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# Hiding the Higgs boson with multiple scalars

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We consider models with multiple Higgs scalar gauge singlets and the resulting restrictions on the parameters from precision electroweak measurements. In these models, the scalar singlets mix with the $SU(2)_L$ Higgs doublet, potentially leading to reduced couplings of the scalars to fermions and gauge bosons relative to the standard model Higgs boson couplings. Such models can make the Higgs sector difficult to explore at the LHC. We emphasize the new physics resulting from the addition of at least two scalar Higgs singlets.

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## I. INTRODUCTION

One of the major goals of the Large Hadron Collider is to probe the electroweak symmetry breaking sector. Models with multiple Higgs singlets have been considered in Ref. [1]. The simplest implementation of the symmetry breaking utilizes a single $SU(2)_L$ scalar Higgs doublet. In this minimal case, the couplings of the Higgs boson to fermions and gauge bosons are fixed in terms of the particle masses, and the phenomenology has been extensively studied. It is of interest, however, to study eextensions of the Higgs doublet model and to examine which possibilities are allowed by current data and how LHC Higgs phenomenology is affected. The most straightforward possibility for enlarging the Higgs sector is to add some arbitrary number of scalar singlets, which couple only to the Higgs doublet.

The phenomenology of models with one scalar singlet in addition to an $SU(2)_L$ doublet has been examined by many authors [2–7]. The case with one additional scalar is similar to that of models with a radion [8]. For a supersymmetric model, the addition of a gauge singlet scalar superfield leads to the next to minimal supersymmetric standard model [9–11], which solves the so-called "$\mu$" problem of the minimal supersymmetric standard model [12]. Alternatively, scalar singlets have been advocated as a signal for a hidden world that interacts only with the scalar sector of the standard model [13–16].

In this paper, we consider nonsupersymmetric models with additional scalar gauge singlets. In the case where there is a $Z_2$ symmetry in the scalar sector, this class of theory generically leads to a dark matter candidate, which is the lightest scalar singlet. Without a $Z_2$ symmetry, the scalar singlets can mix with the standard model Higgs doublet, and there is no dark matter candidate. It is this alternative that we consider here. The existence of multiple scalar singlets leads to changes in the scalar interactions with gauge bosons and fermions. Many authors have considered the case where the lightest scalar has a mass on the order of a few GeV and attempted to construct scenarios that evade the LEP direct Higgs production bounds [3,17]. We consider an alternative case where all the scalars are heavier than the LEP lower bound on the standard model Higgs $M_{H,\mathrm{SM}} > 114$ GeV [18].

The existence of scalars heavier than the LEP bound is restricted by electroweak precision measurements [19–21]. Since the dependence of the electroweak measurements on the scalar masses is logarithmic, it is possible to make quite significant changes in the scalar sector and still be consistent with precision data [22–24]. We compare the predictions of models with multiple Higgs scalars with the restrictions obtained from the $S$, $T$, and $U$ parameters [25]. We examine the cases with one and two scalar singlets and derive some general restrictions on the properties of models with extra scalar singlets. In the standard model, precision electroweak measurements restrict the Higgs mass to be less than about 185 GeV, $M_{H,\mathrm{SM}} <$ 185 GeV [20]. We consider the possibility of discovering a Higgs-like boson with a mass significantly larger than allowed in the standard model in a theory with multiple scalars. As more and more singlets are added, the couplings of the individual scalars to the fermions and gauge bosons become weaker and weaker, and heavy scalars can potentially be compatible with precision measurements. We are motivated by the analysis of Ref. [2], which attempted to hide the Higgs signal at the LHC by introducing multiple Higgs scalars. This reference concluded that a model with three scalars with masses in the 120 GeV region could evade discovery at the LHC.[1]

In Sec. II, we summarize the class of models that we consider in this paper, while Sec. III contains our results for the $S$, $T$, and $U$ parameters. Our results for one and two singlets are contained in Sec. IV, along with a discussion of

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[1]Ref. [2] found that a model with three scalars with masses $m_0 = 118$ GeV, $m_1 = 124$ GeV, and $m_2 = 130$ GeV would elude detection at the LHC with $L = 100\ \mathrm{fb}^{-1}$.

 

the phenomenological implications of our results for Higgs searches at the LHC. Technical details are summarized in two appendices. Section V contains some conclusions.

