \quad (25)$$

Thus, the SM value is larger by almost an order of magnitude.

The modification in the $h \rightarrow \Upsilon\gamma$ decay width due to variation in the $h \rightarrow \gamma\gamma$ decay can be seen in Fig. 10. The left red vertical band in Fig. 10 shows the minimum allowed value of err, which is seen in the case of the new up-type quark. The region to the left of this band is hence ruled out by constraints on $\mu_{\gamma\gamma}$. The right red vertical band shows the maximum allowed value of err, which is seen in the case of the new charged vector boson. The region to the right of this band is hence ruled out by constraints on $\mu_{\gamma\gamma}$. Hence, we can conclude that the modification to the indirect diagram coming from any type of new physics is not enough to

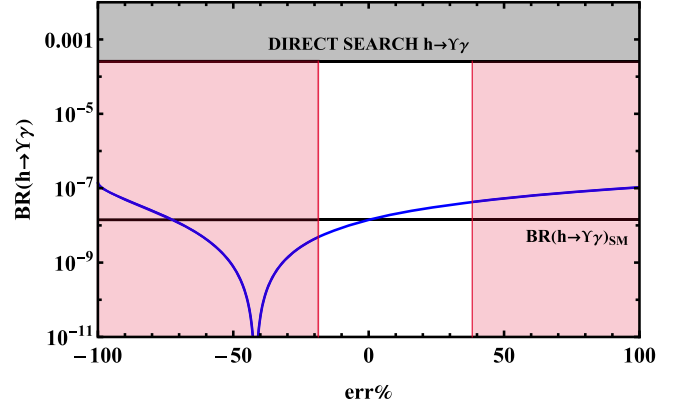


FIG. 10. Branching ratio of $h \rightarrow \Upsilon\gamma$ as a function of err% in the $h \rightarrow \gamma\gamma$ decay width with err = 0 corresponding to the SM case. The black line shows the SM prediction. The gray region depicts the region excluded by direct search of $h \rightarrow \Upsilon\gamma$ [33], while the red regions are ruled out from constraints on $\mu_{\gamma\gamma}$ [Eqs. (20) and (23)].

enhance the $h \rightarrow \Upsilon\gamma$ branching ratio by 2 orders of magnitude compared to the SM prediction.

Thus, the wrong-sign solution is the only possibility that gives rise to a roughly 2 orders of magnitude larger $h \rightarrow \Upsilon\gamma$ decay width. Although the present bound on $h \rightarrow \Upsilon\gamma$ is relatively weak, its future prospects are promising. Among future colliders, the expected number of events for the SM and wrong-sign cases are $N_{\text{event}}^{\text{SM}} = 0.7$, $N_{\text{event}}^{\text{wrong-sign}} = 114$ at the High-Luminosity LHC (HL-LHC) with luminosity 3ab^{-1} . For the future circular collider (hadron-hadron) (FCC-hh) with luminosity 1ab^{-1} , we have $N_{\text{event}}^{\text{SM}} = 3.6$, and $N_{\text{event}}^{\text{wrong-sign}} = 608$. They thus have potential to probe the wrong-sign solution. Furthermore, in the future it might be possible to further increase the signal significance and thus the discovery potential by adopting advanced machine learning-based analysis techniques [39] at the HL-LHC or FCC-hh.

V. CONCLUSIONS

In conclusion, the rare Higgs decay mode $h \rightarrow \Upsilon\gamma$ provides us with a unique testing ground for new physics beyond the SM. This is owing to the fact that in the SM, the direct and indirect Feynman diagrams interfere destructively, almost completely canceling each other. This accidental cancellation makes the SM decay width very small. Thus, any new physics which can disrupt this accidental cancellation can potentially modify the $h \rightarrow \Upsilon\gamma$ decay width by orders of magnitude. Furthermore, due to presence of interference terms, even the information about the sign of the new physics couplings, typically lost in most other decay modes such as $h \rightarrow b\bar{b}$, can be probed in this decay channel.

In this work, we have carried out a systematic and model-independent analysis of possible modifications to the $h \rightarrow \Upsilon\gamma$ decay coming from new physics. Taking into account the bounds on Higgs production and decay processes

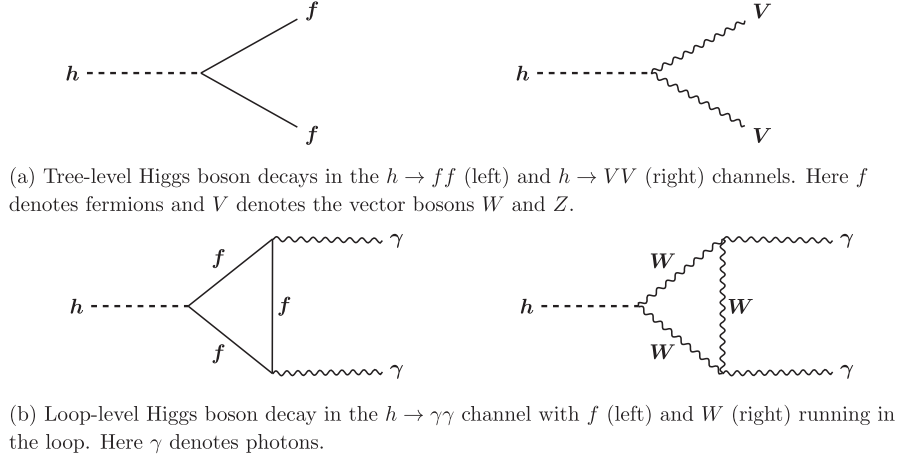


FIG. 11. Feynman diagrams for some leading-order contributions to the SM Higgs boson decays.

from experimental measurements at the LHC, possible modifications have been obtained in the $\Gamma[h \rightarrow \gamma\gamma]$ and hence $\Gamma[h \rightarrow \Upsilon\gamma]$ decay processes due to presence of various types of new particles. We found that while the accidental cancellation of the SM direct and indirect amplitudes can indeed be disrupted by presence of new physics and new particles, the most significant change in $\Gamma[h \rightarrow \Upsilon\gamma]$ occurs if the Higgs has a wrong-sign $hb\bar{b}$ coupling.

In fact, due to a wrong-sign $hb\bar{b}$ coupling, the $h \rightarrow \Upsilon\gamma$ decay width increases by almost 2 orders of magnitude compared to the SM value. We further found that no other new physics can change the SM value of the $h \rightarrow \Upsilon\gamma$ decay width by such a large amount. Thus, $h \rightarrow \Upsilon\gamma$ offers the most promising probe for wrong-sign $hb\bar{b}$ coupling, particularly due to the fact that direct $hb\bar{b}$ decay measurements cannot distinguish between right-sign and wrong-sign $hb\bar{b}$ couplings. Finally, if the LHC or any future collider ever observes the $h \rightarrow \Upsilon\gamma$ decay mode with a significantly enhanced decay width compared to the SM value, then it will be a conclusive evidence of wrong-sign $hb\bar{b}$ coupling and the presence of more than one Higgs boson.

ACKNOWLEDGMENTS

The work of S.M. is supported by KIAS Individual Grants (No. PG086002) at Korea Institute for Advanced Study. The work of R. S. is supported by the Government of India, SERB Startup Grant No. SRG/2020/002303. The work of A. B. is supported by Fundação para a Ciência e a Tecnologia (FCT, Portugal) through the PhD Grant No. UI/BD/154391/2023 and through Projects No. UID/00777/2025 [40] and No. CERN/FIS-PAR/0019/2021.

APPENDIX A: MEASURING THE COUPLINGS OF THE HIGGS BOSON

Here we present a brief discussion of the potential decay modes of the 125 GeV scalar. For the sake of brevity,

throughout this work we will simply call it the Higgs (h) boson.³ The Higgs boson couplings can be constrained by measuring its decay widths to various particles. As shown in Fig. 11, they can be broadly classified into two categories: a) Higgs decay through its direct coupling with other particles, and b) loop-induced decays, the most prominent such decay being $h \rightarrow \gamma\gamma$.

