

# Bounds on Higgs-portal models from the LHC Higgs data

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**ABSTRACT:** In a number of Higgs-portal models, an SU(2) isospin-singlet scalar boson generically appears at the electroweak scale and can mix with the Standard Model (SM) Higgs boson with a mixing angle  $\alpha$ . This singlet scalar boson can have renormalizable couplings to a pair of dark matter particles, vector-like leptons or quarks, or new gauge bosons, thereby modifying the Higgs signal strengths in a nontrivial way. In this work, we perform global fits to such models using the most updated LHC Higgs-boson data and discuss the corresponding implications on Higgs-portal-type models. In particular we find that the current LHC Higgs-boson data slightly favors the SM over the Higgs-portal singlet-scalar models, which has to be further examined using the upcoming LHC Higgs-boson data. Finally, without non-SM particles contributing to the  $H\gamma\gamma$  and  $Hgg$  vertices, the Higgs-portal models are constrained as follows:  $\cos\alpha \gtrsim 0.86$  and  $\Delta\Gamma_{\text{tot}} \lesssim 1.24$  MeV at 95% confidence level (CL).

**KEYWORDS:** Phenomenological Models

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## Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Formalism</b>	<b>3</b>
2.1	SM Higgs couplings	3
2.2	Couplings of the singlet scalar and the mixing	4
2.3	Signal strength	6
<b>3</b>	<b>Models</b>	<b>6</b>
3.1	Dark matter models with dark gauge symmetries and/or Higgs portals	6
3.2	Non-SUSY $U(1)_{B-L}$ extensions of the SM	8
3.3	Vector-like fermions for enhanced $H(125) \rightarrow \gamma\gamma$ and/or $H(125) \rightarrow gg$	9
3.4	Summary of the models	9
<b>4</b>	<b>Results</b>	<b>10</b>
4.1	SD	11
4.2	SL	11
4.3	SQ	12
<b>5</b>	<b>Discussion</b>	<b>14</b>

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## 1 Introduction

After the discovery of the 125 GeV boson at the LHC [1, 2], many analyses have been performed on the Higgs-boson data in order to identify the nature of the observe boson. So far, its properties are very close to those of the Standard Model (SM) Higgs boson: namely, (i) the spin, parity, and charge conjugation quantum numbers are equal to  $J^{PC} = 0^{++}$ , which are in accordance with the SM Higgs boson, and (ii) its couplings to the SM particles are close to those of the SM Higgs boson at the end of the LHC Run I, which is indeed a remarkable achievement. The Higgs couplings to the SM particles are often parameterized in terms of the  $\kappa$ 's defined as follows [3]:

$$\kappa_i^2 = \frac{\Gamma(H \rightarrow ii)}{\Gamma(H \rightarrow ii)_{\text{SM}}}, \quad \kappa_H^2 = \frac{\Gamma_{\text{tot}}(H) + \Delta\Gamma_{\text{tot}}}{\Gamma_{\text{SM}}}, \quad (1.1)$$

where  $i = W, Z, f, g, \gamma$ , and  $\Gamma_{\text{SM}}$  denotes the SM total decay width while  $\Gamma_{\text{tot}}(H)$  and  $\Delta\Gamma_{\text{tot}}$  denote, respectively, the total decay width into the SM particles with modified couplings and an arbitrary non-SM contribution to the total decay width. The current best fits to the  $\kappa_i$ 's for  $i = W, Z, f$  from the ATLAS [4] and the CMS [5] collaborations are summarized in table 1.

	$\kappa_W$	$\kappa_Z$	$\kappa_t$	$\kappa_b$	$\kappa_\tau$	$\kappa_\mu$
ATLAS	$0.68^{+0.30}_{-0.14}$	$0.95^{+0.24}_{-0.19}$	$[-0.80, -0.50] \cup [0.61, 0.80]$	$[-0.7, 0.7]$	$[-1.15, -0.67] \cup [0.67, 1.14]$	-
CMS	$0.95^{+0.14}_{-0.13}$	$1.05^{+0.16}_{-0.16}$	$0.81^{+0.19}_{-0.15}$	$0.74^{+0.33}_{-0.29}$	$0.84^{+0.19}_{-0.18}$	$0.49^{+1.38}_{-0.49}$

**Table 1.** The best fit values of  $\kappa$ 's from the ATLAS [4] and CMS [5] at the end of the LHC Run I. The errors or the ranges are at 68% CL.

New physics beyond the Standard Model (BSM) will be manifest itself if  $\kappa_i \neq 1$  for some  $i$  in this approach. Very often it is assumed that the new physics effects are decoupled from the SM sector, thereby can be described by nonrenormalizable higher dimensional operators [6–11]. This assumption encompasses a large class of BSMs, but still leaves out another large class of BSMs with an isospin-singlet scalar boson (of a mass around the electroweak (EW) scale) that could mix with the SM Higgs boson. This singlet scalar boson itself can couple to new particles such as a pair of dark matter (DM) particles, new vector-like quarks and/or leptons, new charged or neutral vector bosons, etc., just to name a few (see ref. [12] for more comprehensive discussion). Such a mixing between the singlet scalar boson and the SM Higgs boson does not decouple and cannot be captured by the usual higher dimensional operators, and therefore has to be treated in a separate manner.

In ref. [12], a new parameterization was proposed which is suitable in the presence of a new singlet scalar boson that mixes with the SM Higgs boson. The singlet-mixed-in case deserves closer investigation, because many BSMs with good physics motivations come with an extra singlet scalar boson that can mix with the SM Higgs boson. This includes a large class of hidden-sector dark matter models such as Higgs-portal fermion or vector DM models, and DM models with local dark gauge symmetries, as well as nonsupersymmetric  $U(1)_{B-L}$  model, vector-like fermions that could affect  $h \rightarrow gg, \gamma\gamma$ , or models with the dilaton coupled to the trace of energy-momentum tensor.

The Higgs-boson properties could be affected by the presence of new physics from different origins. The approach using  $\kappa_i$ 's is simple and straightforward but in general it is difficult to further analyze the origin of new physics that had modified the  $\kappa$ 's from the SM values. There are basically two different approaches to consider the new physics effects: one assumes either (i) the full  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge symmetry or (ii) its unbroken subgroup  $SU(3)_C \times U(1)_{em}$  only in the effective Lagrangian for Higgs physics. Though either approach works as long as one is interested in any possible deviations of the Higgs couplings from the SM values, it would be more proper to impose the full gauge symmetry for investigations at the EW scale, because the energy and momentum transfer would be  $\sim O(m_Z)$  or higher. On the other hand, if we only impose the unbroken subgroup of the SM gauge group, the observed Higgs boson could be a mixture of the SM Higgs boson and other neutral scalar bosons that could mix with the SM Higgs boson after electroweak symmetry breaking (EWSB). Therefore, in order to isolate the effects of the mixing between the singlet scalar boson and the SM Higgs boson, we shall impose the full SM gauge symmetry when we construct the effective Lagrangian for the SM Higgs boson and the singlet scalar boson.

In this paper, we perform the global fits to new physics scenarios with an extra singlet scalar boson mixed with the SM Higgs boson using the most recent Higgs data from LHC@7 and 8 TeV. In section 2, we set up the formalism used in this analysis, and compare it with the approach by the LHC Higgs Cross section Working Group. In section 3, we give brief description of the models which are covered by our formalism. In section 4, we perform the numerical analysis with global fits to the LHC Higgs data, and present the best  $\chi^2$  fit for each model, and discuss the corresponding implications. Finally we summarize the results in section 5.