## II. THE MODELS

We consider a class of models with $N$ scalar singlets, $S_i$, along with an $SU(2)_L$ doublet, $H$,

$$H = \begin{pmatrix} \Phi^+ \\ \frac{1}{\sqrt{2}}(h + v_H) \end{pmatrix}, \qquad S_i = s_i + v_{s_i}. \tag{1}$$

We assume that the scalar potential is such that all scalars get a vacuum expectation value

$$\langle H \rangle = \frac{v_H}{\sqrt{2}} \qquad \langle S_i \rangle = v_{s_i}. \tag{2}$$

Since the singlets do not couple to the $SU(2)_L \times U(1)_Y$ gauge bosons, they do not contribute to $M_W$ and $M_Z$ and hence $v_H$ must take the standard model value $v_H = 246$ GeV. The vacuum expectation values are determined from the scalar potential

$$\begin{aligned} V_{\text{scalar}} = {} & \mu_H^2 |H|^2 + \lambda_H (|H|^2)^2 + \Sigma_i \mu_i |H|^2 S_i \\ & + \frac{1}{2}\Sigma_{ij}\mu_{ij}^2 S_i S_j |H|^2 + \Sigma_i M_i^3 S_i + \Sigma_{ij} M_{ij}^2 S_i S_j \\ & + \Sigma_{ijk}\lambda_{ijk} S_i S_j S_k + \Sigma_{ijkl}\lambda_{ijkl} S_i S_j S_k S_l. \end{aligned} \tag{3}$$

Note that we make no assumptions about possible $Z_2$ symmetries in the scalar sector, and in general $h$ will mix with the $s_i$ scalars to form the mass eigenstates.

The $N + 1$ scalar mass eigenstates are defined to be $\phi_i$, $i = 0 \ldots N$, with masses, $m_i$. We assume that $m_0$ is the lightest scalar. The mass eigenstates are related to the gauge eigenstates by an $(N + 1) \times (N + 1)$ unitary matrix $V$

$$\begin{pmatrix} \phi_0 \\ \phi_1 \\ \cdot \\ \cdot \\ \cdot \\ \phi_N \end{pmatrix} = V \begin{pmatrix} h^0 \\ s_1 \\ \cdot \\ \cdot \\ \cdot \\ s_N \end{pmatrix}. \tag{4}$$

Our results are expressed in terms of the elements of the mixing matrix $V$, which can be calculated in any given model. The couplings of the scalars to the gauge bosons and fermions are[2]

$$\begin{aligned} L = {} & -\Sigma_{i=0,N} V_{0i}\phi_i \left\{ \frac{m_f}{v_H}\bar{f}f + 2M_W^2 W_\mu^+ W^{\mu-} + M_Z^2 Z_\mu Z^\mu \right\} \\ & - \frac{1}{2v_H^2}\sum_{i,j=0,N} V_{0i}V_{0j}\phi_i\phi_j \\ & \times \{2M_W^2 W_\mu^+ W^{\mu-} + M_Z^2 Z_\mu Z^\mu\}. \end{aligned} \tag{5}$$

The production rates of the $\phi_i$ are suppressed by $|V_{0i}|^2$ relative to the standard model Higgs boson production rates. The branching ratios of the lightest scalar, $\phi_0$, to standard model particles are identical to the standard model branching ratios, while the branching ratios for the heavier scalars depend on whether the channels $\phi_i \to \phi_j\phi_k$ are kinematically accessible [3].

## III. LIMITS FROM PRECISION ELECTROWEAK MEASUREMENTS

The limits on the parameters of the scalar sector from precision electroweak measurements can be studied assuming that the dominant contributions resulting from the expanded scalar sector are to the gauge boson 2-point functions [25,26], $\Pi_{XY}^{\mu\nu}(p^2) = \Pi_{XY}(p^2)g^{\mu\nu} + B_{XY}(p^2)p^\mu p^\nu$, with $XY = \gamma\gamma$, $\gamma Z$, $ZZ$, and $W^+W^-$. We define the $S$, $T$, and $U$ functions following the notation of Peskin and Takeuchi [25],

$$\begin{aligned} \alpha S &= \left(\frac{4s_\theta^2 c_\theta^2}{M_Z^2}\right)\left\{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0) - \Pi_{\gamma\gamma}(M_Z^2) - \frac{c_\theta^2 - s_\theta^2}{c_\theta s_\theta}(\Pi_{\gamma Z}(M_Z^2) - \Pi_{\gamma Z}(0))\right\} \\ \alpha T &= \left(\frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} - \frac{2s_\theta}{c_\theta}\frac{\Pi_{\gamma Z}(0)}{M_Z^2}\right) \\ \alpha U &= 4s_\theta^2\left\{\frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2} - c_\theta^2\left(\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2}\right) - 2s_\theta c_\theta\left(\frac{\Pi_{\gamma Z}(M_Z^2) - \Pi_{\gamma Z}(0)}{M_Z^2}\right) - s_\theta^2\frac{\Pi_{\gamma\gamma}(M_Z^2)}{M_Z^2}\right\}, \end{aligned} \tag{6}$$

where $s_\theta \equiv \sin\theta_W$ and $c_\theta \equiv \cos\theta_W$ and any definition of $s_\theta$ can be used in Eq. (6), since the scheme dependence is higher order.