The Higgs boson has several decay modes, each quantified by the branching ratio given by

$$BR_{XX} = \frac{\Gamma[h \rightarrow XX]}{\Gamma[h \rightarrow all]}, \quad (A1)$$

where $\Gamma[h \rightarrow XX]$ is the decay width of the process $h \rightarrow XX$ and $\Gamma[h \rightarrow all]$ is the total decay width. The subscript XX denotes that the branching ratio is for the decay mode $h \rightarrow XX$; X being the given SM or BSM particle to which the Higgs is decaying. For the SM case, one can calculate the branching ratios theoretically, and if the 125 GeV scalar is the SM Higgs, then they will be as shown in Fig. 12.

Note that Fig. 12 only shows the branching ratios for the first few leading decay modes. The Higgs has other rarer decay modes, including decay modes involving hadrons. One such rare hadronic decay mode is $h \rightarrow \Upsilon\gamma$, on which we will concentrate in the later sections.

The signal strength modifier or μ parameter is often used to quantify Higgs boson decays in comparison to the SM predictions. It is defined as the ratio of the experimentally measured Higgs boson yield to the yield as predicted by the Standard Model:

$$(\mu_{XX})_{\text{Exp}} = \frac{(\sigma)_{\text{measured}}}{(\sigma)_{\text{SM}}} \frac{(BR_{XX})_{\text{measured}}}{(BR_{XX})_{\text{SM}}}, \quad (A2)$$

³Note that we are not identifying it with the SM Higgs particle. Whenever we discuss the SM case, we will call it the SM Higgs boson.

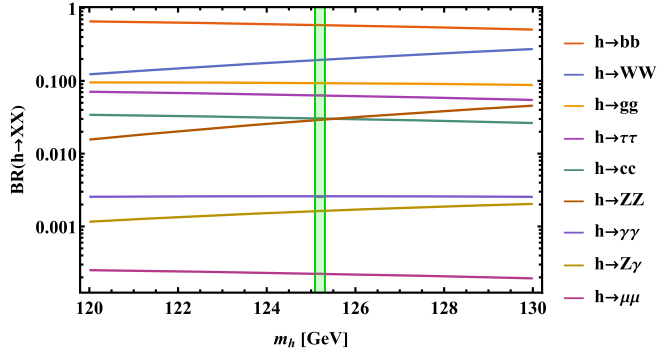


FIG. 12. Branching ratios of various Higgs decay processes in the SM vs the mass of the Higgs boson. The experimentally measured mass is 125.20 ± 0.11 GeV [41].

where σ is the Higgs production cross section and BR_{XX} is the branching ratio of a specific decay channel $h \rightarrow XX$. To compare the calculations of new physics models with experimental measurements, the following formula is used to characterize the μ parameter:

$$(\mu_{XX})_{NP} = \frac{(\sigma)_{NP} (BR_{XX})_{NP}}{(\sigma)_{SM} (BR_{XX})_{SM}}, \quad (A3)$$

where $(\sigma)_{NP}$ is the Higgs production cross section in the given new physics model and $(BR_{XX})_{NP}$ is the branching ratio of the decay channel $h \rightarrow XX$ for the same new physics model.

Since the discovery in 2012 of the $(\mu_{XX})_{Exp}$ parameter, both CMS [31] and ATLAS [32] have measured this parameter for several Higgs decay modes; see the summary in Table IV.

As we can see in Table IV, due to background contamination and limitations in detection of final state particles, there is a considerable amount of uncertainty in the measurements of the Higgs boson decay modes. The decay to gauge bosons (ZZ and WW) are relatively clean, resulting in lower uncertainties. The decay to quarks (such as $b\bar{b}$) on the other hand, has a strong background from QCD multijet generation and thus a high amount of

TABLE IV. Experimentally measured μ parameters by CMS [31] Collaboration with uncertainties ($\pm 1\sigma$) for various decay modes of h . The analogous ATLAS Collaboration measurements can be found in Ref. [32].

Decay mode	$(\mu_{XX})_{Exp}$
$h \rightarrow b\bar{b}$	$1.02^{+0.16}_{-0.15}$
$h \rightarrow \tau\tau$	$0.84^{+0.10}_{-0.10}$
$h \rightarrow WW$	$0.99^{+0.09}_{-0.09}$
$h \rightarrow ZZ$	$1.03^{+0.11}_{-0.10}$
$h \rightarrow \gamma\gamma$	$1.12^{+0.09}_{-0.09}$
$h \rightarrow \mu\mu$	$1.15^{+0.44}_{-0.41}$

TABLE V. Branching ratios of rare Higgs decay modes as predicted by the SM [23,24]. Here, ρ^0 , ω , ϕ , J/ψ , and Υ are mesons.

Decay mode	Branching ratio
$h \rightarrow \rho^0 \gamma$	1.68×10^{-5}
$h \rightarrow \omega \gamma$	1.48×10^{-6}
$h \rightarrow \phi \gamma$	2.31×10^{-6}
$h \rightarrow J/\psi \gamma$	2.46×10^{-6}
$h \rightarrow \Upsilon(1S) \gamma$	1.41×10^{-8}

uncertainty. The decay to light charged leptons such as the muon have a low background, but due to their small masses, they have small couplings with the Higgs boson, so their decay widths are relatively difficult to detect. The most significant experimental uncertainties in measuring the rate of decay to two photons ($\gamma\gamma$) are related to photon identification.

Apart from the decay modes listed in Table IV, there are also several predicted SM Higgs decay processes with very small decay widths, which make them very hard to detect. These are called rare Higgs decays. Some of these processes are given in Table V with their SM predicted branching ratios.

Surprisingly, the $h \rightarrow \Upsilon \gamma$ branching ratio is the smallest among the processes given in Table V, in spite of the Υ meson being the heaviest and thus having the largest coupling with the Higgs boson. This happens due to an accidental cancellation between the two diagrams involved in this process. Note that due to the close nature of the cancellation, the SM branching ratio of $h \rightarrow \Upsilon \gamma$ is extremely sensitive to the values of the input parameters, and different groups have reported slightly different values of the SM branching ratios [23–26]. However, since in our work we are interested in new physics effects which can change the branching ratio by orders of magnitude, the high sensitivity to input parameters will not have any appreciable effect on our results and conclusions.

APPENDIX B: OTHER POSSIBLE MODIFICATIONS TO THE INDIRECT DIAGRAM

In this Appendix, we discuss one by one the modifications to the indirect decay diagram induced by all types of particles other than new heavy charged vector bosons (discussed in Sec. IVA).

1. New heavy charged leptons

We begin with looking at the possibility of a new heavy vectorlike charged lepton pair l'_L, l'_R . The charged lepton needs to couple with Higgs, which depending on its $SU(2)_L$ charge can be through Yukawa coupling with SM charged leptons or through another new pair of charged leptons with appropriate $SU(2)_L$ charges. We look at the

TABLE VI. Charges of the new $SU(2)_L$ singlet leptons.

Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
l'_L	$\frac{1}{2}$	1	$(\mathbf{1}, \mathbf{1}, -1)$
l'_R	$\frac{1}{2}$	1	$(\mathbf{1}, \mathbf{1}, -1)$

simplest possibilities of $SU(2)_L$ singlet and doublet leptons in detail. The conclusions drawn can then be easily generalized to other cases.

a. Vectorlike singlet leptons

The charges of the vectorlike singlet leptons are given in Table VI. The relevant new terms in the Lagrangian in this case are given by

$$-\mathcal{L} = m_{l'} \bar{l}'_L l'_R + g_{hl} \bar{L}_i \Phi l'_R, \quad (\text{B1})$$

where $L_i = (\nu_{L,i}, e_{L,i})$; $i = 1, 2, 3$ are the SM lepton doublets and Φ is the SM Higgs doublet. Since they have the same electric charge and spin, the new leptons mix with the SM ones and the new mixed state acts as the fourth generation of the lepton family. The Feynman diagram for the process that contributes to the indirect diagram in $h \rightarrow \Upsilon\gamma$ decay in this case is shown in Fig. 13. The contribution to the $h \rightarrow \gamma\gamma$ decay amplitude in this case can be calculated from the formula given in Appendix C, as follows:

$$\mathcal{A}'_{\text{new}}(h \rightarrow \gamma\gamma) = 2g_{hl} \frac{v}{m_{l'}} A_{1/2}^h(\tau_{l'}), \quad (\text{B2})$$

where g_{hl} is the $hl'l'$ effective coupling, $m_{l'}$ is the mass of the new lepton, $\tau_{l'} = m_h^2/4m_{l'}^2$, and v is the VEV of the Higgs field. The form factor $A_{1/2}^h$ is given in Eq. (C4).

