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Probing Variant Axion Models at LHC

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Abstract

We study collider implications of variant axion models which naturally avoid the cosmological domain wall problem. We find that in such models the branching ratio of $h \to \gamma\gamma$ can be enhanced by a factor of 5 up to 30 as compared with the standard model prediction. The $h \to \gamma\gamma$ process is therefore a promising channel to discover a light Higgs boson at the LHC and to probe the Peccei-Quinn charge assignment of the standard model fields from Yukawa interactions.

I. INTRODUCTION

The strong CP problem is one of the profound problems in the standard model (SM). One of the elegant solutions was proposed by Peccei and Quinn [1]. They introduced a global chiral $U(1)_{PQ}$ symmetry, which is explicitly broken by the quantum chromodynamics (QCD) anomaly. In association with spontaneous breaking of the PQ symmetry, the axion appears as the pseudo Nambu-Goldstone boson coupled to the QCD anomaly. The effective CP phase θ is set to be 0 due to the dynamics of the axion.

In order to accommodate the PQ mechanism, we need to introduce an additional Higgs field and assign appropriate PQ charges to the Higgs field(s) and the quarks. However the PQ charge assignment is not unique, and there is a variety of axion models. In addition to the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) [2, 3] and Kim-Shifman-Vainshtein-Zakharov (KSVZ) [4, 5] invisible axion models, there is a class of models known as variant axion models in which quarks of the same chirality are assigned different PQ charges and therefore coupled to different Higgs fields [6, 7]. Although the original motivation of the model was to revive the Peccei-Quinn-Weinberg-Wilczek (PQWW) [1, 8, 9] axion model by making it consistent with experiments, it is straightforward to extend the setup to the invisible axion model.

There is a variety of astrophysical and cosmological constraints on the axion models [10–13]. Of particular importance is the constraint from the cosmological domain wall problem [14]. Suppose that the PQ symmetry is restored during or after inflation. Then domain walls may be formed in association of the spontaneous breaking, if there are multiple degenerate vacua. Let us denote the multiplicity by $N_{\rm DW}$. The DFSZ model, which is a natural extension of the original PQWW model, is plagued with the domain wall problem with $N_{\rm DW} = 3$ [1]. On the other hand, the KSVZ model has $N_{\rm DW} = 1$ and therefore avoids the problem *iff* there is only one heavy quark which carries a PQ charge. Interestingly, the variant axion models in which one of the two Higgs doublets couples to only one quark flavor has $N_{\rm DW} = 1$ and therefore naturally avoid the domain wall problem [15, 16].

In this paper we study the variant axion models [6, 7] and focus on the implications for the Higgs boson search at the Large Hadron Collider (LHC). In the SM, the dominant production mechanism for a Higgs boson at the LHC is so-called gluon-gluon fusion (GGF) via a top

[1] The value of $N_{\rm DW}$ can be 6, depending on the interaction between the Higgs doublets and the PQ singlet [15].

quark loop, followed by the vector-boson-fusion (VBF) process through the annihilation of two vector bosons. If the light Higgs boson is mainly contained in the scalar field with a PQ charge which has a larger expectation value, we find that the GGF process can be highly suppressed or slightly enhanced depending on the quark flavor to which the Higgs is coupled, and that the VBF process remains similar to the SM result. Moreover, the decay branching ratio of the Higgs boson to two photons, $h \to \gamma\gamma$, which is the most important search channel of the light Higgs boson at the LHC, can be significantly enhanced due to the suppression in the $h \to b\bar{b}$ as compared with the SM prediction.

The rest of the paper is organized as follows. In Sec. II we briefly explain the variant axion models. The phenomenology of the Higgs boson is studied in Sec. III, and finally, Sec. IV is devoted for discussions and conclusions.

II. VARIANT AXION MODELS

We introduce two Higgs doublets Φ_1 and Φ_2 which carry the same quantum numbers of the SM gauge group:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + h_1 + i g_1) \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + i g_2) \end{pmatrix}, \tag{1}$$

where v_1 and v_2 are the vacuum expectation values (vev). For later use, we define $\tan\beta \equiv v_2/v_1$ with $0 \le \beta \le \pi/2$. We assign PQ charges 0 and -1 to Φ_1 and Φ_2, respectively [2]. A PQ singlet field σ which carries a PQ charge 1 is assumed to have a large vev $v(\ge 10^9\,\text{GeV})$ in order to make the axion invisible [10]. Based on the quantum numbers of the Higgs and PQ scalar fields, we have the following renormalizable scalar potential,

$$\begin{aligned} V(\Phi_1, \Phi_2, \sigma) \;=\; & \lambda_1 \left(|\Phi_1|^2 - \frac{v_1^2}{2} \right)^2 + \lambda_2 \left(|\Phi_2|^2 - \frac{v_2^2}{2} \right)^2 + \lambda \left(|\sigma|^2 - \frac{v^2}{2} \right)^2 \\ & + a\,|\Phi_1|^2 |\sigma|^2 + b\,|\Phi_2|^2 |\sigma|^2 + \left(m\, \Phi_1^\dagger \Phi_2 \sigma + \text{h.c.} \right) \\ & + d\,|\Phi_1^\dagger \Phi_2|^2 + e\,|\Phi_1|^2\,|\Phi_2|^2 \,. \end{aligned} \tag{2}$$