The scalar contributions to $S$, $T$, and $U$ from loops containing the $\phi_i$ are gauge invariant [27] and can be found in Appendix 1 of Ref. [28] or from Ref. [29].[3]

[2]Note that the Goldstone bosons have standard model couplings.

[3]The standard model contributions to the gauge boson 2-point functions can be found from Appendix 1 of Ref. [28] by setting $\delta = \gamma = 0$ and dropping the contributions involving $K^0$ and $H^\pm$. Our convention in this note for the sign of the 2-point functions is opposite from that of Ref. [28].

$$S_\phi = \frac{1}{\pi}\Sigma_i |V_{0i}|^2\left\{B_0(0, m_i, M_Z) - B_0(M_Z, m_i, M_Z) + \frac{1}{M_Z^2}[B_{22}(M_Z, m_i, M_Z) - B_{22}(0, m_i, M_Z)]\right\}$$
$$T_\phi = \frac{1}{4\pi s_\theta^2}\Sigma_i |V_{0i}|^2\left\{-B_0(0, m_i, M_W) + \frac{1}{c_\theta^2}B_0(0, m_i, M_Z) + \frac{1}{M_W^2}(B_{22}(0, m_i, M_W) - B_{22}(0, m_i, M_Z))\right\}$$
$$(U+S)_\phi = \frac{1}{\pi}\Sigma_i |V_{0i}|^2\left\{B_0(0, m_i, M_W) - B_0(M_W, m_i, M_W) + \frac{1}{M_W^2}[-B_{22}(0, m_i, M_W) + B_{22}(M_W, m_i, M_W)]\right\}. \tag{7}$$

The definitions of the Passarino-Veltman $B$ functions are given in Appendix A. The contributions from the Goldstone bosons are identical to the standard model case and hence are not included in Eq. (7).[4]

Using the results in Appendix A,

$$S_\phi = \frac{1}{\pi}\Sigma_i |V_{0i}|^2\left\{-\frac{1}{8}\frac{m_i^2}{M_Z^2} + \frac{m_i^2}{m_i^2 - M_Z^2}\left(1 - \frac{m_i^2}{4M_Z^2}\right)\ln\left(\frac{M_Z^2}{m_i^2}\right) + F_1(M_Z^2, m_i, M_Z) - \frac{m_i^2}{2M_Z^2}F_2(M_Z^2, m_i, M_Z) + C_S\right\}$$
$$T_\phi = -\frac{3}{16\pi s_\theta^2}\Sigma_i |V_{0i}|^2\left\{\frac{m_i^2}{m_i^2 - M_W^2}\ln\left(\frac{M_W^2}{m_i^2}\right) - \frac{m_i^2}{c_\theta^2(m_i^2 - M_Z^2)}\ln\left(\frac{M_Z^2}{m_i^2}\right) + C_T\right\} \tag{8}$$
$$(U+S)_\phi = \frac{1}{\pi}\Sigma_i |V_{0i}|^2\left\{-\frac{1}{8}\frac{m_i^2}{M_W^2} + \frac{m_i^2}{M_i^2 - M_W^2}\left(1 - \frac{m_i^2}{4M_W^2}\right)\ln\left(\frac{M_W^2}{m_i^2}\right) + F_1(M_W^2, m_i, M_W) - \frac{m_i^2}{2M_W^2}F_2(M_W^2, m_i, M_W) + C_U\right\},$$

where the terms $C_S$, $C_T$, and $C_U$ represent contributions that are independent of $m_i$.

In order to compare with fits to data, we must subtract from Eq. (7) the standard model Higgs boson contribution evaluated at a reference Higgs mass, $M_{H,\mathrm{ref}}$,