## 2 Formalism

In the following, we first describe the SM Higgs couplings to SM particles including fermions  $f$  and gauge bosons  $W, Z, \gamma, g$ , and define a set of ratios  $b_{W,Z,f,\gamma,g}$ , which denote the size of the couplings relative to the corresponding SM one. Without loss of generality, we define a similar set of ratios  $c_{W,Z,f,\gamma,g}$  for the singlet scalar boson couplings to the fermion  $f$  and gauge bosons  $W, Z, \gamma, g$  relative to the corresponding one of the SM Higgs boson. After then we describe the mixing between the SM Higgs field and the singlet field via a mixing angle  $\alpha$ .

### 2.1 SM Higgs couplings

The couplings of the SM Higgs  $h$  to fermions are given by

$$\mathcal{L}_{h\bar{f}f} = - \sum_{f=u,d,l} \frac{gm_f}{2M_W} b_f h \bar{f} f, \quad (2.1)$$

and its couplings to the massive vector bosons by

$$\mathcal{L}_{hVV} = g M_W \left( b_W W_\mu^+ W^{-\mu} + b_Z \frac{1}{2 \cos^2 \theta_W} Z_\mu Z^\mu \right) h, \quad (2.2)$$

where  $\theta_W$  is the weak mixing angle. In the SM limit, we have  $b_f = b_W = b_Z = 1$ .

While the SM Higgs coupling to two photons is defined through the amplitude for the decay process  $h \rightarrow \gamma\gamma$  and it can be written as

$$\mathcal{M}_{\gamma\gamma h} = -\frac{\alpha M_H^2}{4\pi v} S_h^\gamma (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) \quad (2.3)$$

where  $\epsilon_{1\perp}^\mu = \epsilon_1^\mu - 2k_1^\mu(k_2 \cdot \epsilon_1)/M_H^2$ ,  $\epsilon_{2\perp}^\mu = \epsilon_2^\mu - 2k_2^\mu(k_1 \cdot \epsilon_2)/M_H^2$  with  $\epsilon_{1,2}$  being the wave vectors of the two photons and  $k_{1,2}$  being the momenta of the corresponding photons with  $(k_1 + k_2)^2 = M_H^2$ . Including some additional loop contributions from non-SM particles and retaining only the dominant loop contributions from the third-generation fermions and  $W^\pm$ , the scalar form factor is given by

$$S_h^\gamma = 2 \sum_{f=b,t,\tau} N_C Q_f^2 b_f F_{sf}(\tau_f) - b_W F_1(\tau_W) + \Delta S_h^\gamma \equiv b_\gamma S_{\text{SM}}^\gamma, \quad (2.4)$$

where  $\tau_x = M_H^2/4m_x^2$ ,  $N_C = 3$  for quarks and  $N_C = 1$  for taus, respectively. The additional contribution  $\Delta S_h^\gamma$  from non-SM particles is assumed to be real. Taking  $M_H = 125.5$  GeV,

we find  $S_{\text{SM}}^\gamma = -6.64 + 0.0434i$ . For the loop functions and the normalization of the amplitude, we refer to ref. [13].

The SM Higgs coupling to two gluons is given similarly as in  $h \rightarrow \gamma\gamma$ . The amplitude for the decay process  $h \rightarrow gg$  can be written as

$$\mathcal{M}_{ggh} = -\frac{\alpha_s M_H^2 \delta^{ab}}{4\pi v} S_h^g (\epsilon_{1\perp}^* \cdot \epsilon_{2\perp}^*) \quad (2.5)$$

where  $a$  and  $b$  ( $a, b = 1$  to  $8$ ) are indices of the eight SU(3) generators in the adjoint representation. Again, including some additional loop contributions from new non-SM particles, the scalar form factor is given by

$$S_h^g = \sum_{f=b,t} b_f F_{sf}(\tau_f) + \Delta S_h^g \equiv b_g S_{\text{SM}}^g. \quad (2.6)$$

The additional contribution  $\Delta S_h^g$  is assumed to be real. Taking  $M_H = 125.5$  GeV, we find  $S_{\text{SM}}^g = 0.651 + 0.0501i$ .

Finally, for the SM Higgs coupling to  $Z$  and  $\gamma$ , the amplitude for the decay process  $h \rightarrow Z(k_1, \epsilon_1) \gamma(k_2, \epsilon_2)$  can be written as

$$\mathcal{M}_{Z\gamma h} = -\frac{\alpha}{2\pi v} S_h^{Z\gamma} [k_1 \cdot k_2 \epsilon_1^* \cdot \epsilon_2^* - k_1 \cdot \epsilon_2^* k_2 \cdot \epsilon_1^*] \quad (2.7)$$

where  $k_{1,2}$  are the momenta of the  $Z$  boson and the photon (we note that  $2k_1 \cdot k_2 = M_H^2 - M_Z^2$ ), and  $\epsilon_{1,2}$  are their polarization vectors. The scalar form factor is given by

$$S_h^{Z\gamma} \equiv b_{Z\gamma} S_{\text{SM}}^{Z\gamma} \quad (2.8)$$

$$= 2 \sum_{f=t,b,\tau} Q_f N_C^f m_f^2 \frac{I_3^f - 2 \sin^2 \theta_W Q_f^2}{\sin \theta_W \cos \theta_W} b_f F_f^{(0)} + M_Z^2 \cot \theta_W b_W F_W + \Delta S_h^{Z\gamma}. \quad (2.9)$$

The additional contribution  $\Delta S_h^{Z\gamma}$  is assumed to be real. Taking  $M_H = 125.5$  GeV, we find  $S_{\text{SM}}^{Z\gamma} = -11.0 + 0.0101i$ . For the loop functions and the normalization of the amplitude, we refer to ref. [32].

## 2.2 Couplings of the singlet scalar and the mixing

The relative strength of the couplings of the singlet scalar boson  $s$  before mixing can be defined similarly in terms of a set of ratios  $c_i$  ( $i = f, W, Z, \gamma, g$ ). Here the  $c_i$  parameterize the couplings of  $s$  to the SM particles in a way similar to those of the SM Higgs boson  $h$ :

$$\mathcal{L}_{s\bar{f}f} = - \sum_{f=u,d,l} \frac{gm_f}{2M_W} c_f s \bar{f} f, \quad (2.10)$$

$$\mathcal{L}_{sVV} = g M_W \left( c_W W_\mu^+ W^{-\mu} + c_Z \frac{1}{2 \cos^2 \theta_W} Z_\mu Z^\mu \right) s,$$

$$S_s^\gamma = 2 \sum_{f=b,t,\tau} N_C Q_f^2 c_f F_{sf}(\tau_f) - c_W F_1(\tau_W) + \Delta S_s^\gamma \equiv c_\gamma S_{\text{SM}}^\gamma,$$

$$S_s^g = \sum_{f=b,t} c_f F_{sf}(\tau_f) + \Delta S_s^g \equiv c_g S_{\text{SM}}^g,$$

$$S_s^{Z\gamma} = 2 \sum_{f=t,b,\tau} Q_f N_C^f m_f^2 \frac{I_3^f - 2 \sin^2 \theta_W Q_f^2}{\sin \theta_W \cos \theta_W} c_f F_f^{(0)} + M_Z^2 \cot \theta_W c_W F_W + \Delta S_s^{Z\gamma} \equiv c_{Z\gamma} S_{\text{SM}}^{Z\gamma}.$$

