A RADIATIVELY IMPROVED FERMIOPHOBIC HIGGS BOSON SCENARIO

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The naive fermiophobic scenario is unstable under radiative corrections, due to the chiral-symmetry breaking induced by fermion mass terms. In a recent study, the problem of including the radiative corrections has been tackled via an effective field theory approach. The renormalized Yukawa couplings are assumed to vanish at a high energy scale Λ, and their values at the electroweak scale are computed via modified Renormalization Group Equations. We show that, in case a fermiophobic Higgs scenario shows up at the LHC, a linear collider program will be needed to accurately measure the radiative Yukawa structure, and consequently constrain the Λ scale.

1 Introduction

The standard model (SM) Higgs boson search [1] is approaching its completion with the operation of the LHC at a larger-than-nominal luminosity. In a few months, the ATLAS and CMS experiments will be able either to find out a SM-Higgs-like signal (and subsequently start the exploration of its properties) or to exclude the existence of a SM Higgs boson. In the latter case, exploring the possibility of a Higgs boson with characteristics different from the SM ones will in general take longer. An exception to this expectation could be given by a light fermiophobic Higgs boson.

A fermiophobic (FP) Higgs boson by definition is decoupled from fermions. As a consequence, its branching ratios (BR's) for decays into photons and vector bosons are enhanced for light Higgs masses, where the SM decays into fermion pairs are dominant. In particular, assuming vanishing Higgs widths into fermions in the SM framework gives rise to an enhancement of the BR into photon pairs by a factor about [110, 30, 10, 5] for the Higgs mass $m_H \simeq [100, 110, 120, 130]$ GeV, respectively, and would increase all the decay rates into vector bosons for $m_H \leq 150$ GeV [2]. On the other hand, the main Higgs production mechanism through gluon fusion, which depends on the Higgs coupling to heavy colored fermions, is missing for the FP Higgs boson, and total production rates are in general depleted. The combination of an enhanced decay rate and a depleted production would anyway make the detection of a FP Higgs lighter than about 120 GeV remarkably easier than in the SM picture, where the discovery of a Higgs boson through the depleted $H \to \gamma\gamma$ signature is quite challenging.

In general, assuming vanishing Higgs couplings to fermions implies a mechanism for the generation of fermion masses different from the SM one. In the SM, fermion masses, as well as vector boson masses, arise as the result of the spontaneous Electroweak-Symmetry Breaking

(EWSB) induced by the Higgs field. The vacuum expectation value of the Higgs field sets, through the Yukawa coupling constants, also the fermion masses, and produces spontaneous Chiral Symmetry Breaking (ChSB) in the Lagrangian. Decoupling the Higgs boson from fermions by switching off Yukawa couplings is presently phenomenological acceptable [3], but makes the theory non-renormalizable. This implies that in order to compute radiative corrections to the "naive" (i.e. tree-level) FP scenario one needs further assumptions.

In a recent paper, we addressed the issue of evaluating the radiative Yukawa couplings in a general FP Higgs scenario [3]. There are at least two possible ways to proceed. First, one can build up a renormalizable extension of the SM predicting a FP Higgs boson at tree-level. This implies in general an increase in the number of the degrees of freedom of the Higgs sector [4]. Then, radiative corrections are computable, although known models do not predict large effects in the Yukawa couplings since the ChSB scale is of the order of the EWSB scale. Second, one can try to find a general description of a wide class of possibilities where the Higgs mechanism generates the vector boson masses just as in the SM, but where fermion masses have a different (unknown) origin. This can be pursued by considering the SM with non-vanishing fermion masses but no Yukawa couplings as an effective field theory (EFT).

In [3], we adopted the latter (more general) approach by switching off tree-level Yukawa couplings in the SM Lagrangian. In particular, while in the SM the ChSB, associated to the non-vanishing fermion masses, and the EWSB, associated to the non-vanishing vector-boson masses, are both set at the same energy scale by the vacuum expectation value $v \simeq 246$ GeV of the Higgs field, we assume ChSB and fermion masses are generated by some new mechanism at an energy scale Λ, that will be in general larger or much larger than the electroweak scale (contributions to EWSB arising from the ChSB mechanism are assumed to be small). Then, we assume that $m_H \leq v$ and, for simplicity, only SM degrees of freedom propagate at energies below Λ. In this framework, the condition of vanishing Yukawa couplings at some energy scale is unstable under radiative corrections. Because of ChSB, radiative effects regenerate Yukawa couplings, with a control parameter given by fermion masses.