$$\begin{aligned}S_{H,\mathrm{ref}} &= \frac{1}{\pi}\left\{-\frac{1}{8}\frac{M_{H,\mathrm{ref}}^2}{M_Z^2} + \frac{M_{H,\mathrm{ref}}^2}{M_{H,\mathrm{ref}}^2 - M_Z^2}\left(1 - \frac{M_{H,\mathrm{ref}}^2}{4M_Z^2}\right)\ln\left(\frac{M_Z^2}{M_{H,\mathrm{ref}}^2}\right) + F_1(M_Z^2, M_{H,\mathrm{ref}}, M_Z)\right.\\
&\quad\left. - \frac{M_{H,\mathrm{ref}}^2}{2M_Z^2}F_2(M_Z^2, M_{H,\mathrm{ref}}, M_Z) + C_S\right\}\\
T_{H,\mathrm{ref}} &= -\frac{3}{16\pi s_\theta^2}\left\{\frac{M_{H,\mathrm{ref}}^2}{M_{H,\mathrm{ref}}^2 - M_W^2}\ln\left(\frac{M_W^2}{M_{H,\mathrm{ref}}^2}\right) - \frac{M_{H,\mathrm{ref}}^2}{c_\theta^2(M_{H,\mathrm{ref}}^2 - M_Z^2)}\ln\left(\frac{M_Z^2}{M_{H,\mathrm{ref}}^2}\right) + C_T\right\}\\
(U+S)_{H,\mathrm{ref}} &= \frac{1}{\pi}\left\{-\frac{1}{8}\frac{M_{H,\mathrm{ref}}^2}{M_W^2} + \frac{M_{H,\mathrm{ref}}^2}{M_{H,\mathrm{ref}}^2 - M_W^2}\left(1 - \frac{M_{H,\mathrm{ref}}^2}{4M_W^2}\right)\ln\left(\frac{M_W^2}{M_{H,\mathrm{ref}}^2}\right) + F_1(M_W^2, M_{H,\mathrm{ref}}, M_W)\right.\\
&\quad\left. - \frac{M_{H,\mathrm{ref}}^2}{2M_W^2}F_2(M_W^2, M_{H,\mathrm{ref}}, M_W) + C_U\right\}.\end{aligned} \tag{9}$$

Finally, we compare the quantities from Eqs. (7) and (9),

$$\Delta S_\phi = S_\phi - S_{H,\mathrm{ref}} \qquad \Delta T_\phi = T_\phi - T_{H,\mathrm{ref}} \qquad \Delta U_\phi = U_\phi - U_{H,\mathrm{ref}}, \tag{10}$$

with a fit to experimental data in order to obtain limits on the allowed masses and mixing angles. For $m_i$, $M_{H,\mathrm{ref}} \gg M_W$, $M_Z$, we find the familiar forms [25],

$$\Delta S_\phi = \frac{1}{12\pi}\Sigma_i |V_{0i}|^2 \log\left(\frac{m_i^2}{M_{H,\mathrm{ref}}^2}\right)$$
$$\Delta T_\phi = -\frac{3}{16\pi c_\theta^2}\Sigma_i |V_{0i}|^2 \log\left(\frac{m_i^2}{M_{H,\mathrm{ref}}^2}\right) \qquad \Delta U_\phi = 0. \tag{11}$$

For $m_i \sim M_W, M_Z$ the $\mathcal{O}(\frac{M_W^2}{m_i^2}, \frac{M_Z^2}{m_i^2})$ terms that are neglected in Eq. (11) are numerically important.[5] Our fitting proceedure includes the complete result and is described in Appendix B.

## IV. RESULTS

In this section, we consider models with one and two scalar singlets in addition to the $SU(2)_L$ doublet, and extract the regions of parameter space allowed by precision electroweak measurements. The goal is to draw some general conclusions about the Higgs discovery potential in models with expanded scalar sectors.

The dominant discovery channel for much of the Higgs mass range is $\phi_i \to ZZ^* \to 4$ leptons. The production rates of the $\phi_i$ are reduced from the standard model rates by $|V_{0i}|^2$. For $m_i \lesssim 200$ GeV, the $\phi_i$ scalar decay width is less than or comparable to the detector resolution [30,31], so

[4]Equation (7) is in agreement with the results of Ref. [5] when the Goldstone boson contributions are included.

[5]Reference [2] retains only the logarithmic contributions.

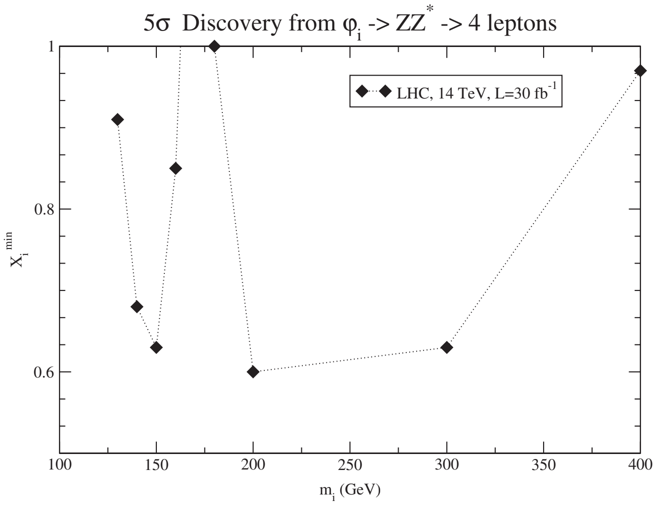


FIG. 1. Minimum value of $X_i$ for which a $5\sigma$ significance in the $\phi_i \to ZZ^* \to 4$ lepton channel is obtained with the ATLAS detector at the LHC with $\sqrt{s} = 14$ TeV and $\int L = 30\ \text{fb}^{-1}$ [31].