In order to avoid the domain wall problem, we couple Φ_2 to only one quark flavor, while

[2] This choice is for understanding the Yukawa structure. In order to get rid of the mixing with the Nambu-Goldstone boson eaten by the Z boson, we need to assign the PQ charges of opposite sign and equal magnitude to both Higgs fields.

Φ_1 is coupled to the rest of the quarks and the leptons [3] . We consider the following three cases; Φ_2 is coupled to (1) the u quark; (2) the c quark; and (3) the t quark by assigning a PQ charge -1 to u_R, c_R, or t_R in each case [4]. The relevant Yukawa interactions are given by

$$-\mathcal{L}_{\rm Yukawa} = y_{ij}^{(d)} \bar{Q}_{Li} \Phi_1 d_{Rj} + y_i^{(u)} \bar{Q}_{Li} \tilde{\Phi}_3 u_R + y_i^{(c)} \bar{Q}_{Li} \tilde{\Phi}_4 c_R + y_i^{(t)} \bar{Q}_{Li} \tilde{\Phi}_5 t_R, \tag{3}$$

where the subscripts i and j denote the generations, and Q_L, u_R, d_R are the left-handed quark doublet, right-handed up-type and down-type quarks, respectively, and $\tilde{\Phi}_a \equiv i\sigma_2 \Phi_a^*$. The three models correspond to

$$\begin{aligned} \text{Model U} &: \Phi_3 = \Phi_2, \quad \Phi_4 = \Phi_1, \quad \Phi_5 = \Phi_1, \\ \text{Model C} &: \Phi_3 = \Phi_1, \quad \Phi_4 = \Phi_2, \quad \Phi_5 = \Phi_1, \\ \text{Model T} &: \Phi_3 = \Phi_1, \quad \Phi_4 = \Phi_1, \quad \Phi_5 = \Phi_2. \end{aligned} \tag{4}$$

The above potential (2) contains a massless degrees of freedom, the axion a, which mainly resides in the phase of σ. The axion acquires a coupling to the QCD anomaly term through the Yukawa interactions (3), and thus solving the strong CP problem [6, 7].

Note that, since we couple different Higgs fields to the quarks of the same chirality, the flavor violation is not automatically absent [17]. However the flavor constraint does not affect the following discussion, and so, we simply neglect the tree-level Higgs-mediated flavor changing processes in the following discussion.

The peculiar Yukawa structure of the variant axion model makes it cosmologically viable since the domain wall problem is absent. Interestingly, as we will see in the next section, due to the Yukawa structure, the production and decay branching ratios of the light Higgs boson are significantly modified.

III. PHENOMENOLOGY

After the electroweak symmetry is broken, two CP even Higgs bosons are left at the weak scale. The heavy and light Higgs fields, denoted by H and h, respectively, are mixtures of

[3] We can couple Φ_2 instead of Φ_1 to the leptons without affecting the domain wall problem. Then, e.g. $h \to \tau^+\tau^-$ would be enhanced (or suppressed).

[4] If the weak mixing angles come from only a rotation of the up-quark sector, we can safely assign the PQ charge -1 to d_R, s_R or b_R instead of u_R, c_R or t_R.

h_1 and h_2 defined in Eq. (1) and can be written as

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \tag{5}$$

where α is a mixing angle varying from $-\pi/2$ to $\pi/2$. In the limit of $\sin\alpha \to 0$, the light (heavy) Higgs mainly contains h_2 (h_1), and bear in mind that Φ_2 is assigned a PQ charge.