The modification in the $h \rightarrow \gamma\gamma$ decay width is shown in Fig. 14. As we can see in Fig. 14, the new lepton interferes destructively with the existing SM $h \rightarrow \gamma\gamma$ loops. This is to be expected, as the SM contribution is dominated by the W boson loop and we have added a new fermion in the loop whose contribution will be opposite in sign to the bosonic loop, leading to destructive interference.⁴

Furthermore, there is no modification to the production of h in this case, as the new lepton is not a colored particle and hence, it does not run in the gluon fusion loop. The overall modification to the $\mu_{\gamma\gamma}$ parameter and the $h \rightarrow \Upsilon\gamma$ branching ratio are shown in Fig. 15. The points in Fig. 15 are generated assuming the coupling g_{hl} to be in the perturbative range ($\leq \sqrt{4\pi}$). Since the new lepton interferes destructively with the existing SM $h \rightarrow \gamma\gamma$ loops, the $h \rightarrow \Upsilon\gamma$ decay width is also decreased. Thus, this case cannot lead to any enhancement in the $h \rightarrow \Upsilon\gamma$ branching ratio.

⁴Note that even in the SM, the fermionic loops (dominated by the top loop) actually interfere destructively with the W boson loop.

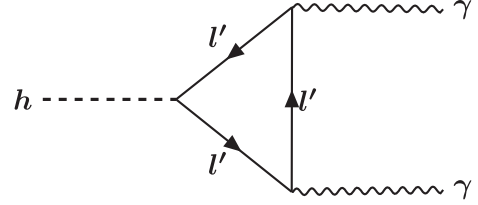


FIG. 13. Feynman diagram for the $h \rightarrow \gamma\gamma$ process with the new lepton running in the loop.

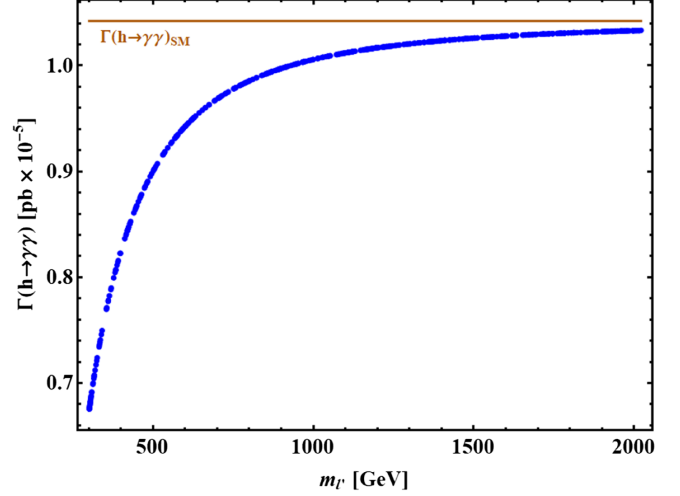


FIG. 14. $h \rightarrow \gamma\gamma$ decay width vs mass of the new lepton for $g_{hl} = 1$.

b. Vectorlike doublet leptons

The charges of the vectorlike doublet leptons are given in Table VII. The relevant new terms in the Lagrangian in this case are given by

$$-\mathcal{L} = m_{l'} \bar{l}'_L l'_R + g_{hl} \bar{l}'_L \Phi e_R, \quad (\text{B3})$$

where e_R are the SM right-handed charged leptons. Note that henceforth we will suppress the family generation index for the sake of brevity. The production and decay properties of the Higgs boson in this case are very similar to the case of vectorlike singlet leptons. We again get a destructive interference leading to a decrease in $h \rightarrow \Upsilon\gamma$ branching ratio. Similar behavior is observed for any $SU(2)_L$ representation of new charged leptons. Hence, we can conclude that additional charged leptons beyond the SM cannot mimic the wrong-sign-like enhancement of the $h \rightarrow \Upsilon\gamma$ branching ratio.

2. New heavy quarks

Now we move on to the case when new heavy quarks are added to the SM particle content. We start with the scenario where up-type quarks are added and will discuss the down-type quarks afterwards. Like the charged lepton case, for quarks also we can add particles belonging to different

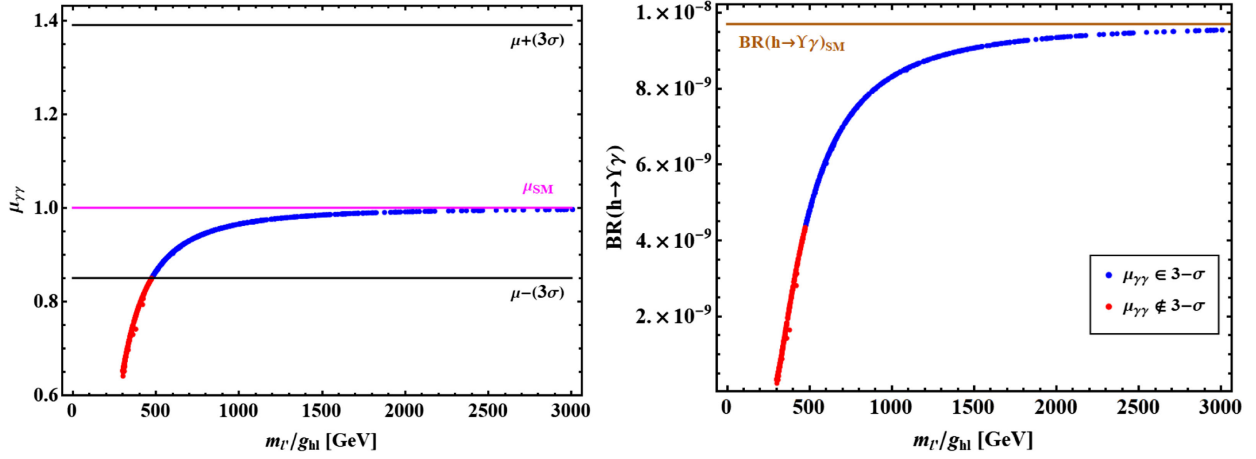


FIG. 15. Left: $\mu_{\gamma\gamma}$ vs ratio of mass of the new vectorlike singlet lepton to g_{hl} . The solid black lines are the experimentally measured $\mu_{\gamma\gamma}$ at $\pm 3\sigma$ uncertainty [31]. The magenta line is $\mu_{\gamma\gamma}$ in the SM. Right: Branching ratio of $h \rightarrow Y\gamma$ vs ratio of mass of the new vectorlike singlet lepton to g_{hl} , depicting the allowed values of $\mu_{\gamma\gamma}$ at each point.

representations of $SU(2)_L$. As before, we discuss the $SU(2)_L$ singlet cases first and will argue that the higher $SU(2)_L$ representations will not change the conclusions.

a. Vectorlike singlet up-type quarks

We add a vectorlike pair of heavy up-type quarks T'_L, T'_R to the SM particle content with charges as shown in Table VIII. The relevant new terms in the Lagrangian in this case are given by

$$-\mathcal{L} = m_{T'} \bar{T}'_L T'_R + g_{hT} \bar{Q} \tilde{\Phi} T'_R, \quad (\text{B4})$$

where $Q = (u_L, d_L)$ is the SM quark doublet and $\tilde{\Phi} = i\sigma_2 \Phi^*$. σ_2 is the second Pauli matrix. Since they have the same electric charge and spin, the new up-type quark mixes with SM up-type quarks and the new mixed state acts as the fourth generation of the up-type quark family. The Feynman diagram for the process that contributes to the indirect diagram in $h \rightarrow Y\gamma$ decay in this case is shown in Fig. 16. The contribution to the $h \rightarrow \gamma\gamma$ decay amplitude in

this case can be calculated from the formula given in Appendix C, as follows:

$$\mathcal{A}_{\text{new}}^{T'}(h \rightarrow \gamma\gamma) = \frac{8}{3} g_{hT} \frac{v}{m_{T'}} A_{1/2}^h(\tau_{T'}), \quad (\text{B5})$$

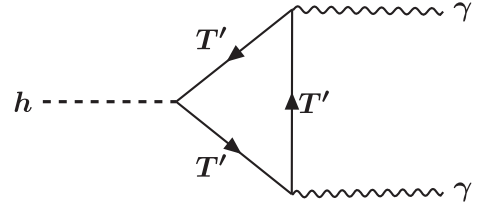


FIG. 16. Feynman diagram for the $h \rightarrow \gamma\gamma$ process with the new up-type quark running in the loop.