We then impose that the Yukawa couplings vanish at the (renormalization) scale $\Lambda \gg m_H$, which is the renormalization condition for the fermion-Higgs boson decoupling. In perturbation theory, this condition should be replaced by the finite one-loop threshold conditions of the Yukawa couplings at the Λ scale, calculated in the framework of a renormalizable UV completion of the theory above the scale Λ. Since $m_f \ll \Lambda$, $Y_f(\Lambda)$ are expected (by ChSB and dimensional analysis arguments) to be of order $\mathcal{O}(m_f/\Lambda) \ll 1$, and $Y_f(\Lambda) = 0$ should be seen as a particular approximation. Then, we use the EFT approach to compute the universal (i.e., independent of the particular UV completion of the theory above Λ) leading-log components of the Yukawa couplings at the m_H scale through Renormalization Group (RG) equations. The RG equations as computed in the SM [5] (where Y_f's and m_f's are related by spontaneous ChSB induced by the SM Higgs field) do not fit the present framework, and new RG equations were derived in [3] by keeping Y_f's and m_f's as independent parameters. The numerical values for the radiative Yukawa couplings derived in this approach (as well as the results shown below on BR's and cross sections) can be found in [3, 6].

In Figure 1 (upper-left), the total Higgs width is shown versus m_H for the improved FP-Higgs scenario at different values of the Λ scale. The small Higgs total width considerable enhances BR's for radiative decays into fermion pairs, especially at large Λ [Figure 1 (upper-right)]. In particular, BR($b\bar{b}$) $> 10\%$ for $\Lambda > 10^7$ GeV. Also shown, in the same plot, is the

BR for the flavor-changing decay $H \to bs$ as computed in [6]. In Figure 1 (lower-left), one can see that, for Λ near the GUT scale, BR($b\bar{b}$) can almost reach the SM value for $m_H < 110$ GeV.

Present experimental bounds on the improved FP scenario are expected to depend non-trivially on the Λ scale assumed. In particular, at $\Lambda \sim m_H$ (where log effects vanish in the RG equations) one should recover the m_H bounds found, assuming a tree-level FP scenario, at LEP [7], Tevatron [8], and LHC [9], while at $\Lambda \sim M_{GUT}$ one should approach the SM Higgs mass limits [10–13]. At intermediate Λ's, milder bounds are expected due to the interplay of an enhanced BR($\gamma\gamma$) (that is anyway lower than in the tree-level FP scenario) and a BR($b\bar{b}$) that is non-vanishing, but less than its SM value. Just as an example of the m_H bounds behavior versus Λ, we present in Figure 1 (lower-right), what is obtained by the help of the code Higgsbounds [14], version 3.4.0beta, after modeling the Higgs couplings via the effective Yukawa couplings of the improved FP scenario.

In Figure 2, we present production rates corresponding to different Higgs decay signatures at the LHC at 7 TeV of pp c.m. collision energy (VBF stands for vector-boson-fusion production, while WH refers to the Higgs associated production with a W boson). Dashed (blue) lines show, for reference, the corresponding SM rates, where the gg fusion gives the dominant mechanism. Dash-dotted (black) lines refer to the tree-level FP scenario. Note that, for a light Higgs, the FP scenario rates overshoot the SM ones, while, for $m_H > 130$ GeV, they are considerable lower than them. This makes the FP scenario evade most of the present Tevatron and LHC bounds at both intermediate and large m_H [11–13].

In case a FP Higgs scenario shows up at the LHC with $m_H < 150$ GeV, a linear collider program [15] would be crucial to achieve the accuracy on the Higgs BR's measurements that are needed to get a precise Λ determination [6]. In Figure 3, we show the production rates corresponding to Higgs decays into $\gamma\gamma$ (upper-left) and $b\bar{b}$ (upper-right) at an e^+e^- collider with $\sqrt{S} \simeq 350$ GeV. Note that the sensitivity to Λ of the $\gamma\gamma$ signature drops quite rapidly when m_H increases. On the other hand, the $b\bar{b}$ signature is particularly sensitive to the scale Λ, and would allow a Λ determination up to relatively large Higgs masses (i.e. $m_H \sim 150$ GeV).

A linear collider program would also allow to test the correlation of BR's for different fermionic channels. Figure 3 shows the correlations of the Higgs branching ratios {BR($H \to cc$), BR($H \to \tau\tau$)} (lower-left) and the flavor-changing BR($H \to bs$) (lower-right), versus the BR($H \to bb$), for different values of the Higgs mass $m_H = 110, 120, 130$ GeV and Λ scale. Flavor changing decay BR's for $H \to bs$ have been computed through RG equations for the off-diagonal Yukawa couplings in the flavor space [6]. BR($H \to bs$) of the order of $(10^{-4} - 10^{-3})$, for $\Lambda = (10^4 - 10^{16})$ GeV, have been obtained to be confronted with the corresponding BR$_{SM}(H \to bs) < 10^{-7}$.