The Higgs couplings to the gauge bosons are given by

$$HVV \ : \ \cos(\beta-\alpha)\ g_{\rm SM}^{hVV}, \tag{6}$$

$$hVV \ : \ \sin(\beta-\alpha)\ g_{\rm SM}^{hVV}, \tag{7}$$

where V denotes either W-boson or Z-boson, and $g_{\rm SM}^{hVV}$ denotes the coupling between the corresponding gauge bosons to the Higgs boson in the SM. Therefore, if we consider a small mixing angle, i.e., $|\sin\alpha| \ll 1$, with moderately large $\tan\beta \gtrsim 5$, the couplings of the light Higgs boson to the gauge bosons are almost the same as the SM case [5]. We take $\tan\beta = 5$ throughout this paper as a reference value in the numerical results. The difference among the three models is therefore the couplings of the light Higgs to heavy quarks. As can be seen from Eqs. (3) and (4), Φ_1 generates all the fermion masses except for the u (c, t) quark in the model U (C, T), resulting in different branching ratios and production cross sections for the light Higgs boson. We will focus on the light Higgs boson h whose mass is smaller than 130 GeV and its decay to two photons, $h \to \gamma\gamma$, since this is the main search channel at the LHC. We assume all the other degrees of freedom (the heavy neutral, CP-odd, and charged Higgs bosons) are heavy enough to be neglected in the following study.[6]

A. Model U

In this setup, the u quark is special since it is coupled to Φ_2, while the other fermions are coupled to Φ_1. The couplings of the light Higgs boson to the up, charm, bottom and

[5] In this limit, the light Higgs boson h mainly resides in the Higgs field with a larger vev, Φ_2.

[6] For instance, there is a lower bound on the charged Higgs boson mass $M_{H^+} \gtrsim 300\,{\rm GeV}$ [18] in the model T.

top quarks are given by

$$huu \ : \ \frac{\cos\alpha}{\sin\beta} g_{\rm SM}^{huu}, \tag{8}$$

$$hcc \ : \ -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{hcc}, \tag{9}$$

$$hbb \ : \ -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{hbb}, \tag{10}$$

$$htt \ : \ -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{htt}, \tag{11}$$

where $g_{\rm SM}^{hff}$ is the coupling of fermion f to the Higgs boson in the SM. The other down-type quarks and leptons have couplings similar to the bottom quark case. We can drop the huu coupling in the following analysis, since the u quark Yukawa coupling is tiny, and it does not play any important role at collider experiments.

We are interested in the case of $|\sin\alpha| \ll 1$ and $\tan\beta \gtrsim 5$, for which the light Higgs boson h is contained mainly in h_2 [7]. The couplings to the fermions other than the u quark are then enhanced by $\tan\beta$, but suppressed by $\sin\alpha$. If the mixing $\sin\alpha$ is sufficiently small (i.e., $|\sin\alpha| \ll \cot\beta$), the couplings to those fermions, especially to the heavy quarks, can be suppressed. If this is the case, the partial decay width of the light Higgs to a fermion pair (except for the u quark) will be highly suppressed compared to the SM prediction, while W^+W^- and ZZ decay modes remain almost unchanged. Since the $h \to gg$ is mainly through a top-quark loop, its partial width is suppressed as well. For $h \to \gamma\gamma$, the partial decay width is slightly enhanced; this can be understood from the fact that the contribution from the top-quark loop, which partially cancels that of the W-boson loop in the SM, is now suppressed. Note that the main decay mode of the Higgs is $h \to b\bar{b}$ for $M_h \lesssim 130\,\text{GeV}$ in the SM. Therefore, if the $h \to b\bar{b}$ is suppressed, the branching fractions of all the other modes are enhanced accordingly.

We show the branching fractions of various decay processes and the enhancement or the suppression factor compared to the SM prediction as a function of M_h in Fig. 1. We consider two cases: no mixing ($\sin\alpha = 0$) in the upper panel and a small (but non-zero)

[7] In order for the top Yukawa coupling not to blow up at high energies, $\tan\beta$ cannot be much larger than unity in the models U and C. For a smaller value of $\tan\beta (\gtrsim 1)$, the production cross section of the Higgs through VBF and the decay width of $h \to \gamma\gamma$ become smaller. Note however that the branching fraction of $h \to \gamma\gamma$ is not sensitive to $\tan\beta$ and can be still enhanced over the SM value, as long as $h \to W^+W^-$ is the dominant decay mode.

mixing ($\sin\alpha = -0.05$) in the lower panel. Furthermore, due to the absence of the signals of the Higgs boson in the past and current experiments at LEP and Tevatron, the mass and the branching ratios of the Higgs boson are constrained, as shown by the shaded regions in Fig. 1 [8]. In the case of $\sin\alpha = 0$, the Higgs boson with a mass smaller than about 109 GeV is excluded by the direct search of $h \to \gamma\gamma$ at the LEP II [21]. The decay branching ratio of $h \to \gamma\gamma$ can be as large as 1% to 6% for a Higgs boson lighter than 130 GeV, which is about a factor of 5 to 30 enhancement compared to the SM prediction. If the mixing angle α is small but non-zero, the $h \to b\bar{b}$ decay branching ratio can become non-negligible. The $h \to \gamma\gamma$ is enhanced by a factor 4 at $M_h = 130$ GeV and by a factor of 10 at $M_h = 112$ GeV below which the mass region is excluded by the search of $h \to b\bar{b}$ in LEP II [22].