we use the narrow width approximation and neglect effects of the finite scalar widths. For the lightest Higgs boson $\phi_0$, the Higgs branching ratios are identical to the standard model branching ratios. For the heavier Higgs bosons, the scalar branching ratios depend on whether the $\phi_i \to \phi_j\phi_k$ channel is accessible for some $\phi_j$ and $\phi_k$. Whether or not this channel is open depends on the scalar mass spectrum, along with the parameters of the scalar potential. We define $\zeta_{ijk} = 1(0)$ if the decay $\phi_i \to \phi_j\phi_k$ is (is not) allowed. The signal for $\phi_i$ production with the subsequent decay to standard model particles is then suppressed from the standard model rate by [3]

$$X_i^2 = |V_{0i}|^2 \frac{|V_{0i}|^2\Gamma_h^{\text{SM}}}{|V_{0i}|^2\Gamma_h^{\text{SM}} + \sum_{jk}\zeta_{ijk}\Gamma(\phi_i \to \phi_j\phi_k)}, \quad (12)$$

where $\Gamma_h^{\text{SM}}$ is the total width in the standard model for a Higgs boson of mass $m_i$. For $\zeta_{ijk} = 0$, $X_i = V_{0i}$. From Eq. (12), $X_i$ is always less than one, so the addition of scalar singlets reduces the significance of the usual Higgs discovery channels.

Figure 1 shows the minimum value of $X_i$, $X_i^{\text{min}}$, for which a $5\sigma$ significance in the $\phi_i \to ZZ^* \to 4$ lepton channel can be found at the LHC with $\sqrt{s} = 14$ TeV and $L = 30\ \text{fb}^{-1}$. This figure is obtained by rescaling recent ATLAS studies [31]. As long as the $\phi_i \to \phi_j\phi_k$ channel is closed for the heavier scalars, then this limit can be trivially applied for all $\phi_i$ and $V_{0i}$.[6] For a model with one singlet and one $SU(2)_L$ doublet (and hence 2 physical Higgs bosons), if both scalars have masses less than $m_{\phi_i} \sim 160$ GeV, then since at least one of the scalars must have $V_{0i} > 1/\sqrt{2}$, at least one scalar can be discovered through the $\phi_i \to ZZ^* \to 4$ lepton channel. The situation changes when a second singlet is added. Now there are three physical scalars, and it is possible for all scalars to have masses less than $\sim$160 GeV and to have mixing angles $V_{0i} \sim 1/\sqrt{3}$. In this case, none of the scalars will be seen (at least with $L = 30\ \text{fb}^{-1}$) in the $\phi_i \to ZZ^* \to 4$ lepton channel. This is a generalization of the result of Ref. [2] and can be straightforwardly applied to examples with more singlets.

In the region 165 GeV $\lesssim m_i \lesssim$ 180 GeV, the $\phi_i \to ZZ^* \to 4$ lepton channel does not lead to a $5\sigma$ discovery with 30 $\text{fb}^{-1}$. In this mass region, the most useful discovery channel is $\phi_i \to W^+W^- \to e^\pm\nu\mu^\mp\nu$, which yields a $>5\sigma$ discovery for 140 GeV $\lesssim m_i \lesssim$ 185 GeV for $X_i \sim 1$ [31]. For $m_i \sim 160$ GeV, a $5\sigma$ discovery is possible with $X_i \gtrsim 0.7$.

### A. Fit with one singlet

Figures 2 and 3 show results with one singlet scalar in addition to the $SU(2)_L$ scalar doublet. The scalar sector is described by the masses of the two scalars $m_0$ and $m_1$, and one mixing angle which we take to be $V_{01}$ ($V_{00} = \sqrt{1 - V_{01}^2}$). The fit to the experimental limits on $\Delta S$, $\Delta T$ and $\Delta U$ is performed as described in Appendix B, and the maximum allowed value of $V_{01}$ for various values of $m_0$ is shown in Fig. 2. (For simplicity, we assume $\zeta_{ijk} = 0$ for all $i$, $j$, $k$.) For $V_{01} \sim 0$, $\phi_0$ is predominantly the neutral component of the $SU(2)_L$ doublet with nearly standard model couplings, and the 95% confidence level limit on the allowed value of $m_0$ is just the 95% confidence level limit of this fit in the standard model $M_{H,\text{SM}} \lesssim 166$ GeV. There is no limit on $m_1$ in this case.