Since all the relative couplings  $c_i$ 's come from nonrenormalizable interactions between the singlet scalar  $s$  and the SM particles, except for the Higgs fields, one can simply assume that  $c_i$ 's are naturally suppressed by a heavy mass scale or a loop suppression factor:

$$c_i \sim \text{“0”} + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad \text{or} \quad \text{“0”} + \frac{g^2 m^2}{M^2}.$$

On the other hand, the relative couplings  $b_i$ 's of the SM Higgs boson with deviations coming from higher dimensional operators or additional particles running in the loop can be expressed as

$$b_i \sim \text{“1”} + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad \text{or} \quad \text{“1”} + \frac{g^2 m^2}{M^2},$$

where  $M$  is the mass scale of a new particle that has been integrated out, and  $m$  is the external SM particles with  $m \ll M$ , and  $g$  is a typical coupling of the SM particle and the heavy particle. Note that there would be extra loop suppression factors ( $\sim 1/(4\pi)^2$ ) if the relevant operators are generated at one loop level. The sizes of  $b_i$ 's and  $c_i$ 's then set the stage for our numerical analysis.

One further complication comes from the mixing between the SM Higgs field  $h$  and the singlet field  $s$ . The two mass eigenstates  $H_{1,2}$  are related to the interaction eigenstates by an  $\text{SO}(2)$  rotation:

$$H_1 = h \cos \alpha - s \sin \alpha; \quad H_2 = h \sin \alpha + s \sin \alpha, \quad (2.11)$$

with  $\cos \alpha \equiv c_\alpha$  and  $\sin \alpha \equiv s_\alpha$  describing the mixing between the interaction eigenstates  $h$  (remnant of the SM Higgs doublet) and  $s$  (singlet). In this work, we are taking  $H_1 \equiv H$  for the 125 GeV boson discovered at the LHC and  $H_2$  can be either heavier or lighter than  $H_1$ . We are taking  $\cos \alpha > 0$  without loss of generality.

Then, the relative couplings of the observed Higgs boson  $H$  to fermions  $f$ , gauge bosons  $W, Z, \gamma, g$  are then given by

$$b_i \cos \alpha - c_i \sin \alpha \quad (i = f, W, Z, \gamma, g). \quad (2.12)$$

We observe that  $k_i = (b_i c_\alpha - c_i s_\alpha)^2$ , see eq. (1.1). Note that the loop-induced Higgs decay with  $i = g, \gamma$  can be modified by several different origins; (i) from scalar mixing denoted by  $\alpha$ , (ii) from the singlet scalar couplings denoted by  $c_{g,\gamma}$ , especially when the singlet scalar couples to extra vector-like quarks and/or leptons or charged vector bosons, (iii) from modifications of the top and/or  $W$  boson couplings in the loop which are denoted by  $b_t$  and  $b_W$ , which arise from higher dimensional operators involving the SM Higgs doublet and the SM chiral fermions with the full SM gauge symmetry, (iv) from the couplings of the SM Higgs doublet to extra vector-like quarks and/or leptons or charged vector bosons, and (v) from some new physics effects that directly modify the couplings of the SM Higgs interaction eigenstate.

The  $\kappa_i$  parameterization is effective and simple but is highly degenerate, since different values of  $c_\alpha, b_i, c_i$  can lead to the same value of  $\kappa_i$ . It would be impossible to separate the true origin of new physics generating  $\kappa \neq 1$  in the  $\kappa$  parameterization.

### 2.3 Signal strength

The theoretical signal strengths may be written as

$$\hat{\mu}(\mathcal{P}, \mathcal{D}) \simeq \hat{\mu}(\mathcal{P}) \hat{\mu}(\mathcal{D}), \quad (2.13)$$

where  $\mathcal{P} = \text{ggF}, \text{VBF}, \text{VH}, \text{ttH}$  denote the Higgs production mechanisms: gluon fusion (ggF), vector-boson fusion (VBF), and associated productions with a  $V = W/Z$  boson (VH) and top quarks (ttH) and  $\mathcal{D} = \gamma\gamma, ZZ, WW, b\bar{b}, \tau\bar{\tau}$  the decay channels.

More explicitly, we are taking

$$\hat{\mu}(\text{ggF}) = (b_g c_\alpha - c_g s_\alpha)^2, \quad \hat{\mu}(\text{VBF}) = \hat{\mu}(\text{VH}) = (b_V c_\alpha - c_V s_\alpha)^2, \quad \hat{\mu}(\text{ttH}) = (b_t c_\alpha - c_t s_\alpha)^2 \quad (2.14)$$

with  $V = Z, W$  and

$$\hat{\mu}(\mathcal{D}) = \frac{B(H \rightarrow \mathcal{D})}{B(H_{\text{SM}} \rightarrow \mathcal{D})} \quad (2.15)$$

with

$$B(H \rightarrow \mathcal{D}) = \frac{\Gamma(H \rightarrow \mathcal{D})}{\Gamma_{\text{tot}}(H) + \Delta\Gamma_{\text{tot}}} = \frac{(b_i c_\alpha - c_i s_\alpha)^2 B(H_{\text{SM}} \rightarrow \mathcal{D})}{\Gamma_{\text{tot}}(H)/\Gamma_{\text{SM}} + \Delta\Gamma_{\text{tot}}/\Gamma_{\text{SM}}}, \quad (2.16)$$

where  $i = \gamma, Z, W, b$  and  $\tau$  for  $\mathcal{D} = \gamma\gamma, ZZ, WW, b\bar{b}$  and  $\tau\bar{\tau}$ , respectively. Note that we introduce an arbitrary non-SM contribution  $\Delta\Gamma_{\text{tot}}$  to the total decay width. Incidentally,  $\Gamma_{\text{tot}}(H)$  becomes the SM total decay width  $\Gamma_{\text{SM}}$  when  $c_\alpha = 1, b_f = b_V = 1, \Delta S_h^{\gamma, g, Z\gamma} = 0$ ,<sup>1</sup> and  $\Delta\Gamma_{\text{tot}} = 0$ . For more details, we refer to ref. [32].

## 3 Models

In a number of phenomenologically well motivated BSM models, there often appears a SM singlet scalar boson that can mix with the SM Higgs boson. Adding an extra singlet field to the SM is the simplest extension of the SM Higgs sector in terms of new degrees of freedom. A singlet scalar boson  $s$  does not affect the  $\rho$  parameter at tree level, and is not that strongly constrained by the electroweak precision tests (EWPT). It can also make the electroweak phase transition strongly first order [33, 34], and enables us to consider electroweak baryogenesis if there are new sources of CP violation beyond the Kobayashi-Maskawa (KM) phase in the SM with three generations. Finally, if we imposed a new discrete  $Z_2$  symmetry  $s \rightarrow -s$ , the singlet scalar  $s$  could make a good dark matter candidate [35–37]. This is the standard list for the rationales for considering a singlet scalar  $s$ .

However, there are many more interesting scenarios where a singlet scalar appears in a natural way and plays many important roles. Let us list some examples, referring to ref. [12] for more extensive discussion.

