Universal doublet-singlet Higgs couplings and phenomenology at the CERN Large Hadron Collider

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We consider a minimal extension of the standard model where a real, gauge singlet scalar field is added to the standard spectrum. Introducing the Ansatz of universality of scalar couplings, we are led to a scenario which has a set of very distinctive and testable predictions: (i) the mixing between the standard model Higgs and the new state is near maximal, (ii) the ratio of the two Higgs mass eigenstates is fixed ($\sim \sqrt{3}$), (iii) the decay modes of each of the two eigenstates are standard model like. We also study how electroweak precision tests constrain this scenario. We predict the lighter Higgs to lie in the range of 114 and 145 GeV, and hence the heavier one between 198 and 250 GeV. The predictions of the model can be tested at the upcoming LHC.

I. INTRODUCTION

The electroweak symmetry breaking scenario of the standard model (SM) will undergo a thorough scrutiny at the Large Hadron Collider (LHC). The scalar sector of the SM consists of a single SU(2) Higgs doublet. However, there is no fundamental reason why there should be only one Higgs doublet. The construction of the SM scalar sector with just one SU(2) doublet relies essentially on the principle of minimality. Indeed, a single complex scalar doublet is sufficient to implement spontaneous gauge symmetry breaking which can account for the masses of the gauge bosons as well as the fermions. However, in most of the extensions of the SM one has a richer Higgs structure, with more than one doublet and/or gauge singlets. The motivation for these extensions of the SM arises from attempts to solve some of the drawbacks of the SM, like the hierarchy problem, the flavor puzzle, the dark matter problem, to name a few.

At present, it is not clear what is the preferred solution to any of the above problems. Nevertheless, quite a few such attempts advocate the inclusion of one or more gauge singlet scalars with several virtues. For example, in the supersymmetric extension, the addition of a singlet chiral superfield can provide a solution to the μ-problem in MSSM [1]. Such an addition can also alleviate the stringent limit on the Higgs mass from LEP 2, and provide a new invisible decay channel for the SM like Higgs boson [2]. Moreover, with an additional Z_2 symmetry, a singlet Higgs extension can also provide a viable candidate for the dark

matter of the universe [3,4]. It also facilitates first order electroweak phase transition, as needed to produce the observed baryon asymmetry of the universe, by lowering the Higgs mass [5]. Such electroweak singlets, together with the doublets, also arise naturally in extra dimensional models of gauge, Higgs, and matter unification [6]. From another theoretical perspective, as noted in [7], the Higgs mass term in the SM is the only super-renormalizable interaction which respects Lorentz and the SM gauge symmetry. More specifically, a hidden sector (gauge singlet) dimension-2 scalar operator $\mathcal{O}$ can have an interaction like $|H|^2\mathcal{O}^2$ which is not suppressed by inverse powers of large scales. This leads to a mixing between the Higgs and a gauge singlet field after H acquires a vacuum expectation value (vev).

One drawback of the general extension of the SM with a scalar singlet, even with a Z_2 symmetry, is that the model is not predictive. The masses of both the Higgs bosons, as well as their mixing angle are unknown. The phenomenological implications for such a general extension has been studied from the collider and cosmological perspectives [4,5,8]. In the present work, we advocate a more predictive scenario in which the only unknown parameter is the mass of the lighter Higgs boson, and the predictions can be easily tested at the LHC. To achieve this, for the scenario with a real singlet scalar in addition to the SM doublet, we introduce an Ansatz of universality of scalar couplings (as will be discussed below), and explore its consequences within our restricted and predictive scenario.

II. OUR MODEL

We denote the SM Higgs doublet by H and the real gauge singlet by S. We introduce a Z_2 symmetry under

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which $S \rightarrow -S$. Thus S is blind to both gauge and Yukawa interactions. The scalar potential reads ($H \equiv \frac{1}{\sqrt{2}} \times (h_1 + ih_2, h_3 + ih_4)^T$):

$$V(H, S) = -\mu_H^2(H^\dagger H) - \tfrac{1}{2}\mu_S^2 S^2 + \lambda_H(H^\dagger H)^2$$
$$+ \tfrac{1}{2}\lambda_{HS}(H^\dagger H)S^2 + \tfrac{1}{4}\lambda_S S^4. \qquad (1)$$

By using the minimization equations when both H an S acquire vevs, and working in the unitary gauge, one obtains:

$$H(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix},$$

$$S(x) = \eta + s(x), \quad \text{where,} \quad v^2 = \frac{\mu_H^2 - \frac{\lambda_{HS}}{2\lambda_S}\mu_S^2}{\lambda_H - \frac{\lambda_{HS}^2}{4\lambda_S}}, \qquad (2)$$

$$\eta^2 = \frac{\mu_S^2 - \frac{\lambda_{HS}}{2\lambda_H}\mu_H^2}{\lambda_S - \frac{\lambda_{HS}^2}{4\lambda_H}}.$$

The scalar mass-squared matrix in the (h, s) basis is then given by

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{HS}v\eta \\ \lambda_{HS}v\eta & 2\lambda_S \eta^2 \end{pmatrix}. \qquad (3)$$

Thus the scalar sector is described in terms of 5 parameters: the two vevs and three dimensionless couplings, of which only the doublet vev is known as $v \simeq 246$ GeV. The remaining 4 parameters can be experimentally determined if both the physical scalar states are discovered, their mixing angle is measured, and the coupling of the two states is determined (from a possible decay of the heavier state into the lighter one).