In conclusion, in the study presented here we stressed that a model with a Higgs boson that is decoupled from fermions at tree-level leads to a framework that is unstable under radiative corrections. Although Yukawa couplings are set to zero at tree level, the non-vanishing fermion masses give rise to ChSB in the Lagrangian that radiatively regenerates Yukawa couplings. We adopted an effective field theory approach to compute radiative corrections in the FP Higgs framework. This might provide a unified description of a wide class of possibilities for the unknown mechanism of fermion mass generation. In case the scale Λ of ChSB is much larger that the electroweak scale, the radiatively generated BR($H \to bb$) could approach its SM value. LHC is about to test the present scenario. In case a FP Higgs pattern shows up with $m_H < 150$ GeV, a linear collider will be crucial to accurately measure

BR($H \to bb, cc, \tau\tau$), and determine the Λ scale. In particular, the rates of $e^+e^- \to ZH \to Zb\bar{b}$ are remarkably sensitive to Λ. An analysis of the accuracy expected at a linear collider in the improved FP Higgs scenario would be crucial to set the machine potential to carry out a measurement of the ChSB scale.

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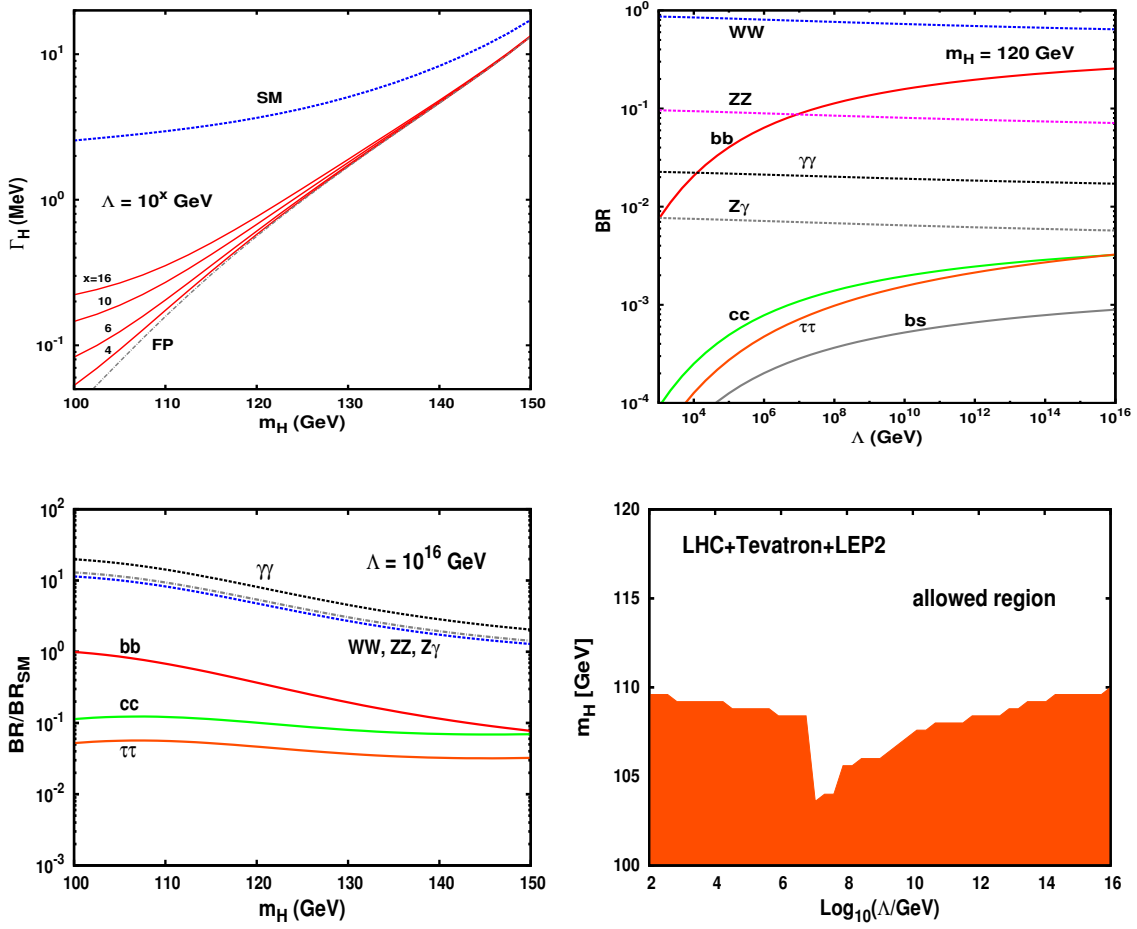
Figure 1: Upper-left plot shows the total Higgs width Γ_H versus m_H, for $\Lambda = 10^{4,6,10,16}$ GeV. Upper-right plot presents the Higgs BR for different decays, at $m_H = 120$ GeV, versus the scale Λ. Lower-left plot shows the Higgs BR's normalized to their SM values versus m_H, for $\Lambda = 10^{16}$ GeV. Lower-right plot presents the exclusion regions at 95% C.L. (orange/grey area) in the (m_H, Λ) plane, as obtained through the code Higgsbounds, version 3.4.0beta.
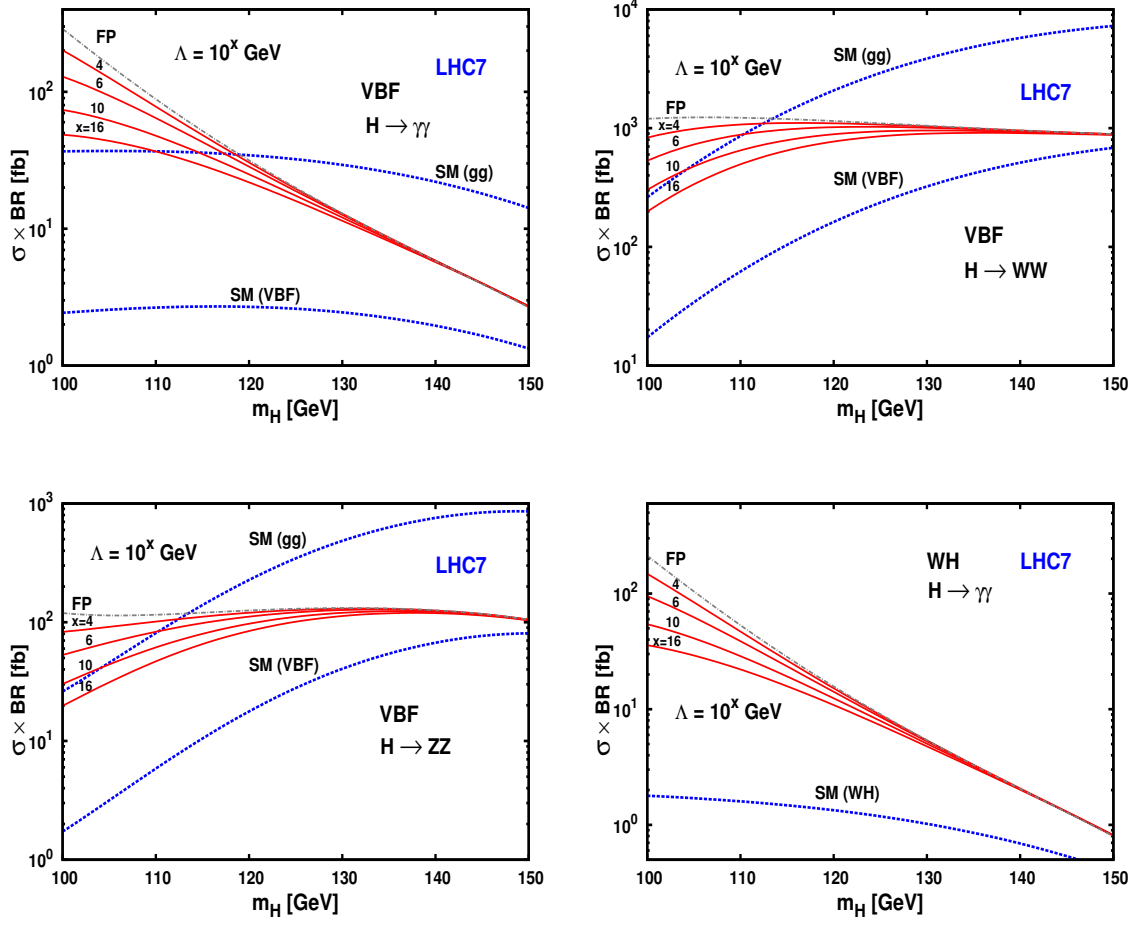
Figure 2: Total cross sections times Higgs branching ratio (BR) at the LHC at $\sqrt{S} = 7$ TeV, for different Higgs production mechanism and decay channels, for a set of Λ values. The