### 3.1 Dark matter models with dark gauge symmetries and/or Higgs portals

First of all, let us consider DM models where weak scale DM is stabilized by some spontaneously broken local dark gauge symmetries [14–25]. This possibility is not that often

<sup>1</sup>We note  $b_{\gamma, g, Z\gamma} = 1$  when  $b_f = b_V = 1$  and  $\Delta S_h^{\gamma, g, Z\gamma} = 0$ .

considered seriously. However if we remind ourselves of the logic behind  $U(1)_{\text{em}}$  gauge invariance, electric charge conservation, existence of massless photon and electron stability and non-observation of  $e \rightarrow \nu\gamma$ , one would realize immediately the same logic could be applied to the DM model building. One might think that this assumption may be too strong, since the lower bound on the DM lifetime is much weaker than that on the proton lifetime. This is in fact true, but this can be understood since proton is a composite particle, a bound state of 3 quarks with color gauge interaction, and baryon number violating operator in the SM is dim-6 or higher. Likewise longevity of DM might be due to some new strong interactions that make DM particle composite. Also, considering all the SM particles feel some gauge interactions, it would be natural to assume that the DM also may feel some gauge interactions (see ref. [26] for a recent review).

In the case the dark matter particle is associated with some dark gauge symmetries, there would generically appear a dark Higgs boson after dark gauge symmetry breaking. The original dark Higgs  $\Phi$  would be charged under some local dark gauge symmetry, but it is a singlet under the SM gauge group in the simplest setup. And after dark gauge symmetry breaking, there would be dark Higgs boson  $h_\Phi$ , which would mix with the SM Higgs boson via the Higgs-portal interaction,

$$\lambda_{H\Phi} \left( H^\dagger H - \frac{v^2}{2} \right) \left( \Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right).$$

A Higgs-portal coupling as small as  $\lambda_{H\Phi} \sim 10^{-6}$  can thermalize the hidden sector DM efficiently.<sup>2</sup> On the other hand, the effects of such a small coupling would be very difficult to observe at colliders.

Also, the dark Higgs can stabilize the EW vacuum up to Planck scale, as well as it can modify the standard Higgs inflation scenario in such a way that a large tensor-to-scalar ratio  $r \sim (0.1)$  could be possible [27], which is independent of the precise values for the top quark and/or Higgs boson masses. Although the dark Higgs boson was introduced in order to break the dark gauge symmetry spontaneously, it has additional niceties in regard of cosmology in the context of the EW vacuum stability and the Higgs inflation assisted by Higgs-portal interaction.

Even if we relax the assumption of the local dark gauge symmetry and consider more phenomenological Higgs-portal DM models, there will still appear a singlet scalar boson that can mix with the SM Higgs boson, if the Higgs-portal DM is a singlet Dirac fermion [28, 29] or a vector boson [16, 30, 31]. Also, it can play an important role in DM phenomenology. For example, one can easily accommodate the galactic center  $\gamma$ -ray excess by DM pair annihilation into a pair of dark Higgs bosons, followed by dark Higgs decays into the SM particles [19, 23–25, 39].

Furthermore, there could be non-standard Higgs decays into a pair of lighter neutral scalar bosons (namely the dark Higgs boson) or a pair of dark gauge bosons, in addition to a pair of dark matter particles. In this case, the total decay width of the observed Higgs boson would receive additional contributions from the final states with dark matter, dark

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<sup>2</sup>See, for example, section III E and figure 5 (right panel) in ref. [38] for more details.



gauge bosons, or dark Higgs bosons, which are parameterized in terms of  $\Delta\Gamma_{\text{tot}}$ . Therefore, we will take the deviation  $\Delta\Gamma_{\text{tot}}$  in the total decay width of the 125 GeV Higgs boson as a free parameter when we perform global fits to the LHC data on the Higgs signal strengths.

These classes of BSM models are phenomenologically very well motivated, and they have very significant impacts on the observed 125 GeV scalar boson. Therefore, it is very important to seek for a singlet scalar that can mix with the SM Higgs boson in all possible ways. The phenomenology associated with the observed Higgs boson measurements is straightforward. The signal strengths of the 125 GeV Higgs boson are suppressed from “1” in a universal manner, namely independent of production and decay channels. Moreover, the 125 GeV Higgs couplings to SM fermions and weak gauge bosons are all suppressed by  $\cos\alpha$  relative to the SM values. One can also search for the heavier Higgs boson in this type of Higgs-portal models [40, 41].

In summary, hidden-sector DM models are characterized by  $b_i = 1$  and  $c_i = 0$  with a few simple implications:

- Couplings to the SM fermions and gauge bosons are all suppressed by the factor  $\cos\alpha$ .
- Decay Width:  $\Gamma(H \rightarrow \mathcal{D}) = \cos^2\alpha \Gamma_{\text{SM}}(H \rightarrow \mathcal{D})$  and  $\Gamma_{\text{tot}}(H) = \cos^2\alpha \Gamma_{\text{SM}}$ . Note that the total decay width of the Higgs boson, including the non-SM decay modes, is given by  $\Gamma_{\text{tot}}(H) + \Delta\Gamma_{\text{tot}}$ .
- Signal strengths:  $\hat{\mu}(\mathcal{P}, \mathcal{D}) \simeq \hat{\mu}(\mathcal{P}) \hat{\mu}(\mathcal{D}) = \frac{\cos^4\alpha}{\cos^2\alpha + \Delta\Gamma_{\text{tot}}/\Gamma_{\text{SM}}}$  independently of the production mechanism  $\mathcal{P}$  and the decay channel  $\mathcal{D}$ .
- Varying parameters:  $\cos\alpha$  and  $\Delta\Gamma_{\text{tot}}$ .

In terms of two free parameters  $\cos\alpha$  and  $\Delta\Gamma_{\text{tot}}$ , we perform the  $\chi^2$  minimization procedures on the LHC Higgs signal strength data in the next section.

### 3.2 Non-SUSY $U(1)_{B-L}$ extensions of the SM

Another interesting example of Higgs-portal models is the nonsupersymmetric  $U(1)_{B-L}$  extension of the SM plus 3 RH neutrinos, which is anomaly free, so that no new colored or EW charged fermions are introduced:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - V(H, \Phi) - \left( \frac{1}{2} \lambda_{N,i} \Phi \bar{N}_i^c N_i + Y_{N,ij} \bar{\ell} H^\dagger N + \text{h.c.} \right), \quad (3.1)$$

where the scalar potential  $V(H, \Phi)$  is given by

$$V(H, \Phi) = -\mu_H^2 H^\dagger H - \mu_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_h}{2} |H|^4 - \lambda_{h\phi} |H|^2 |\Phi|^2 + \frac{\lambda_\phi}{2} |\Phi|^4. \quad (3.2)$$

Here the SM singlet scalar  $\Phi$  carries  $B-L$  charge “2”, and after  $B-L$  symmetry breaking from the nonzero VEV of  $\Phi$ , the resulting singlet scalar  $\phi$  will mix with the SM Higgs field.

If the  $B-L$  gauge boson  $Z'$  is light enough, the observed Higgs boson can decay into a pair of  $Z'$  bosons through the mixing between the SM Higgs boson and the  $U(1)_{B-L}$ -charged singlet scalar  $\phi_{B-L}$ , if this decay is kinematically allowed. The current bound on

this model from the Drell-Yan process is that  $v_\phi \gtrsim$  a few TeV, so that  $g_{B-L} \sim$  (a few)  $\times 10^{-3}$  or less, for this to happen. In this case, the Higgs phenomenology is described by two parameters,  $\cos \alpha$  and  $\Delta\Gamma_{\text{tot}}$ , as in DM models with dark gauge symmetry and/or Higgs portals.