TABLE VII. Charges of the new $SU(2)_L$ doublet leptons.

Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
l'_L	$\frac{1}{2}$	1	$(1, 2, -1)$
l'_R	$\frac{1}{2}$	1	$(1, 2, -1)$

TABLE VIII. Charges of the new $SU(2)_L$ singlet up-type quarks.

Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
T'_L	$\frac{1}{2}$	1	$(3, 1, 2/3)$
T'_R	$\frac{1}{2}$	1	$(3, 1, 2/3)$

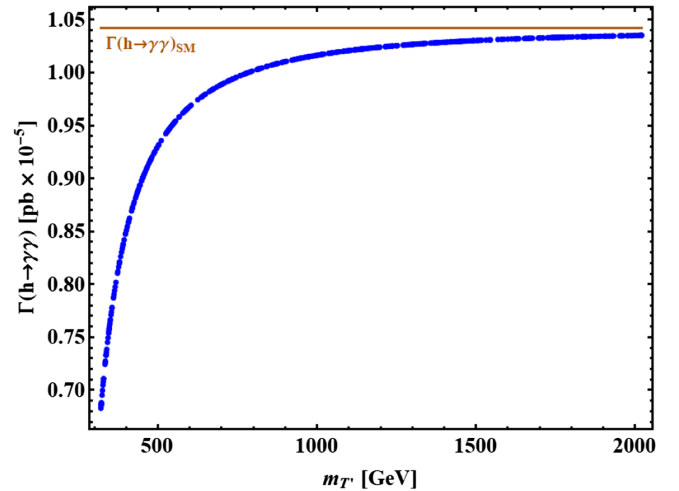


FIG. 17. $h \rightarrow \gamma\gamma$ decay width vs mass of the new up-type quark for $g_{hT} = 1$.

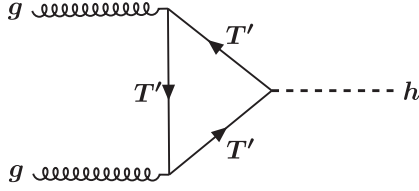


FIG. 18. Feynman diagram for Higgs production via the gluon fusion process with the new up-type quark running in the loop.

where g_{hT} is the effective $hT'T'$ coupling, $m_{T'}$ is the mass of the new up-type quark, and $\tau_{T'} = m_h^2/4m_{T'}^2$. The modification in the $h \rightarrow \gamma\gamma$ decay width can be seen in Fig. 17. As we can see in Fig. 17, the new up-type quark interferes destructively with the existing SM $h \rightarrow \gamma\gamma$ loops since its contribution is opposite in sign to the SM bosonic loop (as in the case of a new lepton).

Furthermore, there is a modification to the production of h in this case. The most constraining production process that gets modified is gluon fusion. The new up-type quark can run in the gluon fusion loop and this modifies the production cross section. The Feynman diagram corresponding to this process is shown in Fig. 18. The modification to the production of h is shown in Fig. 19. As we can see in Fig. 19, there is an increase in the $gg \rightarrow h$ production. This is due to the fact that new up-type quark interferes constructively with the SM $gg \rightarrow h$ loops, which are dominated by the contribution from the top quark. The overall modification to the μ parameter and the $h \rightarrow \Upsilon\gamma$ branching ratio as a result is shown in Fig. 20. The points in Fig. 20 are generated assuming the coupling g_{hT} to be in the perturbative range ($\leq \sqrt{4\pi}$). Due to contribution of the production cross section, there is a increase in the value of $\mu_{\gamma\gamma}$. However, since the $h \rightarrow \Upsilon\gamma$ decay width only depends on the $h \rightarrow \gamma\gamma$ decay width, the $h \rightarrow \Upsilon\gamma$ decay width is

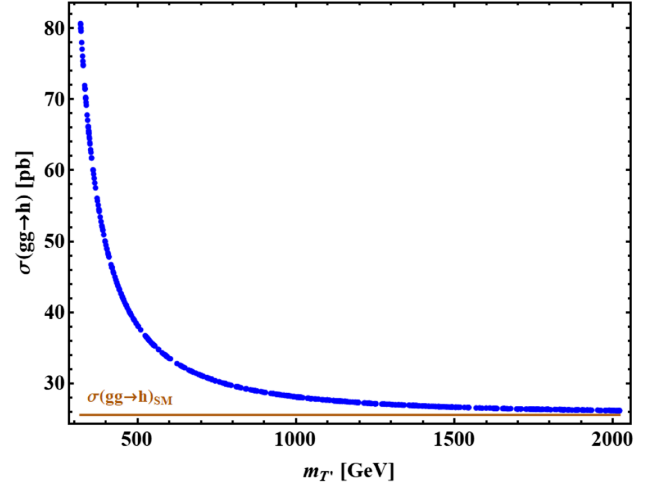


FIG. 19. $pp \rightarrow h$ production cross section vs mass of the new up-type quark for $g_{hT} = 1$.

decreased as the new up-type interferes destructively with the existing SM $h \rightarrow \gamma\gamma$ loops. Thus, this case cannot lead to any enhancement in the $h \rightarrow \Upsilon\gamma$ branching ratio.

b. Vectorlike singlet down-type quarks

We add a vectorlike pair of heavy down-type quarks B'_L, B'_R to the SM particle content with charges as shown in Table IX. The relevant new terms in the Lagrangian in this case are given by

$$-\mathcal{L} = m_{B'} \bar{B}'_L B'_R + g_{hB} \bar{Q} \Phi B'_R. \quad (\text{B6})$$

Since they have the same electric charge and spin, the new down-type quark mixes with SM down-type quarks and the

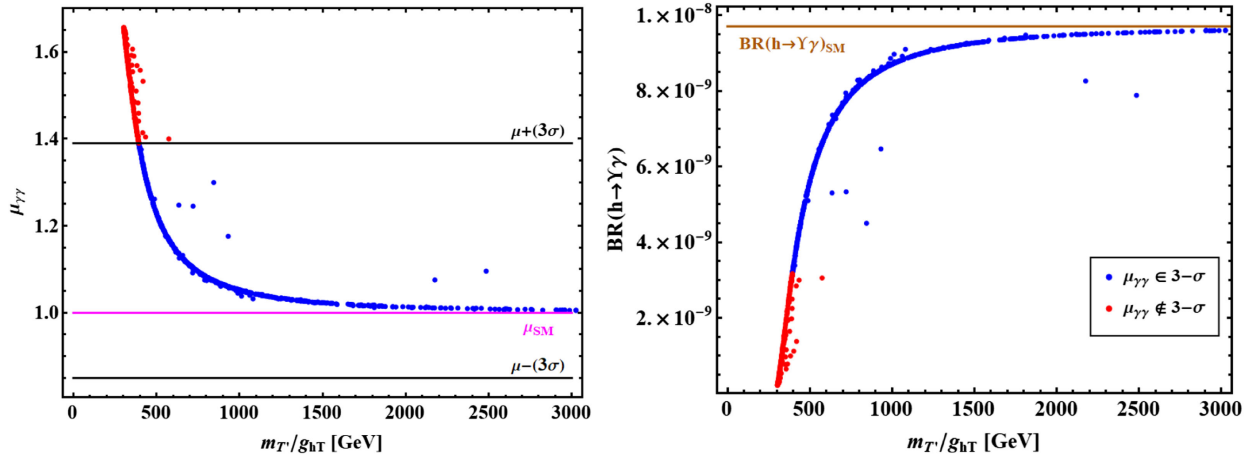


FIG. 20. Left: $\mu_{\gamma\gamma}$ vs ratio of mass of the new vectorlike singlet up-type quark to g_{hT} . The solid black lines are the experimentally measured $\mu_{\gamma\gamma}$ at $\pm 3\sigma$ uncertainty [31]. The magenta line is $\mu_{\gamma\gamma}$ in the SM. Right: Branching ratio of $h \rightarrow \Upsilon\gamma$ vs ratio of mass of the new vectorlike singlet up-type quark to g_{hT} , depicting the allowed values of $\mu_{\gamma\gamma}$ at each point.

TABLE IX. Charges of the new $SU(2)_L$ singlet down-type quarks.