B. Model C

The couplings of the light Higgs to the charm, bottom and top quarks are given by

$$hcc \;:\; \frac{\cos\alpha}{\sin\beta} g_{\rm SM}^{hcc}, \tag{12}$$

$$hbb \;:\; -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{hbb}, \tag{13}$$

$$htt \;:\; -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{htt}, \tag{14}$$

where the notations follow the description in the model U. The main difference from the model U is that the decay into a charm quark pair is not suppressed even in the limit of $|\sin\alpha| \ll \cot\beta$ and $\tan\beta \gtrsim 5$, since the hcc coupling approaches to the SM value. Because of the existence of large $h \to c\bar{c}$ decay branching ratio, the enhancement of $h \to \gamma\gamma$ is not as large as the model U at $M_h \simeq 110$ GeV. As M_h increases, the branching fraction of $h \to \gamma\gamma$ becomes similar to that in model U, since the $h \to W^+W^-$ decay mode quickly dominates the total decay rate. As we can see from Fig. 2, when M_h is smaller than 130 GeV, the branching fraction of $h \to \gamma\gamma$ can be as large as a few percent and about 1% for $\sin\alpha = 0$ and $\sin\alpha = -0.05$, respectively. The excluded mass region in the upper (lower) panel of Fig. 2 is from direct search of $h \to \gamma\gamma$ ($h \to b\bar{b}$) in the LEP II [21, 22].

[8] The decay branching ratios of the light Higgs boson are calculated by modifying the HDECAY [19] and the constrains are obtained using HiggsBounds [20].