For moderate mixing, the heavier scalar $\phi_1$ can be quite heavy. For example, the lightest scalar could have $m_0 \sim 140$ GeV with a coupling $V_{00} \sim 0.7$, while the heavier

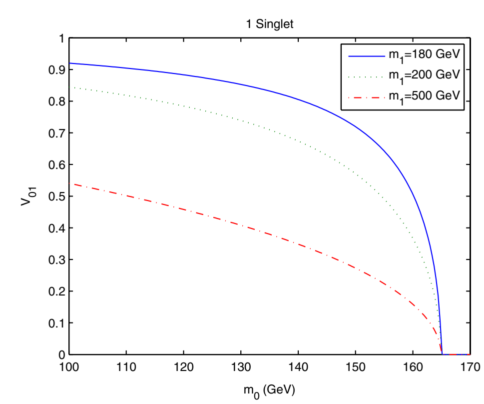


FIG. 2 (color online). Allowed region (at 95% confidence level) in a model with one additional singlet in addition to the usual $SU(2)_L$ doublet. The lightest (heavier) scalar is $m_0$ ($m_1$) and the mixing matrix is defined in Eq. (4). The region below the curves is allowed by fits to $S$, $T$, and $U$.

[6]This also requires that the mass differences between the scalars be greater than the detector resolution.

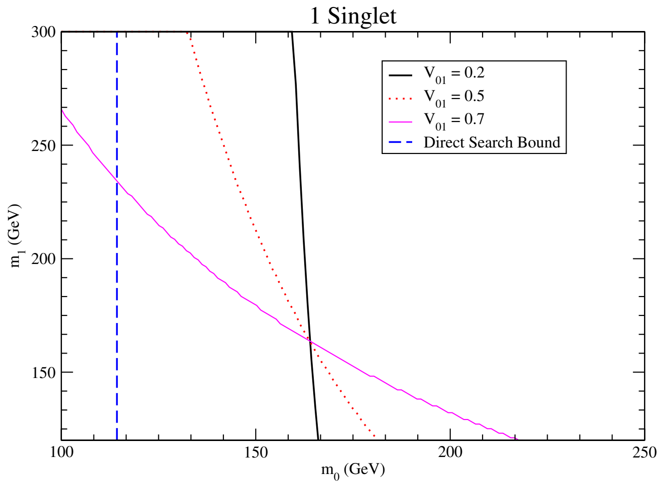


FIG. 3 (color online). Allowed region (at 95% confidence level) in a model with one additional singlet in addition to the usual $SU(2)_L$ doublet. The lightest (heavier) scalar is $m_0$ $(m_1)$, and the mixing matrix is defined in Eq. (4). The region below and to the left of the curves labeled with values of $V_{01}$ are allowed by fits to $S$, $T$, and $U$. The region to the right of the dashed line is allowed by direct search limits from LEP2.

scalar could have a mass $m_1 \sim 200$ GeV with a coupling $V_{01} \sim 0.7$. In this case, comparison with Fig. 1 shows that both scalars could be observed in the $ZZ^* \rightarrow 4$ lepton channel with 30 fb$^{-1}$. If $\phi_1$ becomes too heavy (say $\phi_1 \sim$ 500 GeV), then its coupling to standard model particles is restricted by the precision electroweak measurements to be less than $V_{01} \lesssim 0.5$ (for $m_0 \gtrsim 114$ GeV), and so $\phi_1$ cannot be found in the $ZZ^* \rightarrow 4$ lepton mode with 10 fb$^{-1}$.

Figure 3 demonstrates that scalars that have masses in the 200 GeV range can be compatible with the electroweak precision measurements and have couplings large enough to be discovered at the LHC. In much of the parameter space of this plot, both scalars will be observed.

### B. Fit with two singlets

In this subsection, we examine how the allowed masses of the scalars are changed with the addition of two singlets in addition to the standard model doublet. The scalar sector now has three scalars with masses $m_0$, $m_1$, and $m_2$, and the mixing matrix $V$ is a $3 \times 3$ unitary matrix. The phenomenology is quite different from the case with one singlet. As mentioned previously, with two singlets it is possible to sufficiently suppress the couplings $V_{0i}$ to all scalars such that none of them are observable with 10 fb$^{-1}$ at the LHC if they all satisfy the standard model limit $m_i \lesssim 166$ GeV.