### 3.3 Vector-like fermions for enhanced $H(125) \rightarrow \gamma\gamma$ and/or $H(125) \rightarrow gg$

Right after the first candidate signature for the SM Higgs boson at the LHC, a number of groups considered new vector-like fermions (quarks or leptons) in order to explain the excessive signal strength in the  $H \rightarrow \gamma\gamma$  decay channel. When considering vector-like fermions, one often has to introduce a singlet scalar field at renormalizable interaction level. Note that vector-like fermions can not directly couple to the SM Higgs doublet, and one has to introduce a singlet scalar coupled to them. Only in the presence of a singlet scalar, therefore, they can couple to the SM Higgs through the mixing between the SM Higgs boson and the new singlet scalar.<sup>3</sup> In this case, the mixing between the SM Higgs boson and the new singlet scalar tends to reduce the signal strength for  $H \rightarrow \gamma\gamma$  decay channel, although the loop contributions from the vector-like fermions would generate the singlet scalar decays into  $\gamma\gamma$  and/or  $gg$ . It is essential to consider the mixing effects in the proper way (see, for example, ref. [42]).

In these types of models, the observed Higgs-boson couplings are given by

$$\begin{aligned}
 g_{H\bar{f}f}^S &= (b_f \cos \alpha - c_f \sin \alpha) = \cos \alpha ; \\
 g_{HVV}^S &= (b_V \cos \alpha - c_V \sin \alpha) = \cos \alpha \quad \text{for } V = Z, W ; \\
 S_H^{\gamma,g,Z\gamma} &= (S_h^{\gamma,g,Z\gamma} \cos \alpha - S_s^{\gamma,g,Z\gamma} \sin \alpha) \\
 &= \cos \alpha S_{\text{SM}}^{\gamma,g,Z\gamma} + \left( \Delta S_h^{\gamma,g,Z\gamma} \cos \alpha - \Delta S_s^{\gamma,g,Z\gamma} \sin \alpha \right) \\
 &\equiv \cos \alpha S_{\text{SM}}^{\gamma,g,Z\gamma} + \Delta S_H^{\gamma,g,Z\gamma} ,
 \end{aligned} \tag{3.3}$$

assuming  $b_f = b_V = 1$  and  $c_f = c_V = 0$ .

In this case, the varying parameters are  $\cos \alpha$ ,  $\Delta S_{h,s}^\gamma$  and/or  $\Delta S_{h,s}^g$ , and possibly including  $\Delta\Gamma_{\text{tot}}$ .

### 3.4 Summary of the models

Here we summarize the models in which a singlet scalar boson mixes with the SM Higgs boson: see table 2 for the relevant  $c_F$ 's. More details including the corresponding Lagrangian for each model can be found in ref. [12].

Note that those classes of BSMs described in the subsections III.A and III.B are phenomenologically very well motivated by dark matter and neutrino physics as well as grand unification. Also, their impacts on the observed 125 GeV scalar boson as well as on the EW vacuum stability or Higgs inflation are straightforward:

- The signal strengths of the 125 GeV Higgs boson are suppressed from “1” in a universal manner, namely independent of production and decay channels.

---

<sup>3</sup>More detailed discussions of this class of models can be found in section 3.4 in ref. [12].

Model	Nonzero $c_F$ 's
Pure Singlet Extension	$c_h^2$
Hidden Sector DM	$c_\chi, c_h^2$
non-SUSY $U(1)_{B-L}$	$c_{Z'}, c_h^2$
Dilaton	$c_g, c_W, c_Z, c_\gamma, c_h^2$
Vector-like Quarks	$c_g, c_\gamma, c_{Z\gamma}, c_h^2$
Vector-like Leptons	$c_\gamma, c_{Z\gamma}, c_h^2$
New Charged Vector bosons	$c_\gamma, c_h^2$
Extra charged scalar bosons	$c_g, c_\gamma, c_{Z\gamma}, c_h^2$

**Table 2.** Nonvanishing  $c_F$ 's in various BSMs with an extra singlet scalar boson. For non-SUSY  $U(1)_{B-L}$  model, there would be nonzero  $c_{Z'}$  where  $Z'$  is the  $U(1)_{B-L}$  gauge boson. Since the bound from Drell-Yan is very stringent, we will ignore  $H(125) \rightarrow Z'Z'$ , although it is in principle possible if the gauge coupling is very small  $g_{B-L} \lesssim$  a few  $\times 10^{-3}$ . Details can be found in ref. [12].

- The 125 GeV Higgs couplings to the SM fermions and the weak gauge bosons are all suppressed by  $\cos \alpha$  relative to the SM values.
- The additional singlet scalar boson can improve the stability of EW vacuum up to the Planck scale [29].
- The singlet scalar can improve the EW phase transition to be more strongly first order.
- The mixing between the SM Higgs boson and the singlet scalar boson can modify the predictions for the tensor-to-scalar ratio within the Higgs inflation, and disconnecting the strong correlation of the inflationary observables from the top quark and the Higgs boson masses.

Therefore it is very important to seek for a singlet scalar boson that can mix with the SM Higgs boson in all possible ways.

## 4 Results

We are going to perform the following fits:

- **SD** fit — Singlet Dark Matter model and non-SUSY  $U(1)_{B-L}$  case: varying  $c_\alpha$  and  $\Delta\Gamma_{\text{tot}}$ ,
- **SL** fit — Singlet plus a vector-like Lepton: varying  $s_\alpha$ ,  $\Delta\Gamma_{\text{tot}}$ ,  $\Delta S_h^\gamma$ , and  $\Delta S_s^\gamma$ ,
- **SQ** fit — Singlet plus a vector-like Quark: varying  $s_\alpha$ ,  $\Delta\Gamma_{\text{tot}}$ ,  $\Delta S_h^\gamma$ ,  $\Delta S_s^\gamma$ ,  $\Delta S_h^g$ , and  $\Delta S_s^g$ .

Note, instead of  $c_\alpha$  we vary  $s_\alpha$  in the **SL** and **SQ** fits because we have to specify  $c_\alpha$  and  $s_\alpha$  simultaneously in these fits. Otherwise, one may possibly explore the unphysical regions

Fits	$\chi^2$	$\chi^2/\text{dof}$	$p\text{-value}$	Best-fit values								
				$s_\alpha$	$\Delta\Gamma_{\text{tot}}$ [MeV]	$\Delta S_h^\gamma$	$\Delta S_s^\gamma$	$\Delta S_h^g$	$\Delta S_s^g$	$c_\alpha$	$\Delta S_H^\gamma$	$\Delta S_H^g$
<b>SD</b>	16.76	0.621	0.937	0.000	0.000	—	—	—	—	1.000	—	—
<b>SL</b>	15.66	0.626	0.925	0.129	0.137	-2.953	-16.27	—	—	0.992	-0.835	—
<b>SQ</b>	15.59	0.678	0.872	0.036	0.357	0.875	46.84	1.315	35.54	0.999	-0.832	0.019

**Table 3.** The best-fitted values for **SD**, **SL**, and **SQ** fits. The SM chi-square per degree of freedom is  $\chi_{\text{SM}}^2/\text{d.o.f.} = 16.76/29$ , and  $p\text{-value} = 0.966$ .

of  $\Delta\Gamma_{\text{tot}} < 0$  and  $c_\alpha > 1$  in the **SD** fit in order to study the parametric dependence. We neglect the  $S_{h,s}^{Z\gamma}$  couplings since we do not have any predictive power in the model-independent approach taken in this work.