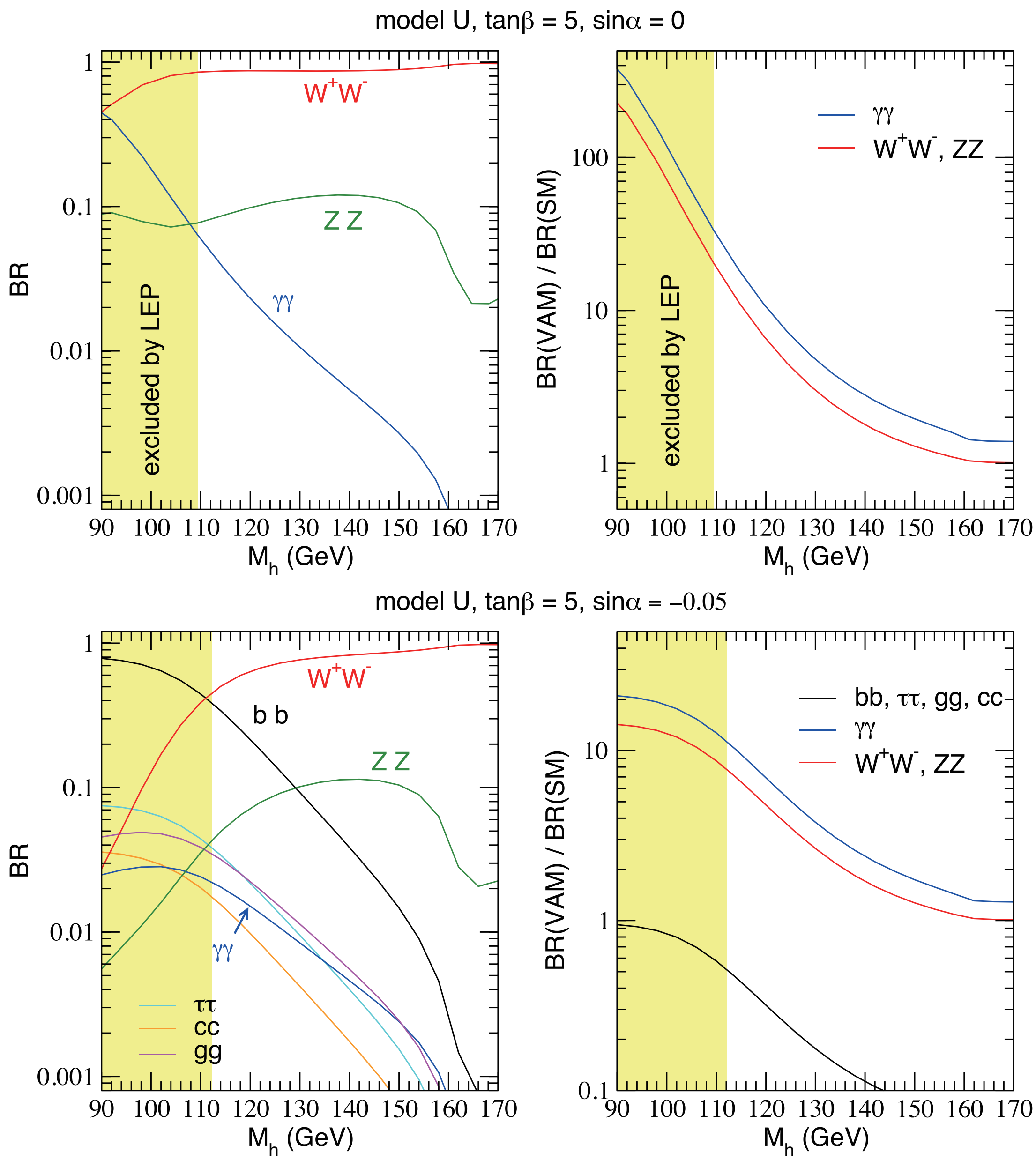

FIG. 1: The branching fractions of various decay processes of the light Higgs for the model U, as a function of the Higgs mass M_h (left). The ratios to the SM predictions are also shown (right). (VAM stands for the variant axion model.) The upper panels are for the limiting case of $\sin\alpha = 0$, and the bottom ones are for $\sin\alpha = -0.05$.