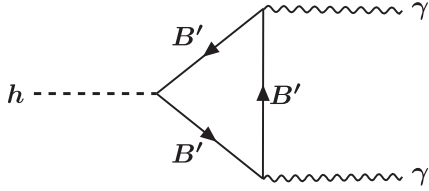
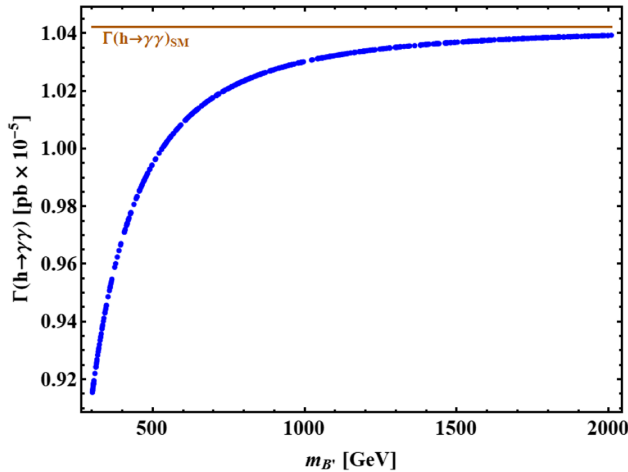
Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
B'_L	$\frac{1}{2}$	1	$(\mathbf{3}, \mathbf{1}, -1/3)$
B'_R	$\frac{1}{2}$	1	$(\mathbf{3}, \mathbf{1}, -1/3)$

new mixed state acts as the fourth generation of the down-type quark family. The Feynman diagram for the process that contributes to the indirect diagram in $h \rightarrow Y\gamma$ decay in this case is shown in Fig. 21. The contribution to the $h \rightarrow \gamma\gamma$ decay amplitude in this case can be calculated from the formula given in Appendix C, as follows:

$$\mathcal{A}_{\text{new}}^{B'}(h \rightarrow \gamma\gamma) = \frac{2}{3} g_{hB} \frac{v}{m_{B'}} A_{1/2}^h(\tau_{B'}), \quad (\text{B7})$$

where $m_{B'}$ is the mass of the new down-type quark and $\tau_{B'} = m_h^2/4m_{B'}^2$.

The modification in the $h \rightarrow \gamma\gamma$ decay width can be seen in Fig. 22: As we can see in Fig. 22, the new down-type quark interferes destructively with the existing SM $h \rightarrow \gamma\gamma$ loops, since its contribution is opposite in sign to the SM

FIG. 21. Feynman diagram for the $h \rightarrow \gamma\gamma$ process with the new down-type quark running in the loop.FIG. 22. $h \rightarrow \gamma\gamma$ decay width vs mass of the new down-type quark for $g_{hB} = 1$.

bosonic loop, as in the case of a new lepton and new up-type quark.

Furthermore, there is a modification to the production of h in this case. The most constraining production process that gets modified is gluon fusion. The new up-type quark can run in the gluon fusion loop and this modifies the production cross section. The Feynman diagram corresponding to this process is shown in Fig. 23. The modification to the production of h is shown in Fig. 24. As we can see in Fig. 24, there is an increase in the $gg \rightarrow h$ production. This is due to the fact that new up-type quark interferes constructively with the SM $gg \rightarrow h$ loops, which are dominated by the contribution from the top quark (as in the case of a new up-type quark). The overall modification to the μ parameter and the $h \rightarrow Y\gamma$ branching ratio as a result is shown in Fig. 25. The points in Fig. 25 are generated assuming the coupling g_{hB} to be in the perturbative range ($\leq \sqrt{4\pi}$). Due to contribution of the production cross section, there is an increase in the value of $\mu_{\gamma\gamma}$. However, since the $h \rightarrow Y\gamma$ decay width only depends on the $h \rightarrow \gamma\gamma$ decay width, the $h \rightarrow Y\gamma$ decay width is decreased as the new down-type interferes destructively with the existing SM $h \rightarrow \gamma\gamma$ loops. Thus, this case cannot lead to any enhancement in the $h \rightarrow Y\gamma$ branching ratio.

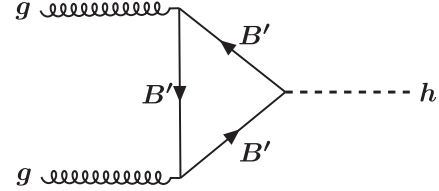
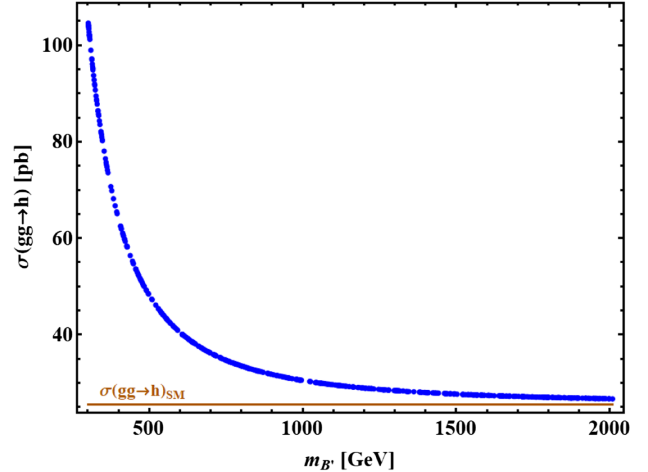


FIG. 23. Feynman diagram for Higgs production via the gluon fusion process with the new down-type quark running in the loop.

FIG. 24. $pp \rightarrow h$ production cross-section vs mass of the new down-type quark for $g_{hB} = 1$.

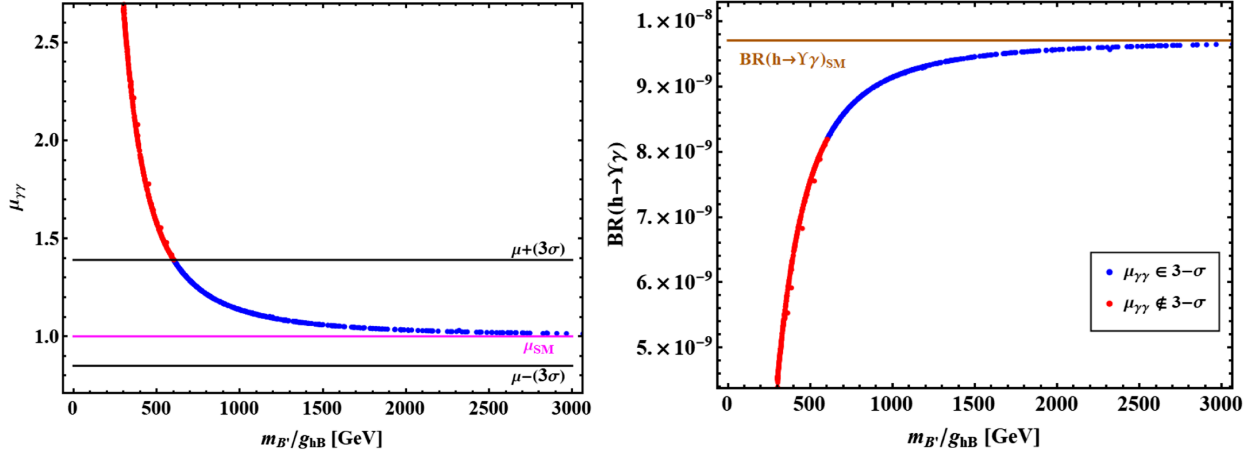


FIG. 25. Left: $\mu_{\gamma\gamma}$ vs ratio of mass of the new vectorlike singlet down-type quark to g_{hB} . The solid black lines are the experimentally measured $\mu_{\gamma\gamma}$ at $\pm 3\sigma$ uncertainty [31]. The magenta line is $\mu_{\gamma\gamma}$ in the SM. Right: Branching ratio of $h \rightarrow \Upsilon\gamma$ vs ratio of mass of the new vectorlike singlet down-type quark to g_{hB} , depicting the allowed values of $\mu_{\gamma\gamma}$ at each point.

c. Vectorlike doublet quarks

The charges of the vectorlike doublet quarks are given in Table X. The relevant new terms in the Lagrangian in this case are given by

$$-\mathcal{L} = m_{f'} \bar{f}'_L f'_R + g_{hT} \bar{f}'_L \tilde{\Phi} u_R + g_{hB} \bar{f}'_L \Phi d_R, \quad (\text{B8})$$

where u_R and d_R are the SM right-handed up-type and down-type quarks, respectively.