upper-left, upper-right and lower-left plots correspond to the Vector-Boson-Fusion (VBF) production and decays $H \rightarrow \gamma\gamma$ $H \rightarrow WW$, and $H \rightarrow ZZ$, respectively, while the lower-right plot shows the rate for associated Higgs-W production (WH) and decay $H \rightarrow \gamma\gamma$. SM curves are also shown for comparison.
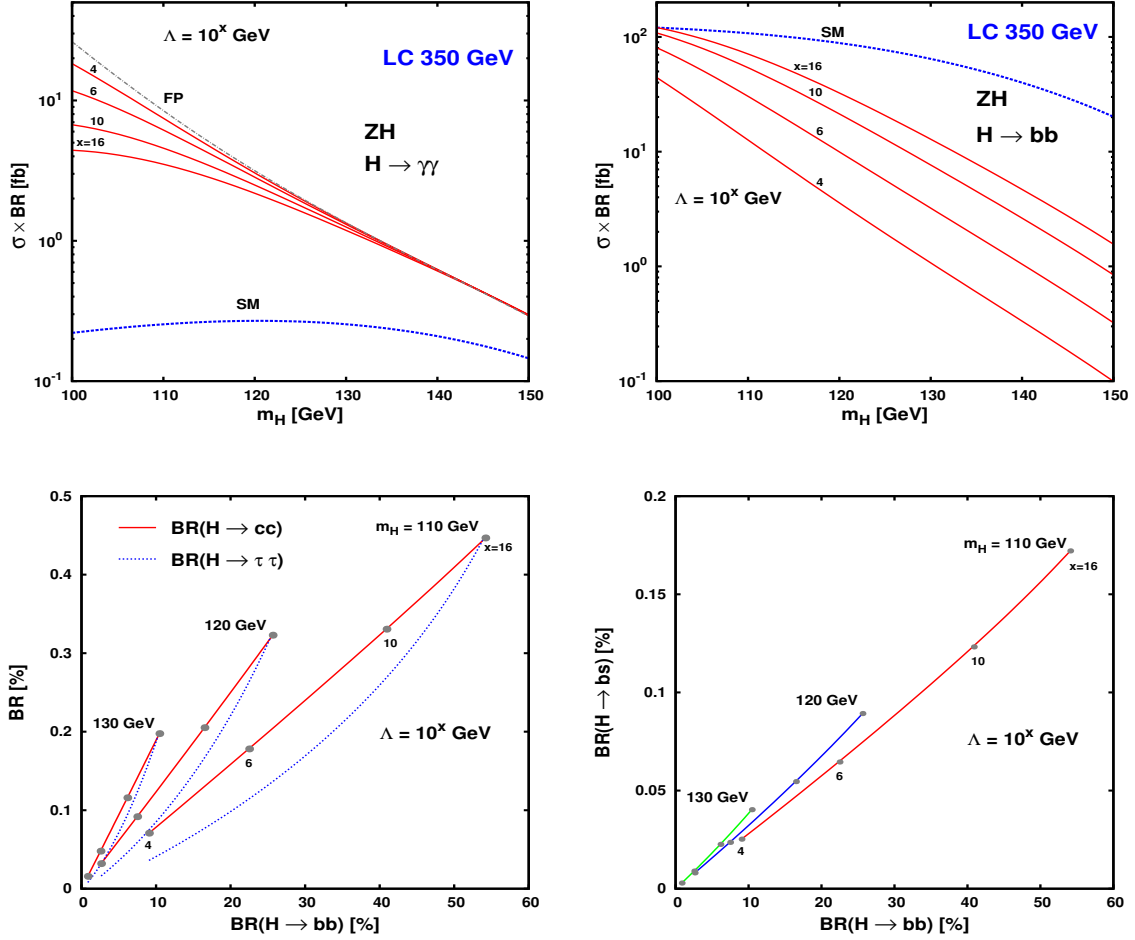
Figure 3: Upper-left- and upper-right plots show to the total cross sections times the Higgs branching ratios BR for the decays $H \rightarrow \gamma\gamma$ and $H \rightarrow bb$, respectively, at a linear collider with $\sqrt{S} = 350$ GeV. SM curves are also shown for comparison. Also shown are the correlations of the Higgs branching ratios [BR($H \rightarrow cc$), BR($H \rightarrow \tau\tau$)] (lower-left) and the flavor-changing BR($H \rightarrow bs$) (lower-right), versus BR($H \rightarrow bb$), for different values of $m_H = 110, 120, 130$ GeV and Λ.

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