Figs. 4 and 5 show the minimum allowed value from the electroweak fit for $V_{01}$ as a function of $V_{00}$ for fixed masses. (We assume $\zeta_{ijk} = 0$ for simplicity). The minimum of $V_{01}$ results from requiring that the coupling to the heaviest scalar $V_{02} = \sqrt{1 - V_{00}^2 - V_{01}^2}$ not be large enough that $\phi_2$ makes a significant contribution to $\Delta S$, $\Delta T$, or $\Delta U$.

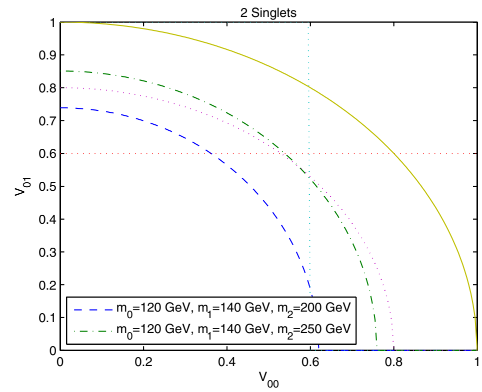


FIG. 5 (color online). Allowed region at 95% confidence level for a model with two singlets in addition to the $SU(2)_L$ scalar doublet. The allowed regions are above and to the right of the dashed and dotted-dashed curves. The solid curve is $\sum_i |V_{0i}|^2 = 1$. The solid curve is $\sum_i |V_{0i}|^2 = 1$. The curved dotted line is $V_{02} = 0.6$, while the straight dotted lines are $V_{00} = 0.6$ and $V_{01} = 0.6$.

The solid red lines in Figs. 4 and 5 are $V_{0i} = 0.6$, which roughly represents the limit of observability in the $\phi_i \rightarrow ZZ^* \rightarrow 4$ leptons channel. In these examples, there is never more than one scalar observable. In the regions enclosed by the dotted lines, all three scalars would elude detection in the $\phi_i \rightarrow ZZ^* \rightarrow 4$ leptons channel with 30 fb$^{-1}$.

The heaviest scalar can have a mass in the $m_2 \sim$ 200–250 GeV range and still have a coupling $V_{02}$ large enough to be observed in the $ZZ^* \rightarrow 4$ lepton channel if $m_0$ and $m_1$ are less than $\sim$160 GeV, although the lighter scalars will have couplings that are too small to be observed in this example. Thus, observation of a scalar Higgs-like particle with $m_i > M_{H,\mathrm{sm}}$ can be considered as a smoking gun for theories with multiple scalar singlets.

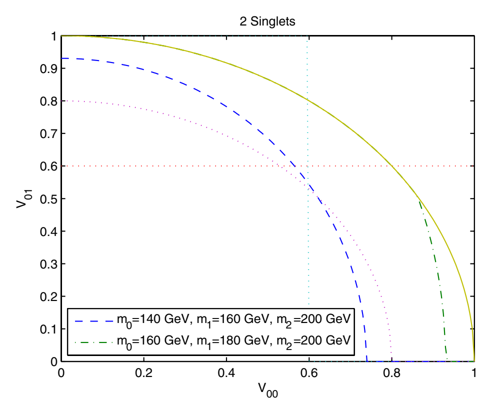


FIG. 4 (color online). Allowed region at 95% confidence level for a model with two singlets in addition to the $SU(2)_L$ scalar doublet. The allowed regions are above and to the right of the dashed and dotted-dashed curves. The solid curve is $\sum_i |V_{0i}|^2 = 1$. The curved dotted line is $V_{02} = 0.6$, while the straight dotted lines are $V_{00} = 0.6$ and $V_{01} = 0.6$.

## V. CONCLUSIONS

We have considered the discovery potential for Higgs bosons in theories with multiple scalar singlets and demonstrated that quite simple modifications of the standard model Higgs sector can reduce the significance of the standard Higgs discovery channels.

The addition of two scalar gauge singlets can change the Higgs sector dramatically from the standard model and also from the case with a single scalar. In this case, it is possible to hide the Higgs boson if all three physical scalars are light, $m_i \lesssim 160$ GeV, with roughly equal mixing angles, $V_{0i} \sim 1/\sqrt{3}$. Alternatively, in this case, the electroweak precision measurements allow a Higgs boson in the 200–250 GeV mass region with couplings to standard model particles that are large enough to allow discovery.