We use the most updated data summarized in ref. [43] and the results of the fits are summarized in table 3. We find that the best-fit values of the **SD** fit are extremely close to the SM ones. For the **SL** and **SQ** fits, we observe that the best-fit values for  $\Delta S_h^{\gamma,g}$  and  $\Delta S_s^{\gamma,g}$  are large while those for  $\Delta S_H^\gamma$  and  $\Delta S_H^g$  are only about  $-0.8$  and  $0.02$ , respectively. In the remaining part of this section, we discuss the details of each fit.

#### 4.1 SD

In the **SD** fit, we scan the regions of parameters:  $c_\alpha \in [0 : 2]$ ,  $\Delta\Gamma_{\text{tot}} \in [-4 : 8 \text{ MeV}]$  including unphysical regions of  $\Delta\Gamma_{\text{tot}} < 0$  and  $c_\alpha > 1$  to study the parametric dependence.

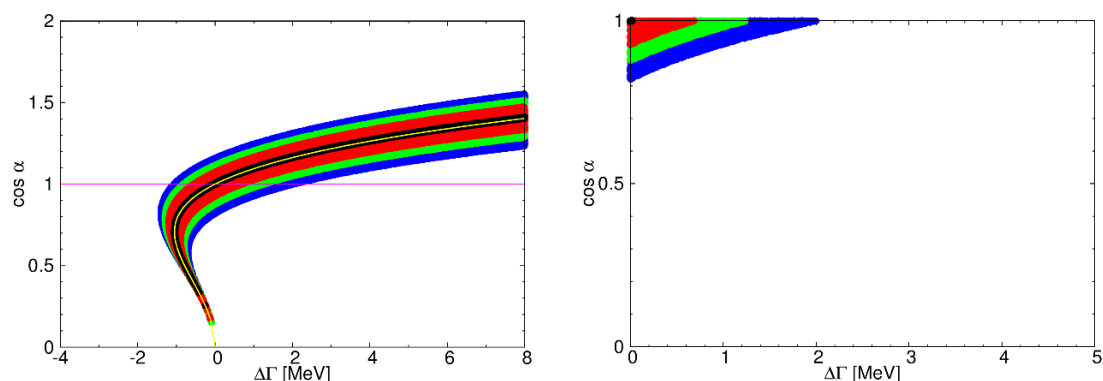
In the left frame of figure 1, we show the 68% ( $\Delta\chi^2 = 2.30$ ), 95% ( $\Delta\chi^2 = 6.18$ ), 99.7% ( $\Delta\chi^2 = 11.83$ ) regions on the  $\Delta\Gamma_{\text{tot}}\text{-}\cos\alpha$  plane. When  $\Delta\Gamma_{\text{tot}} \geq 0$ , we observe that the minima are developed along the yellow line in the black ( $\Delta\chi^2 < 0.01$ ) region which is given by the relation

$$\cos\alpha = \left[ \frac{1}{2} \left( 1 + \sqrt{1 + 4 \frac{\Delta\Gamma_{\text{tot}}}{\Gamma_{\text{SM}}}} \right) \right]^{1/2} \geq 1. \tag{4.1}$$

In fact, the above relation can be obtained by requiring each signal strength to be the same as the SM one or  $\hat{\mu}(\mathcal{P}, \mathcal{D}) = c_\alpha^4 / (c_\alpha^2 + \Delta\Gamma_{\text{tot}}/\Gamma_{\text{SM}}) = 1$ . This implies the the best  $\chi^2$  is obtained in the unphysical region of  $c_\alpha > 1$ . When  $c_\alpha \leq 1$ , we observe that the best  $\chi^2$  is obtained again in the unphysical region of  $\Delta\Gamma_{\text{tot}} < 0$ . If this is still the case in the future data, a large class of DM models (Higgs-portal fermion or vector DM, and DM models with local dark gauge symmetries) will be disfavored compared to the SM, except for the Higgs-portal scalar DM model without extra singlet scalar, for which the Higgs signal strength will be the same as the SM case. From the right frame of figure 1, we see  $\cos\alpha \gtrsim 0.86$  (0.81) and  $\Delta\Gamma_{\text{tot}} \lesssim 1.24$  (2) MeV at 95% (99.7%) CL.

#### 4.2 SL

In the **SL** fit, we scan the regions of parameters:  $s_\alpha \in [-1 : 1]$ ,  $\Delta\Gamma_{\text{tot}} \in [0 : 4 \text{ MeV}]$ ,  $\Delta S_h^\gamma \in [-10 : 10]$ ,  $\Delta S_s^\gamma \in [-100 : 100]$ .



**Figure 1.** The 68% ( $\Delta\chi^2 = 2.30$ ), 95% ( $\Delta\chi^2 = 6.18$ ), 99.7% ( $\Delta\chi^2 = 11.83$ ) confidence-level (CL) regions for the **SD** fit on the  $\Delta\Gamma_{\text{tot}}\text{-}\cos\alpha$  plane. The horizontal line in the left frame shows the physical limit  $\cos\alpha = 1$ . In the right frame, we show the CL regions after applying  $\Delta\Gamma_{\text{tot}} \geq 0$  and  $\cos\alpha \leq 1$ . The best-fit points are along the yellow line passing through the point  $(\Delta\Gamma, \cos\alpha) = (0, 1)$  in the left frame. In the black regions, we have  $\Delta\chi^2 < 0.01$ .

The CL regions are shown in figure 2. We observe that  $\cos\alpha$ ,  $\sin\alpha$ ,  $\Delta\Gamma_{\text{tot}}$  and  $\Delta S_H^\gamma$  are well bounded as:

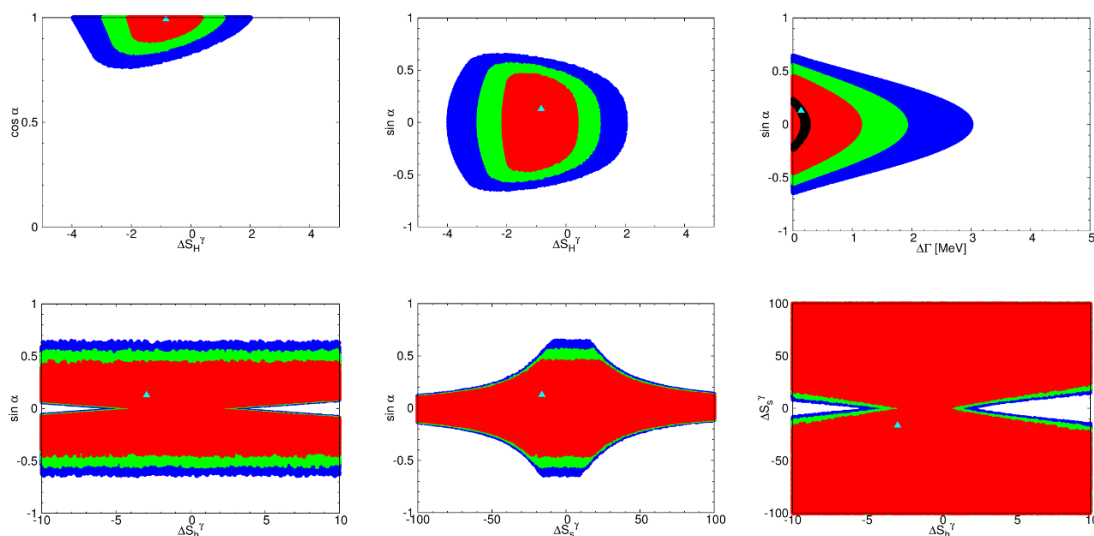
$$\begin{aligned}
 \cos\alpha &\gtrsim 0.83 \text{ (0.76) at 95\% (99.7\%) CL;} \\
 |\sin\alpha| &\lesssim 0.56 \text{ (0.65) at 95\% (99.7\%) CL;} \\
 \Delta\Gamma_{\text{tot}} &\lesssim 1.90 \text{ (3.00) MeV at 95\% (99.7\%) CL;} \\
 -2.95 \text{ (-3.96)} &\lesssim \Delta S_H^\gamma \lesssim 1.10 \text{ (2.02) at 95\% (99.7\%) CL.}
 \end{aligned} \tag{4.2}$$