The production and decay properties of the Higgs boson in this case are very similar to the case of vectorlike up-type and down-type quarks. We again get a destructive interference leading to a decrease in $h \rightarrow \Upsilon\gamma$ branching ratio. Similar behavior is observed for any $SU(2)_L$ representation of new quarks. Hence, we can conclude that additional quarks beyond the SM cannot mimic the wrong-sign-like enhancement of the $h \rightarrow \Upsilon\gamma$ branching ratio.

3. New heavy charged scalars

Next, we discuss the case when a new heavy charged scalar boson H^+ is added to the SM particle content. We look at the simplest possibilities of new $SU(2)_L$ singlet and doublet scalars in detail. The conclusions drawn can be generalized to other cases.

TABLE X. Charges of the new $SU(2)_L$ doublet quarks.

Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
q'_L	$\frac{1}{2}$	1	$(\mathbf{3}, \mathbf{2}, 1/6)$
q'_R	$\frac{1}{2}$	1	$(\mathbf{3}, \mathbf{2}, 1/6)$

a. Singlet charged scalar

The charges of the new singlet charged scalar are given in Table XI. The relevant new terms in the Lagrangian in this case are given by

$$-\mathcal{L} = \mu_{H^+} H^+ H^- + \lambda_{H^+} H^+ H^- H^+ H^- + \lambda_{\Phi H^+} H^+ H^- \bar{\Phi} \Phi. \quad (\text{B9})$$

Since they have the same electric charge and spin, the new charged scalar mixes with the SM charged Goldstone boson.

The Feynman diagrams for the process that contributes to the indirect diagram in $h \rightarrow \Upsilon\gamma$ decay in this case are shown in Fig. 26. The contribution to the $h \rightarrow \gamma\gamma$ decay amplitude in this case can be calculated from the formula given in Appendix C, as follows:

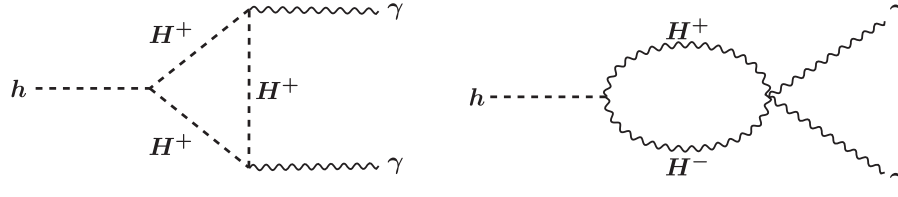
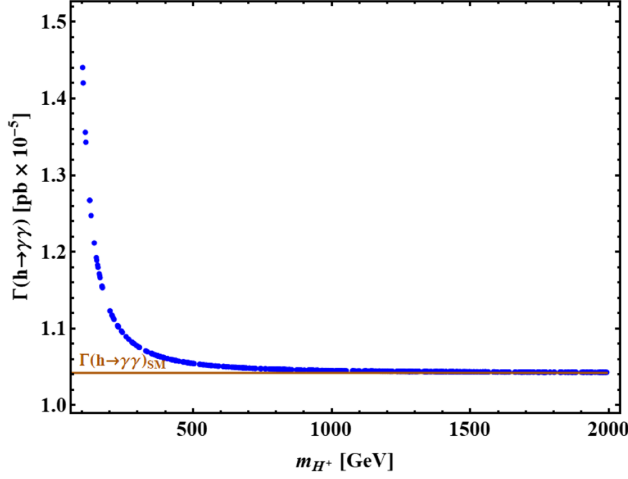
$$\mathcal{A}_{\text{new}}^{H^\pm}(h \rightarrow \gamma\gamma) = g_{hH^\pm} \frac{v}{2m_{H^\pm}^2} A_0^h(\tau_{H^\pm}), \quad (\text{B10})$$

where $m_{H^\pm}$ is the mass of the new charged scalar, $\tau_{H^\pm} = m_h^2/4m_{H^\pm}^2$, and $g_{hH^\pm} = \lambda_{\Phi H^\pm} \frac{v}{\sqrt{2}}$. The form factor A_0^h is given in Eq. (C4).

The modification in the $h \rightarrow \gamma\gamma$ decay width can be seen in Fig. 27: we have taken the sign of $\lambda_{\Phi H^+}$ to be negative to demonstrate the case when the new charged scalar interferes constructively with the existing SM $h \rightarrow \gamma\gamma$ loops. As we can see in Fig. 27, the new

TABLE XI. Charges of the new $SU(2)_L$ singlet scalar.

Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
H^+	0	1	$(\mathbf{1}, \mathbf{1}, 1)$

FIG. 26. Feynman diagrams for the $h \rightarrow \gamma\gamma$ process with the new charged scalar running in the loop.FIG. 27. $h \rightarrow \gamma\gamma$ decay width vs mass of the new charged scalar for $\lambda_{\Phi H^+} = -1$.

charged scalar interferes constructively with the existing SM $h \rightarrow \gamma\gamma$ loops since its contribution is the same sign as the SM bosonic loop.

Furthermore, there is no modification to the production of h in this case, as the new charged scalar is not a colored particle and hence, it does not run in the gluon fusion loop.

The overall modification to the μ parameter and the $h \rightarrow \Upsilon\gamma$ branching ratio as a result is shown in Fig. 28. The points in Fig. 28 are generated assuming the coupling $\lambda_{\Phi H^+}$ to be in the perturbative range ($\leq \sqrt{4\pi}$). Since the new charged scalar interferes constructively with the existing SM $h \rightarrow \gamma\gamma$ loops, the $h \rightarrow \Upsilon\gamma$ decay width is also increased. Thus, this case can lead to an enhancement in the $h \rightarrow \Upsilon\gamma$ branching ratio. However, the 3σ constraint from $h \rightarrow \gamma\gamma$ limits it to be only a small enhancement, as shown in Fig. 28.

b. Doublet scalar

The charges of the new doublet scalar are given in Table XII. The relevant new terms in the Lagrangian in this case are given by

$$\begin{aligned}
 -\mathcal{L} = & m_{22}^2 \Phi'^\dagger \Phi' - m_{12}^2 (\Phi'^\dagger \Phi' + \Phi'^\dagger \Phi) + \frac{\lambda_2}{2} (\Phi'^\dagger \Phi')^2 \\
 & + \lambda_3 \Phi'^\dagger \Phi \Phi'^\dagger \Phi' + \lambda_4 \Phi'^\dagger \Phi' \Phi'^\dagger \Phi \\
 & + \frac{\lambda_5}{2} [(\Phi'^\dagger \Phi')^2 + (\Phi'^\dagger \Phi)^2],
 \end{aligned} \tag{B11}$$

where $\Phi' = (H^+, \frac{1}{\sqrt{2}}(u + \sigma + \eta))$. Since they have the same electric charge and spin, σ mixes with the SM

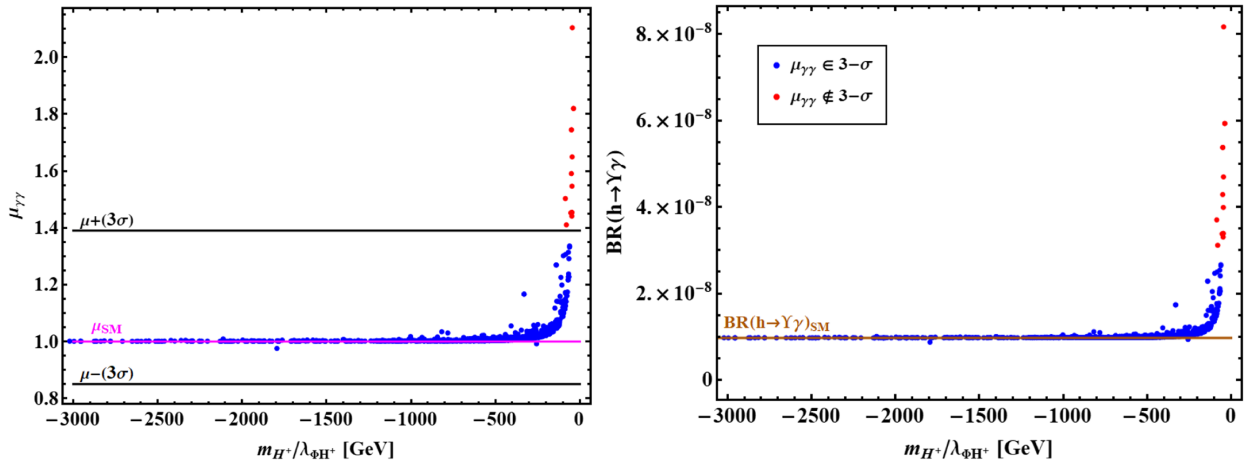


FIG. 28. Left: $\mu_{\gamma\gamma}$ vs ratio of mass of the new singlet charged scalar to $\lambda_{\Phi H^+}$. The solid black lines are the experimentally measured $\mu_{\gamma\gamma}$ at $\pm 3\sigma$ uncertainty [31]. The magenta line is $\mu_{\gamma\gamma}$ in the SM. Right: Branching ratio of $h \rightarrow \Upsilon\gamma$ vs ratio of mass of the new singlet charged scalar to $\lambda_{\Phi H^+}$, depicting the allowed values of $\mu_{\gamma\gamma}$ at each point.