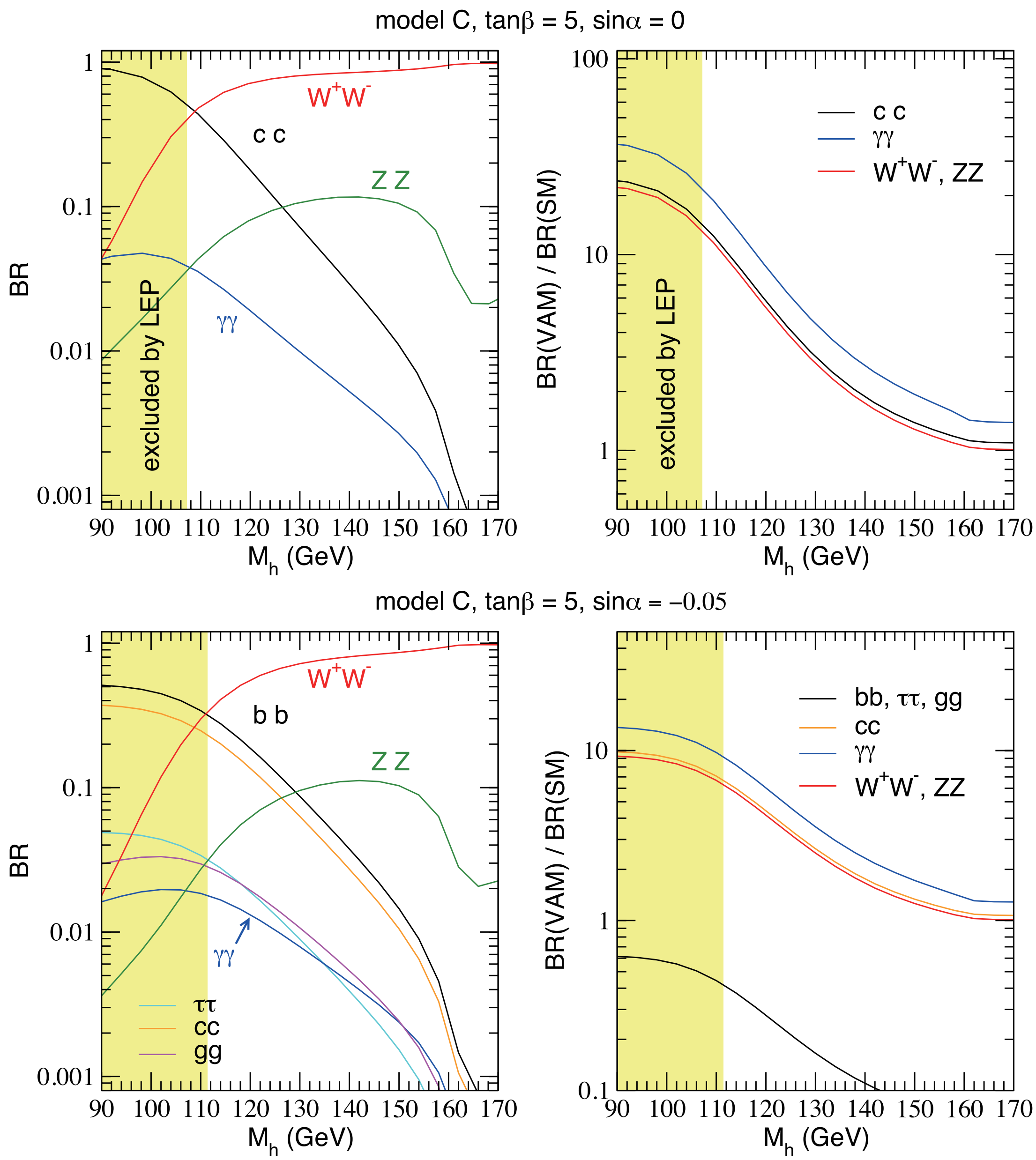

FIG. 2: Same as Fig. 1 but for the model C.

C. Model T

The couplings of the light Higgs to the charm, bottom and top quarks are given by

$$hcc \; : \; -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{hcc}, \tag{15}$$

$$hbb \; : \; -\frac{\sin\alpha}{\cos\beta} g_{\rm SM}^{hbb}, \tag{16}$$

$$htt \; : \; \frac{\cos\alpha}{\sin\beta} g_{\rm SM}^{htt}. \tag{17}$$

The main difference from the other two models is that the htt coupling is not suppressed. Therefore the effective higgs-gluon-gluon coupling is not suppressed, which enhances the decay branching ratio of Higgs to two gluons, $h \to gg$, compared to the other two models. We should mention several advantages in such a setup. The Yukawa structure with large $\tan\beta$ explains why the top quark is much heavier than the other quarks. Furthermore, the flavor changing neutral process does not give any constraints; the top flavor physics in a similar setup has been extensively studied in Ref. [23].

Since the branching ratio of $h \to \gamma\gamma$ is not as large as the model U and model C, the result of LEP II does not impose any constrain for M_h larger than 90 GeV when $\sin\alpha = 0$, as shown in upper panel of Fig. 3. For $\sin\alpha = -0.05$, similarly, $h \to b\bar{b}$ becomes sizable, and the LEP II result [22] excludes the Higgs boson lighter than about 110 GeV.

D. Production cross sections and Higgs search at the LHC

In this section we discuss the prospect for the discovery of the light Higgs for each model and we assume $|\sin\alpha| \ll \cot\beta$ and $\tan\beta \gtrsim 5$ in the following discussion unless otherwise stated. As we mentioned previously, in the SM, the dominant production of a Higgs boson at the LHC is GGF while VBF is sub-dominant. In the models U and C, since the coupling of the Higgs boson to the top quarks is suppressed, the GGF production cross section will decrease significantly and VBF is the same as the SM result. Therefore, the VBF may become the leading production mechanism for the light Higgs boson. On the other hand, in the model T, there is no suppression in the coupling of the Higgs boson to top quarks and gauge bosons, so the production cross section is similar to that in the SM. The production cross sections of GGF and VBF compared to the SM for each model are shown in Fig. 4. For $\sin\alpha = 0$, the GGF process is completely turned off in the models U and C, which is not shown in the plot. In the model T, the GGF process can be enhanced by about 20% for $M_h \lesssim 130$ GeV (red solid line).

At the LHC, $h \to \gamma\gamma$ is the main search channel for a light Higgs boson. It has been shown that the LHC is able to discover such a signal for the SM Higgs boson lighter than about 130 GeV, with the 30 fb^{-1} integrated luminosity and 14 TeV center-of-mass (c.m.) energy in the inclusive search [24, 25]. Furthermore, the CMS collaboration [24] has also studied exclusively $h \to \gamma\gamma$ channel in VBF and in the production of a light Higgs boson in