## ACKNOWLEDGMENTS

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## APPENDIX A

The Passarino-Veltman functions [32] are defined as

$$\begin{aligned}\frac{i}{16\pi^2}B_0(q^2, m_1, m_2) &= \int \frac{d^n k}{(2\pi)^n} \\ &\quad \times \frac{1}{[k^2 - m_1^2][(k+q)^2 - m_2^2]} \\ &\quad \times \frac{i}{16\pi^2}\{g^{\mu\nu}B_{22}(q^2, m_1, m_2) \\ &\quad + q^\mu q^\nu B_{12}(q^2, m_1, m_2)\} \\ &= \int \frac{d^n k}{(2\pi)^n} \\ &\quad \times \frac{k^\mu k^\nu}{[k^2 - m_1^2][(k+q)^2 - m_2^2]}. \end{aligned} \tag{A1}$$

We define

$$\begin{aligned}B_0(p^2, m_1, m_2) &= [N_2]\left\{\frac{1}{\epsilon} - F_1(p^2, m_1, m_2)\right\} \\ B_{22}(p^2, m_1, m_2) &= [N_2]m_1^2\left\{\frac{1+r}{4}\left(\frac{1}{\epsilon}+1\right) - \frac{p^2}{12m_1^2}\left(\frac{1}{\epsilon}+1\right)\right. \\ &\quad \left. - \frac{1}{2}F_2(p^2, m_1, m_2)\right\}, \end{aligned} \tag{A2}$$

where

$$\begin{aligned}F_1(p^2, m_1, m_2) &\equiv \int_0^1 dx \ln\left(1 - x + \frac{x}{r} - \frac{p^2 x(1-x)}{m_2^2}\right) \\ F_2(p^2, m_1, m_2) &\equiv \int_0^1 dx\left\{(1-x) + rx - \frac{p^2}{m_1^2}x(1-x)\right\} \\ &\quad \times \ln\left(x + \frac{(1-x)}{r} - \frac{p^2}{m_2^2}x(1-x)\right). \end{aligned} \tag{A3}$$

We need the special cases [33]

$$\begin{aligned}F_1(0, m_1, m_2) &= -1 - \frac{1}{1-r}\ln(r) \\ F_1(m_2^2, m_1, m_2) &= -2 - \frac{1}{2r}\log(r) + \frac{\beta}{2r}\ln\left(\frac{1-\beta}{1+\beta}\right) \\ F_2(0, m_1, m_2) &= -\frac{1+r}{4} - \frac{1}{2(1-r)}\ln(r) \\ F_2(m_2^2, m_1, m_2) &= \frac{2}{3}\left(1 - \frac{1}{4r}\right)\{1 + F_1(m_2^2, m_1, m_2)\} \\ &\quad - \frac{1}{6r}\log(r) - \left(\frac{1}{3} + \frac{2r}{9}\right), \end{aligned} \tag{A4}$$

and we define

$$\begin{aligned} r &\equiv \frac{m_2^2}{m_1^2} \qquad \beta \equiv \sqrt{1-4r} \\ [N_2] &\equiv \left(\frac{4\pi\mu^2}{m_2^2}\right)^\epsilon \Gamma(1+\epsilon). \end{aligned} \tag{A5}$$

## APPENDIX B

We use the fit to electroweak precision data given in Ref. [5],

$$\begin{aligned}\Delta S &= S - S_{\mathrm{SM}} = -0.126 \pm 0.096 \\ \Delta T &= T - T_{\mathrm{SM}} = -0.111 \pm 0.109 \\ \Delta U &= U - U_{\mathrm{SM}} = +0.164 \pm 0.115, \end{aligned} \tag{B1}$$

with the associated correlation matrix

$$\rho_{ij} = \begin{pmatrix} 1.0 & 0.866 & -0.392 \\ 0.866 & 1.0 & -0.588 \\ -0.392 & -0.588 & 1.0 \end{pmatrix}.$$

$\Delta\chi^2$ is defined as

$$\Delta\chi^2 = \Sigma_{ij}(\Delta X_i - \Delta\hat{X}_i)(\sigma^2)^{-1}_{ij}(\Delta X_i - \Delta\hat{X}_i), \tag{B2}$$

where $\Delta\hat{X}_i = \Delta S, \Delta T$, and $\Delta U$ are the central values of the fit in Eq. (B1), $\Delta X_i = \Delta S_\phi, \Delta T_\phi$, and $\Delta U_\phi$ from Eq. (10), $\sigma_i$ are the errors given in Eq. (B1) and $\sigma^2_{ij} = \sigma_i \rho_{ij} \sigma_j$. The 95% confidence level limit corresponds to $\Delta\chi^2 = 7.815$. We vary the input values of $V_{0i}$ and $m_i$ to find the $\Delta\chi^2 = 7.815$ contours shown in Figs. 2–5. This fit gives a 95% confidence level limit on the standard model Higgs boson of $M_{H,\mathrm{SM}} < 166$ GeV.

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