TABLE XII. Charges of the new $SU(2)_L$ doublet scalar.

Name	Spin	Generations	$(SU(3)_C \otimes SU(2)_L \otimes U(1)_Y)$
Φ'	0	1	$(\mathbf{1}, \mathbf{2}, 1/2)$

Higgs boson, η mixes with the SM pseudoscalar Goldstone boson, and H^+ mixes with the SM charged Goldstone boson.

The decay and production properties of the Higgs boson in this case are similar to the case of a singlet charged scalar. A major difference here is that $g_{hH^+} = (\lambda_3 + \lambda_4 + \lambda_5) \frac{v}{\sqrt{2}}$. The overall modification to the μ parameter and the $h \rightarrow \Upsilon\gamma$ branching ratio in this case is shown in Fig. 29. The points in Fig. 29 are generated assuming the masses of the new charged and neutral scalars to be in the range 500–2000 GeV and the couplings λ_i to be in the perturbative range ($\leq \sqrt{4\pi}$). We also ensure vacuum stability constraints, as follows:

$$\begin{aligned} \lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > \sqrt{\lambda_1 \lambda_2}, \\ (\lambda_3 + \lambda_4) > -\sqrt{\lambda_1 \lambda_2}. \end{aligned} \quad (\text{B12})$$

Depending on the values of the couplings, the new charged scalar can interfere constructively or destructively with existing SM $h \rightarrow \gamma\gamma$ loops. The $h \rightarrow \Upsilon\gamma$ decay width will increase in the case of constructive interference and decrease in the case of destructive interference. Thus, this case can lead to an enhancement in the $h \rightarrow \Upsilon\gamma$ branching ratio. But again, the 3σ constraint

from $h \rightarrow \gamma\gamma$ limits it to be only a small enhancement, as shown in Fig. 29.

APPENDIX C: $h \rightarrow \gamma\gamma$ DECAY WIDTH CALCULATION

The $h \rightarrow \gamma\gamma$ decay width can be calculated as [42–44]

$$\Gamma[h \rightarrow \gamma\gamma] = \frac{\alpha^2 m_h^3}{256\pi^3 v^2} |\mathcal{A}_{\text{SM}} + \mathcal{A}_{\text{new}}|^2, \quad (\text{C1})$$

where m_h is the mass of the Higgs boson, v is the vacuum expectation value of the Higgs field, and $\mathcal{A}_{\text{SM}}$ is the $h \rightarrow \gamma\gamma$ decay amplitude due to SM particles, given as

$$\mathcal{A}_{\text{SM}}(h \rightarrow \gamma\gamma) = 2 \sum_f N_c Q_f^2 A_{1/2}^h(\tau_f) - A_1^h(\tau_{W^\pm}), \quad (\text{C2})$$

and $\mathcal{A}_{\text{new}}$ is the $h \rightarrow \gamma\gamma$ decay amplitude due to new fermions, charged gauge bosons, and charged scalar bosons, given as

$$\begin{aligned} \mathcal{A}_{\text{new}}(h \rightarrow \gamma\gamma) = & 2N_c Q_{f'}^2 g_{hf} \frac{v}{m_{f'}} A_{1/2}^h(\tau_{f'}) \\ & - g_{hV} \frac{v}{2m_V^2} A_1^h(\tau_V) + g_{hH^+} \frac{v}{2m_{H^\pm}^2} A_0^h(\tau_{H^\pm}), \end{aligned} \quad (\text{C3})$$

where N_c is the color factor of a fermion = 3(1) for quarks (leptons); Q_f is the electric charge of a fermion; $m_{f'}$, m_V , and $m_{H^\pm}$ are the masses of the new fermion, new charged gauge boson, and new charged scalar boson, respectively; and g_{hf} , g_{hH^+} , and g_{hV} are the couplings of the Higgs bosons to the new fermions, charged scalar bosons, and

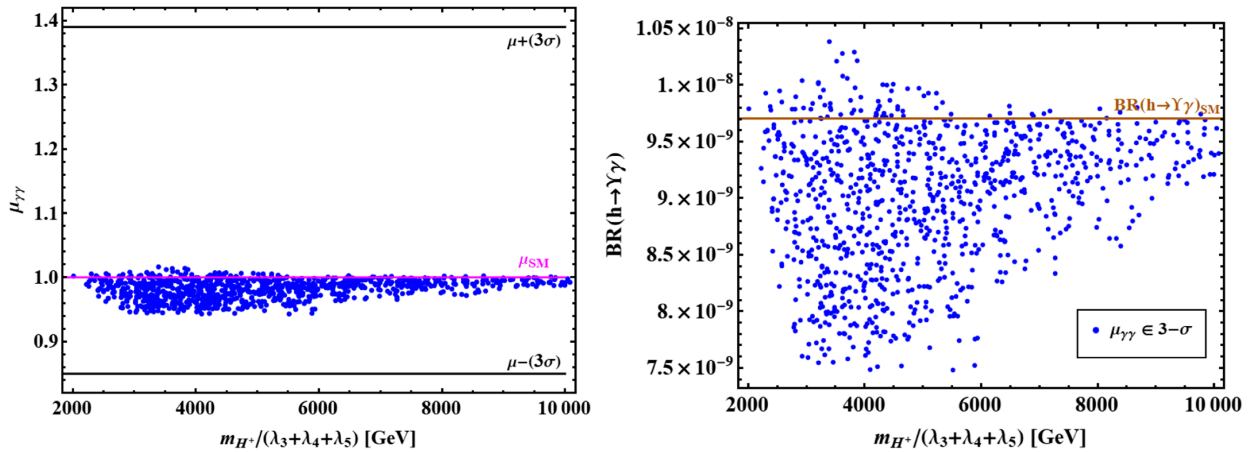


FIG. 29. Left: $\mu_{\gamma\gamma}$ vs ratio of mass of the new doublet charged scalar to $\lambda_3 + \lambda_4 + \lambda_5$. The solid black lines are the experimentally measured $\mu_{\gamma\gamma}$ at $\pm 3\sigma$ uncertainty [31]. The magenta line is $\mu_{\gamma\gamma}$ in the SM. Right: Branching ratio of $h \rightarrow \Upsilon\gamma$ vs ratio of mass of the new doublet charged scalar to $\lambda_3 + \lambda_4 + \lambda_5$, depicting the allowed values of $\mu_{\gamma\gamma}$ at each point.

charged gauge bosons, respectively. The form factors A_i^h for spin- $\frac{1}{2}$, spin-1, and spin-0 particles are given by

$$\begin{aligned} A_{1/2}^h(\tau) &= \tau^{-1}[1 + (1 - \tau^{-1})f(\tau)] \\ A_1^h(\tau) &= 2 + 3\tau^{-1} + 3\tau^{-1}(2 - \tau^{-1})f(\tau) \\ A_0^h(\tau) &= \tau^{-1}[\tau^{-1}f(\tau) - 1], \end{aligned} \quad (\text{C4})$$

where $\tau_i = m_h^2/4m_i^2$ with m_i denoting the loop mass, and the function $f(\tau)$ is defined as

$$f(\tau) = \begin{cases} \arcsin^2(\sqrt{\tau}) & \tau \leq 1 \\ -\frac{1}{4} \left[\ln\left(\frac{\sqrt{\tau} + \sqrt{\tau-1}}{\sqrt{\tau} - \sqrt{\tau-1}}\right) - i\pi \right]^2 & \tau > 1. \end{cases} \quad (\text{C5})$$