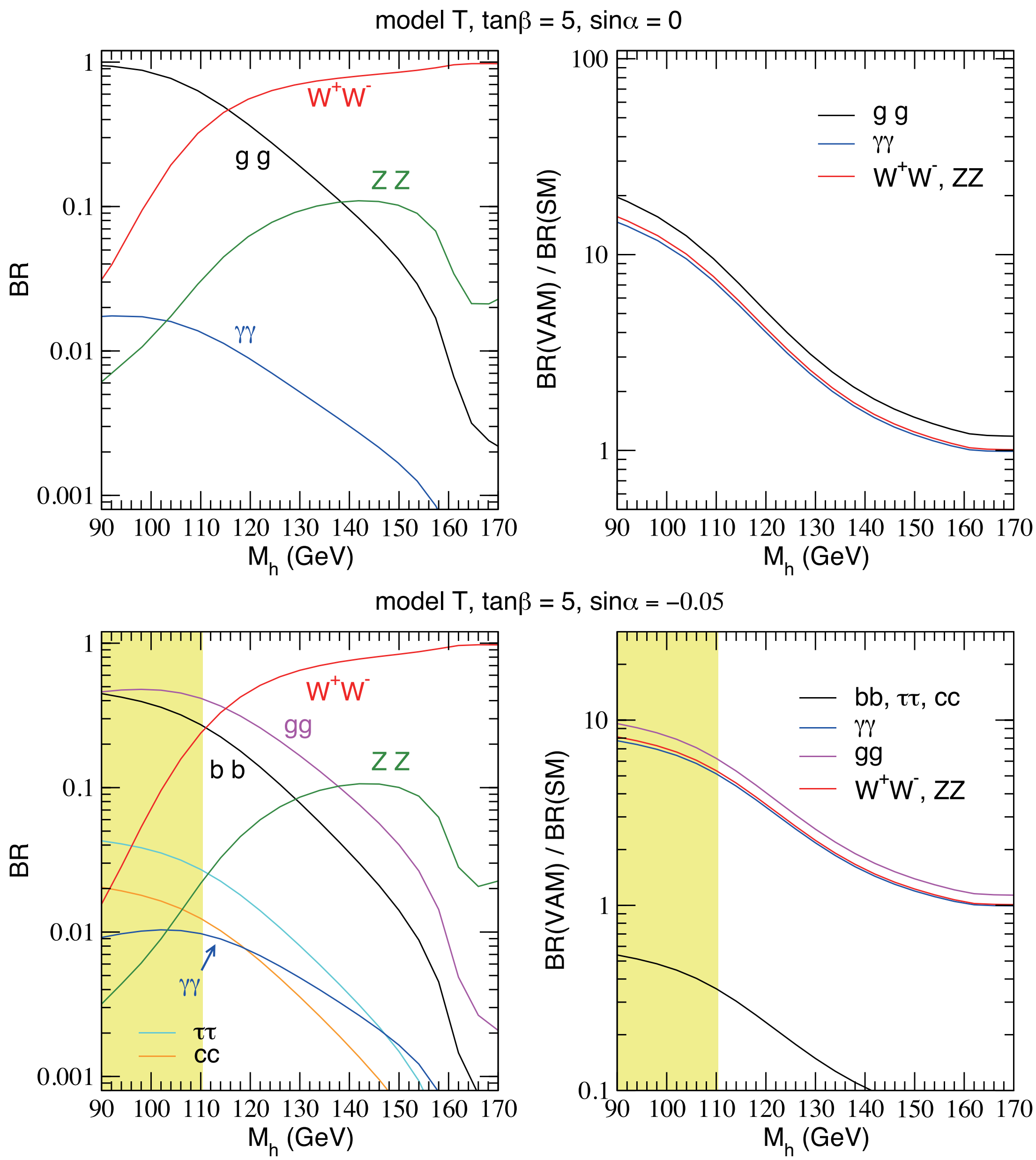

FIG. 3: Same as Fig. 1 but for the model T.

association with a gauge boson, $q\bar{q}' \to W^{\pm *}/Z^* \to W^{\pm}/Zh$, and the estimated significance is about 2.2σ with 30 fb^{-1} luminosity for both processes with 115 GeV $\lesssim M_h \lesssim$ 130 GeV.

For the variant axion models U and C, the GGF process is significantly suppressed, therefore the VBF and associated production with vector boson (VH) become important. For example, the branching ratio of $h \to \gamma\gamma$ is enhanced by a factor of about 8 (5) for $M_h = 120\,\text{GeV}$ in model C when $\sin\alpha = 0$ ($\sin\alpha = -0.05$). One can then estimate from the SM study that such a light Higgs boson should be discovered with only 3 fb^{-1} (10 fb^{-1})