In contrast,  $\Delta S_h^\gamma$  and  $\Delta S_s^\gamma$  are not bounded. From the relation  $\Delta S_H^\gamma = \Delta S_h^\gamma \cos\alpha - \Delta S_s^\gamma \sin\alpha$ , in the limit  $\sin\alpha = 0$ , we see that  $\Delta S_h^\gamma = \Delta S_H^\gamma$  is bounded while  $\Delta S_s^\gamma$  can take on any values. When  $|\sin\alpha|$  takes its largest value,  $\Delta S_s^\gamma$  is most bounded:  $|\Delta S_s^\gamma| \lesssim 20$ , see the lower-middle frame of figure 2. As  $|\Delta S_h^\gamma|$  grows, a cancellation between the two terms  $\Delta S_h^\gamma \cos\alpha$  and  $\Delta S_s^\gamma \sin\alpha$  is needed to obtain the limited value of  $\Delta S_H^\gamma$  together with non-vanishing  $\Delta S_s^\gamma \sin\alpha$ , explaining the wedges in the lower-left and lower-right frames.

The best-fit values for  $\Delta S_h^\gamma$  and  $\Delta S_s^\gamma$  are  $-2.953$  and  $-16.27$ , respectively, even though  $\Delta\chi^2$  does not change much in most regions of the parameter space. Considering  $S_{\text{SM}}^\gamma = -6.64$  and the best-fit value  $\Delta S_H^\gamma = -0.835$ , let alone a certain level of cancellation, it would be very hard to achieve such large values for  $\Delta S_h^\gamma$  and  $\Delta S_s^\gamma$ , unless the vector-like leptons are light, come in with a large multiplicity, and/or their Yukawa couplings to the singlet scalar  $s$  are strong.

### 4.3 SQ

In the **SQ** fit, we scan the regions of parameters:  $s_\alpha \in [-1 : 1]$ ,  $\Delta\Gamma_{\text{tot}} \in [0 : 15 \text{ MeV}]$ ,  $\Delta S_h^\gamma (\Delta S_h^g) \in [-10 : 10]$ ,  $\Delta S_s^\gamma (\Delta S_s^g) \in [-100 : 100]$ .



**Figure 2.** The CL regions for the **SL** fit. The description of the CL regions is the same as in figure 1.

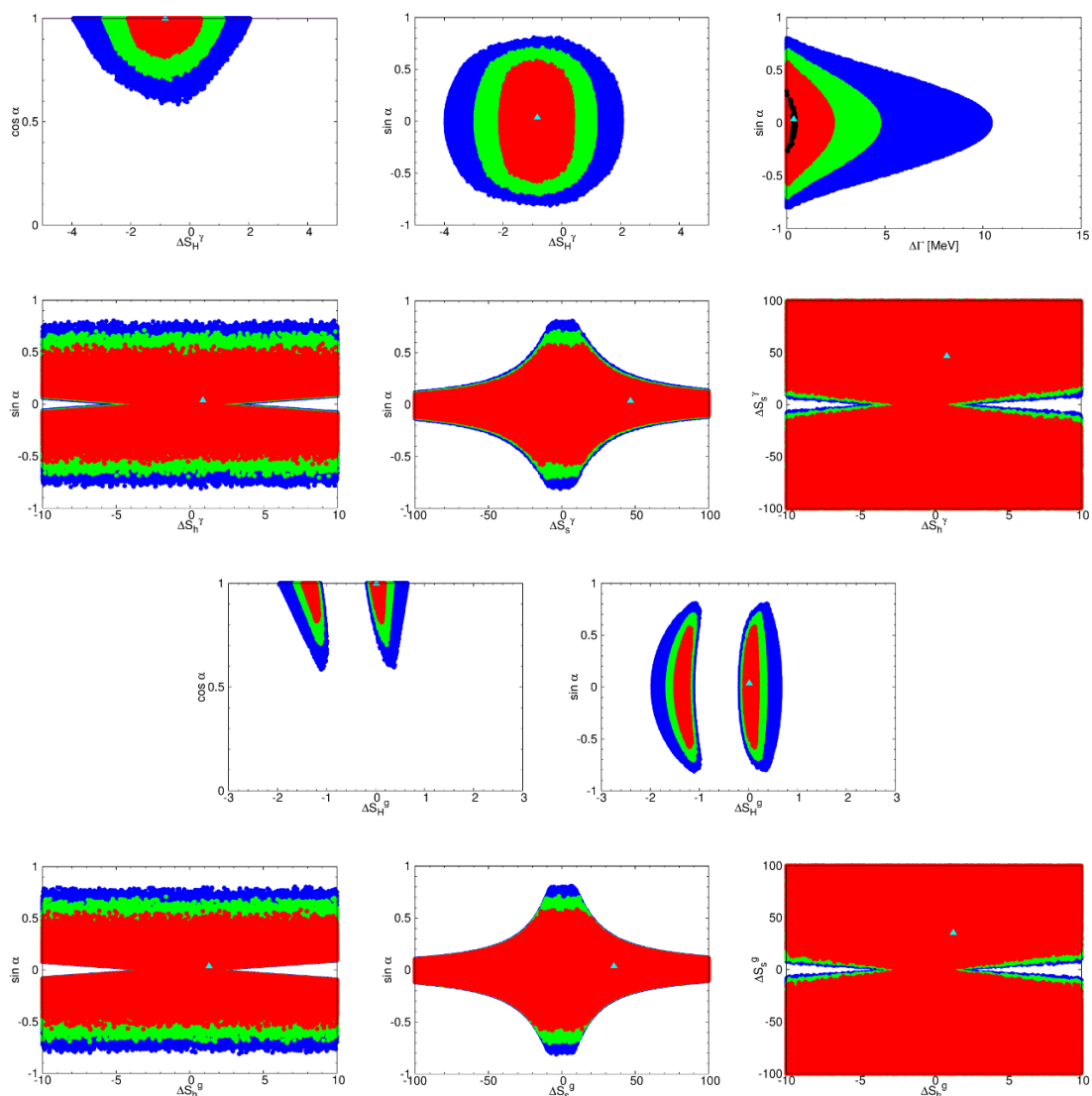
The CL regions are shown in figure 3. We observe that  $\cos \alpha$ ,  $\sin \alpha$ ,  $\Delta\Gamma_{\text{tot}}$ ,  $\Delta S_H^\gamma$ , and  $\Delta S_H^g$ , are well bounded as:

$$\begin{aligned}
 \cos \alpha &\gtrsim 0.70 \text{ (0.58) at 95\% (99.7\%) CL;} \\
 |\sin \alpha| &\lesssim 0.71 \text{ (0.81) at 95\% (99.7\%) CL;} \\
 \Delta\Gamma_{\text{tot}} &\lesssim 4.70 \text{ (10.40) MeV at 95\% (99.7\%) CL;} \\
 -2.94 \text{ (-3.96)} &\lesssim \Delta S_H^\gamma \lesssim 1.14 \text{ (2.05), at 95\% (99.7\%) CL;} \\
 -0.13 \text{ (-0.18)} &\lesssim \Delta S_H^g \lesssim 0.35 \text{ (0.65) and} \\
 -1.65 \text{ (-1.96)} &\lesssim \Delta S_H^g \lesssim -1.08 \text{ (-1.00) at 95\% (99.7\%) CL.}
 \end{aligned}$$