-
- [1] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); **652**, C4(E) (2021).
 - [2] T. Kajita, Nobel lecture: Discovery of atmospheric neutrino oscillations, *Rev. Mod. Phys.* **88**, 030501 (2016).
 - [3] A. B. McDonald, Nobel lecture: The Sudbury Neutrino Observatory: Observation of flavor change for solar neutrinos, *Rev. Mod. Phys.* **88**, 030502 (2016).
 - [4] K. Eguchi *et al.* (KamLAND Collaboration), First results from KamLAND: Evidence for reactor anti-neutrino disappearance, *Phys. Rev. Lett.* **90**, 021802 (2003).
 - [5] M. H. Ahn *et al.* (K2K Collaboration), Indications of neutrino oscillation in a 250 km long baseline experiment, *Phys. Rev. Lett.* **90**, 041801 (2003).
 - [6] G. Aad *et al.* (ATLAS Collaboration), Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* **716**, 1 (2012).
 - [7] S. Chatrchyan *et al.* (CMS Collaboration), Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* **716**, 30 (2012).
 - [8] The international linear collider technical design report—Volume 1: Executive summary, [arXiv:1306.6327](https://arxiv.org/abs/1306.6327).
 - [9] X. Cid Vidal *et al.*, Report from Working Group 3: Beyond the standard model physics at the HL-LHC and HE-LHC, *CERN Yellow Rep. Monogr.* **7**, 585 (2019).
 - [10] A. Abada *et al.* (FCC Collaboration), FCC physics opportunities: Future circular collider conceptual design report volume 1, *Eur. Phys. J. C* **79**, 474 (2019).
 - [11] A. Abada *et al.* (FCC Collaboration), FCC-ee: The lepton collider: Future circular collider conceptual design report volume 2, *Eur. Phys. J. Special Topics* **228**, 261 (2019).
 - [12] A. Abada *et al.* (FCC Collaboration), FCC-hh: The hadron collider: Future circular collider conceptual design report volume 3, *Eur. Phys. J. Special Topics* **228**, 755 (2019).
 - [13] A. Abada *et al.* (FCC Collaboration), HE-LHC: The high-energy large hadron collider: Future circular collider conceptual design report volume 4, *Eur. Phys. J. Special Topics* **228**, 1109 (2019).
 - [14] M. Aaboud *et al.* (ATLAS Collaboration), Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector, *Phys. Lett. B* **786**, 59 (2018).
 - [15] A. M. Sirunyan *et al.* (CMS Collaboration), Observation of Higgs boson decay to bottom quarks, *Phys. Rev. Lett.* **121**, 121801 (2018).
 - [16] N. G. Deshpande and E. Ma, Pattern of symmetry breaking with two Higgs doublets, *Phys. Rev. D* **18**, 2574 (1978).
 - [17] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Theory and phenomenology of two-Higgs-doublet models, *Phys. Rep.* **516**, 1 (2012).
 - [18] E. Ma, Verifiable radiative seesaw mechanism of neutrino mass and dark matter, *Phys. Rev. D* **73**, 077301 (2006).
 - [19] P. M. Ferreira, J. F. Gunion, H. E. Haber, and R. Santos, Probing wrong-sign Yukawa couplings at the LHC and a future linear collider, *Phys. Rev. D* **89**, 115003 (2014).
 - [20] D. Fontes, J. C. Romão, and J. P. Silva, A reappraisal of the wrong-sign $hb\bar{b}$ coupling and the study of $h \rightarrow Z\gamma$, *Phys. Rev. D* **90**, 015021 (2014).
 - [21] D. Fontes, J. C. Romão, and J. P. Silva, $h \rightarrow Z\gamma$ in the complex two Higgs doublet model, *J. High Energy Phys.* **12** (2014) 043.
 - [22] T. Modak and R. Srivastava, Probing anomalous Higgs couplings in $H \rightarrow ZV$ decays, *Mod. Phys. Lett. A* **32**, 1750004 (2017).
 - [23] G. T. Bodwin, F. Petriello, S. Stoynev, and M. Velasco, Higgs boson decays to quarkonia and the $H\bar{c}c$ coupling, *Phys. Rev. D* **88**, 053003 (2013).
 - [24] M. König and M. Neubert, Exclusive radiative Higgs decays as probes of light-quark yukawa couplings, *J. High Energy Phys.* **08** (2015) 012.
 - [25] C. Zhou, M. Song, G. Li, Y.-J. Zhou, and J.-Y. Guo, Next-to-leading order QCD corrections to Higgs boson decay to quarkonium plus a photon, *Chin. Phys. C* **40**, 123105 (2016).
 - [26] N. Brambilla, H. S. Chung, W. K. Lai, V. Shtabovenko, and A. Vairo, Order v^4 corrections to Higgs boson decay into $J/\psi + \gamma$, *Phys. Rev. D* **100**, 054038 (2019).
 - [27] T. Modak, J. C. Romão, S. Sadhukhan, J. P. Silva, and R. Srivastava, Constraining wrong-sign $hb\bar{b}$ couplings with $h \rightarrow \Upsilon\gamma$, *Phys. Rev. D* **94**, 075017 (2016).
 - [28] T. Modak, J. C. Romão, R. Srivastava, J. P. Silva, and S. Sadhukhan, Probing wrong-sign hbb couplings in $h \rightarrow \Upsilon\gamma$, *Springer Proc. Phys.* **203**, 873 (2018).
 - [29] J. F. Gunion and H. E. Haber, The CP conserving two Higgs doublet model: The Approach to the decoupling limit, *Phys. Rev. D* **67**, 075019 (2003).
 - [30] M. Aoki, S. Kanemura, K. Tsumura, and K. Yagyu, Models of Yukawa interaction in the two Higgs doublet model, and their collider phenomenology, *Phys. Rev. D* **80**, 015017 (2009).

- [31] CMS Collaboration, Combined measurements and interpretations of Higgs boson production and decay at $\sqrt{s} = 13$ TeV, Technical Report No. CMS-PAS-HIG-21-018, CERN, Geneva, 2025, <https://cds.cern.ch/record/2929999>.
- [32] ATLAS Collaboration, Combined measurements of Higgs boson production and decay at $\sqrt{s} = 13$ TeV using up to 140 fb^{-1} of data collected by the ATLAS Experiment, Technical Report No. ATLAS-CONF-2025-006, CERN, Geneva, 2025, <https://cds.cern.ch/record/2937634>.
- [33] ATLAS Collaboration, Searches for exclusive Higgs and Z boson decays into a vector quarkonium state and a photon using 139 fb^{-1} of ATLAS $\sqrt{s} = 13$ TeV proton – proton collision data, *Eur. Phys. J. C* **83**, 781 (2023).
- [34] F. Staub, Exploring new models in all detail with SARAH, *Adv. High Energy Phys.* **2015**, 840780 (2015).
- [35] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, FeynRules 2.0—A complete toolbox for tree-level phenomenology, *Comput. Phys. Commun.* **185**, 2250 (2014).
- [36] W. Porod, SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e^+e^- colliders, *Comput. Phys. Commun.* **153**, 275 (2003).
- [37] W. Porod and F. Staub, SPheno 3.1: Extensions including flavour, CP -phases and models beyond the MSSM, *Comput. Phys. Commun.* **183**, 2458 (2012).
- [38] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [39] R. Gambhir, R. Mastandrea, B. Nachman, and J. Thaler, Isolating unisolated upsilons with anomaly detection in CMS open data, *Phys. Rev. Lett.* **135**, 021902 (2025).
- [40] [10.54499/UID/00777/2025](https://cds.cern.ch/record/1054499)
- [41] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [42] A. Djouadi, The anatomy of electro-weak symmetry breaking. I: The Higgs boson in the standard model, *Phys. Rep.* **457**, 1 (2008).
- [43] A. Djouadi, The anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model, *Phys. Rep.* **459**, 1 (2008).
- [44] D. Eriksson, J. Rathsman, and O. Stal, 2HDMC: Two-Higgs-doublet model calculator physics and manual, *Comput. Phys. Commun.* **181**, 189 (2010).