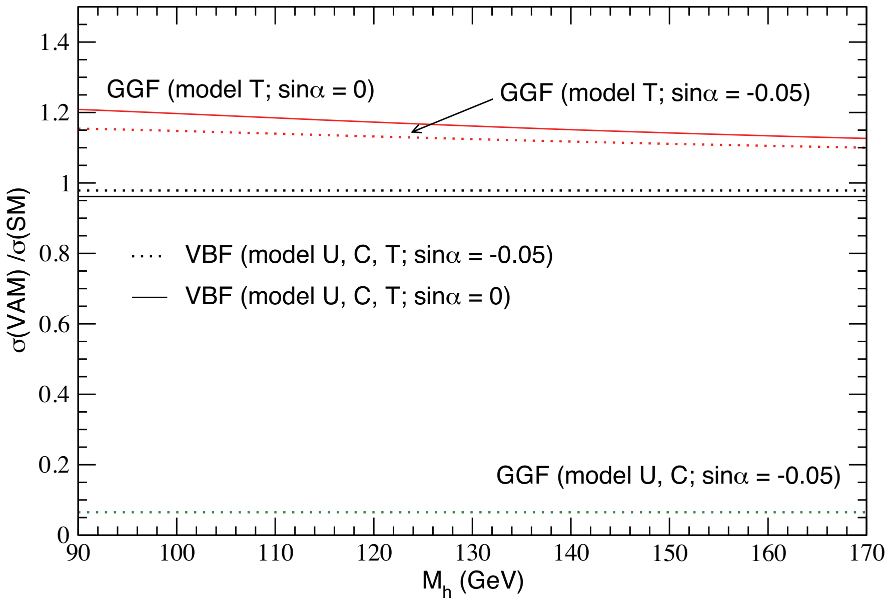

FIG. 4: The ratio of the production cross sections to the SM values for the gluon-gluon fusion (GGF) and the vector-boson fusion (VBF) processes, as a function of the light Higgs mass, M_h. The solid lines are for the case of $\sin\alpha = 0$, while the dotted lines are for $\sin\alpha = -0.05$.

luminosity by event counting, assuming that the production cross sections for VBF and VH are not changed. In the case of the model T, the situation will be more improved compared to the model U and C since the cross sections of all the production processes are similar to the SM predictions while the branching ratio of $h \to \gamma\gamma$ is enhanced. Comparing with the inclusive production cross section of the Higgs boson at the designed 14 TeV c.m. energy at the LHC, the production cross section will be reduced by a factor of $3 \sim 4$ [9] in the current operation of LHC with 7 TeV c.m. energy. If the background decreases by the same factor [10], we expect, by event counting, a strong evidence of the existence of the light Higgs boson with $1 fb^{-1}$ integrated luminosity by the end of 2011. For instance, the statistical significance of the signal can be larger than 3σ (2σ) for a 110 GeV Higgs boson if $\sin\alpha = 0$ $(\sin\alpha = -0.05)$.

[9] The factor is estimated from the decrease of GGF using Higlu [26], since the GGF is dominant process and is about ten times larger than the sub-leading one.

[10] The true suppression factor should be calculated precisely for the 7 TeV c.m. energy at the LHC.

IV. DISCUSSION AND CONCLUSIONS

The variant axion models have a special Yukawa structure, and its phenomenology is similar to the two Higgs doublet models. The model U is similar to the 2HDM type I, in which one of the Higgs doublets has no Yukawa couplings. Indeed, for a large $\tan\beta \gg 1$ and $\sin\alpha = 0$, the model U is almost same as the fermiophobic Higgs scenario [27, 28], which has been studied by the LEP [29] and Tevatron experiments [30]. It is also possible to shut off the light Higgs decay to the down-type quarks in the supersymmetric SM [31, 32], which have some similarities with the model T [28]. One important difference is that the $h \to c\bar{c}$ is suppressed in the model T.

The axion is a plausible candidate for dark matter in our model. The abundance is determined by the breaking scale of the PQ symmetry, $f_a = v$. The axion dark matter is produced from (1) coherent oscillations [12] and (2) axion string and domain wall decays [33–38]. Although the production from the axionic strings and walls involves a relatively large uncertainty, the required value of f_a for the axion to account for the observed dark matter density is of $O(10^{10}) \sim O(10^{11})$ GeV. If the axion is the main component of dark matter, the axion direct search (e.g. ADMX [39]) may be able to detect it.

In this paper we have studied the collider implications of the variant axion models which naturally avoid the cosmological domain wall problem. We have found that, if the light Higgs boson contains mainly the neutral Higgs field which carries a PQ charge, the branching fraction of $h \to \gamma\gamma$ can be significantly enhanced for a moderately large value of $\tan\beta$, due to the suppression of the couplings to the heavy fermions. For the models U and C (T) the enhancement factor can reach 4 to $\mathcal{O}(10)$ (2 to $\mathcal{O}(10)$) for M_h lighter than 130 GeV. Since the GGF process is highly suppressed in the models U and C, the VBF and VH processes are important. With the large decay branching ratio of $h \to \gamma\gamma$, the LHC with 14 TeV c.m. energy will have a greater potential to discover the light Higgs boson with a low luminosity ($\lesssim 10\ fb^{-1}$). In the model T, the production cross sections for the relevant processes are almost the same as the SM predictions. Therefore it will be much easier to discover the Higgs boson through the search of $h \to \gamma\gamma$, compared to the SM. Even for the early operation of LHC with 7 TeV c.m. energy and 1 fb^{-1} liminosity, we may be able to have a strong evidence of the existence of the light Higgs boson.

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