One may make similar observations for  $\Delta S_h^{\gamma:g}$  and  $\Delta S_s^{\gamma:g}$  as in the **SL** case. The parameters  $\Delta S_h^{\gamma:g}$  and  $\Delta S_s^{\gamma:g}$  are, in general, not bounded. When  $\sin \alpha = 0$ ,  $\Delta S_h^{\gamma:g} = \Delta S_H^{\gamma:g}$  and so they are bounded as  $\Delta S_H^{\gamma:g}$ . When  $|\sin \alpha|$  takes its largest values,  $|\Delta S_s^{\gamma:g}| \lesssim 10$ . We also observe the wedges along  $\sin \alpha = 0$  and  $\Delta S_s^{\gamma:g} = 0$  due to the cancellation between  $\Delta S_h^{\gamma:g} \cos \alpha$  and  $\Delta S_s^{\gamma:g} \sin \alpha$  when  $|\Delta S_h^{\gamma:g}| > |\Delta S_H^{\gamma:g}|$ .

The best-fit values for  $\Delta S_h^\gamma (\Delta S_h^g)$  and  $\Delta S_s^\gamma (\Delta S_s^g)$  are  $0.875(1.315)$  and  $46.84(35.54)$ , respectively, even though  $\Delta\chi^2$  does not change much in most regions of the parameter space. Considering  $S_{\text{SM}}^\gamma = -6.64 (S_{\text{SM}}^g = 0.65)$  and the best-fit value  $\Delta S_H^\gamma = -0.832 (\Delta S_H^g = 0.019)$ , let alone a certain level of cancellation, it would be very difficult to achieve such large values for  $\Delta S_h^{\gamma:g}$  and  $\Delta S_s^{\gamma:g}$ , unless the vector-like quarks are light, come in with a large multiplicity, and/or their Yukawa couplings to the singlet scalar  $s$  are strong.

Before closing this section, it is worth mentioning the experimental constraints on vector-like quarks and leptons. The vector-like quarks and leptons have been searched at the Tevatron and at the LHC. The current best limits on vector-like quarks are from the ATLAS collaboration with  $20.3 \text{ fb}^{-1}$  luminosity at 8 TeV [44]. The limits range between



**Figure 3.** The CL regions for the **SQ** fit. The description of the CL regions is the same as in figure 1.

715 GeV and 950 GeV for up-type vector-like quarks and those for down-type ones between 575 GeV and 813 GeV. Considering these limits, we observe that one should have  $\mathcal{O}(100)$  vector-like quarks to accommodate the large best-fit values of  $\Delta S_s^{\gamma,g}$  shown in table 3, assuming  $\mathcal{O}(1)$  Yukawa couplings of vector-likes quarks to the singlet scalar  $s$ .

## 5 Discussion

The Higgs-portal model involving a mixing between the SM Higgs field and an  $SU(2)$  singlet scalar boson is indeed the simplest extension to the SM Higgs sector, and gives rise to interesting phenomenology. In particular, this type of models can provide dark matter candidates, which exist in the hidden sector and interact with the SM sector through the

mixing. Since it involves the mixing, so it will have non-negligible effects on the SM Higgs boson properties. In this work, we have used the most updated Higgs boson data from LHC@7 and 8 TeV to obtain very useful constraints on the models. In the simplest of this class of models — the singlet with a dark matter candidate (**SD**), the deviations from the SM Higgs couplings can be parameterized by the mixing  $\cos\alpha$  and the deviation in the total decay width  $\Delta\Gamma_{\text{tot}}$ . We found that the **SD** model does not provide a better fit than the SM, and thus we obtain the 95% CL on the parameters:

$$\cos\alpha \gtrsim 0.86, \quad \Delta\Gamma_{\text{tot}} \lesssim 1.24 \text{ MeV}. \quad (5.1)$$

When more exotic particles are involved in the hidden sector, for example the vector-like leptons (**SL**) or vector-like quarks (**SQ**) in this work, the  $H\gamma\gamma$  and  $Hgg$  vertices are modified non-trivially, and thus more parameters are involved. The constraints on  $\cos\alpha$  and  $\Delta\Gamma_{\text{tot}}$  become somewhat less restrictive than the **SD** case (at 95%CL):

$$\begin{aligned} \mathbf{SL} : \cos\alpha &\gtrsim 0.83, \quad \Delta\Gamma_{\text{tot}} \lesssim 1.9 \text{ MeV} \\ \mathbf{SQ} : \cos\alpha &\gtrsim 0.70, \quad \Delta\Gamma_{\text{tot}} \lesssim 4.7 \text{ MeV}. \end{aligned}$$

The allowed ranges for other parameters can be found in the previous section.

We also offer the following comments on our findings:

- The SM gives the best fit in terms of  $\chi^2/d.o.f.$  although the difference from other best fits (**SD**, **SL**, **SQ**) are not statistically significant yet.
- **SD**: in this case, the best  $\chi^2$  occurs in the unphysical region: either  $c_\alpha > 1$  or  $\Delta\Gamma < 0$ . If this is still the case in the future data, a large class of DM models (Higgs-portal fermion or vector DM, and DM models with local dark gauge symmetries) and non-SUSY  $U(1)_{B-L}$  models will be strongly disfavored. However, the usual Higgs-portal scalar DM model with  $Z_2$  symmetry without the extra singlet scalar may still be viable, since the Higgs signal strength in that model will be the same as the SM case.
- **SL**: this case corresponds to the vector-like leptons in the loop for  $H \rightarrow \gamma\gamma$ . We get a reasonably good fit. Nevertheless, we need a rather large value for  $\Delta S_s^\gamma = -16.27$ , which might be possible only if the vector-like leptons are light, they come in with a large multiplicity, or the Yukawa couplings of the vector-like lepton to the singlet scalar  $s$  is strong.
- **SQ**: this case corresponds to the vector-like quarks in the loop for  $H \rightarrow \gamma\gamma$  and  $H \rightarrow gg$ . We get a reasonably good fit. However, we need a rather large value for  $\Delta S_s^\gamma = 46.84$ , which might be possible only if the vector-like quarks are light, they come in with a large multiplicity, or their Yukawa coupling is very large.
- **SL** and **SQ**: though the best-fit values for  $\Delta S_h^{\gamma,g}$  and  $\Delta S_s^{\gamma,g}$  are large, those for  $\Delta S_H^{\gamma,g} = \Delta S_h^{\gamma,g} \cos\alpha - \Delta S_s^{\gamma,g} \sin\alpha$  are only about  $-0.8$  and  $0.02$ , respectively.



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