At this point, we introduce a simple Ansatz of "universality of scalar couplings (USC)" at the weak scale, leading to

$$\mu_H^2 \simeq \mu_S^2 \equiv \mu^2 \quad \text{and} \quad \lambda_H \simeq \lambda_{HS} \simeq \lambda_S \equiv \lambda. \qquad (4)$$

The USC Ansatz (which puts a given real component inside the doublet H, e.g. h_3, and the real singlet S at par in terms of their strengths) is admittedly *ad hoc*. Its merit resides in its simplicity and predictive power. However, it should be noted that an analogous hypothesis of universality of strength of Yukawa couplings is in remarkably good agreement with the observed pattern of quark masses and mixings [9]. At this point one may ask whether the USC Ansatz could result from an extra symmetry imposed on the Lagrangian. We will comment further on this towards the end. With this Ansatz, the scenario becomes very predictive:

(i) The mixing angle between h and s is near-maximal ($\simeq \pi/4$).
(ii) The physical mass-squares are: $m_1^2 \simeq \lambda v^2$ and $m_2^2 \simeq 3m_1^2$, where $v^2 \simeq 2\mu^2/3\lambda = (246 \text{ GeV})^2$.

So we have only one unknown parameter, which we may take to be the mass of the lighter Higgs. It is not possible to pin down its value but we can constrain it from direct searches and electroweak precision tests.

III. DIRECT SEARCH LIMITS

The lower limit $m_h > 114.4$ GeV in the SM arises from nonobservation of Higgs in associated production in LEP-2 via the Bjorken process $e^+e^- \rightarrow Zh$. In many extensions of the SM (such as ours), the ZZh coupling strength for the lightest Higgs boson is reduced by a factor ζ compared to that in the SM. In general, the direct lower bound on the lightest Higgs boson mass is significantly diluted if $\zeta < 0.2$ [10]. In our model, $\zeta^2 = 0.5$, and thus the SM direct mass limit of 114.4 GeV still stands for the lighter Higgs boson in our model. Hence the heavier Higgs boson mass $m_2(= \sqrt{3}m_1) > 198$ GeV.

IV. ELECTROWEAK PRECISION TESTS

The electroweak precision observables significantly restrict the allowed range of masses for the two Higgs bosons in our model. The preferred value of the SM Higgs is $m_h = 76^{+33}_{-24}$ GeV. The 95% CL upper limit of $m_h < 144$ GeV is raised to 186 GeV if the direct search limit of $m_h > 114.4$ GeV is enforced in the fit [11]. The Higgs contribution to the T and S parameters are logarithmic. Since the top quark mass is now known to a very good accuracy (170.9 ± 1.8 GeV), instead of doing a rigorous numerical fit to our model, we demand that the two-state $\{m_1, m_2\}$ system mimics the effect of pure SM Higgs of mass m_h. If we apply this criterion on the T parameter, then using the explicit formula given in [5], we obtain the following simplified relation for maximal mixing between the two states:

$$h^{(2h/(h-1))} \simeq r_1^{(r_1/(r_1-1))} r_2^{(r_2/(r_2-1))}, \qquad (5)$$

where, $h = m_h^2/M_V^2$ and $r_{1,2} = m_{1,2}^2/M_V^2$. Here, $r_2 = 3r_1$ (as noted above). We take M_V as an "average" between W and Z boson masses. Using Eq. (5), we obtain $m_1 < 145$ GeV and $m_2 < 250$ GeV, since $m_h < 186$ GeV. The constraint from the S parameter does not significantly alter those upper limits.

V. UNITARITY BOUNDS

Based on a partial wave analysis of longitudinal gauge boson scattering, the unitarity upper limit of the SM Higgs mass was derived as $m_h^2 \lesssim 16\pi v^2/3 \simeq (1 \text{ TeV})^2$ [12]. This bound means that if the Higgs mass exceeds the above critical value, then weak interactions will become strong in the TeV scale and perturbation theory will break down. In the present situation, m_h^2 will be replaced by ($\cos^2\phi m_1^2 + \sin^2\phi m_2^2$), where ϕ is the Higgs mixing angle. Since $\phi \simeq \pi/4$ and $m_2^2 \simeq 3m_1^2$, it follows that the unitarity upper limit

on the lighter Higgs state is stronger than the SM upper limit, namely, $m_1 \lesssim (1/\sqrt{2})$ TeV.

VI. PHENOMENOLOGICAL IMPLICATIONS

Our model has several definite phenomenological implications which can be tested at the LHC.

(i) The model has only one unknown parameter which can be taken to be m_1, the mass of the lighter Higgs boson (h_1). It predicts the existence of a second Higgs boson, h_2, with mass $\sqrt{3}m_1$.

(ii) The mixing angle is predicted to be maximal ($\simeq \pi/4$). This can be tested by measuring the production cross sections of h_1 and h_2 at the LHC.

(iii) In our model, since $m_2 < 2m_1$, the decay $h_2 \to h_1 h_1$ is not allowed. This is in contrast to a large set of general models, with a doublet and a singlet Higgs, where this decay is allowed [5].

(iv) The branching ratios of h_1 and h_2 decays into fermions would remain the same as in the SM, although the partial decay widths will be equally affected due to the mixing. This feature can be tested at the LHC and can be scrutinized even more accurately at the ILC.

(v) Since the scalar mixing is maximal, both Higgses can be produced with sizable cross sections at the LHC in the allowed mass ranges: $114.4 \lesssim m_1 \lesssim 145$, $198 \lesssim m_2 \lesssim 250$ (all in GeV).

VII. DISCUSSION OF THE ANSATZ

At this point, we ask if our Ansatz of universal scalar couplings may follow from some symmetry. In the framework of the $SU(2) \times U(1)$ electroweak gauge model this is certainly not possible, since the H and S fields transform differently under the gauge symmetry. But constraints of the USC type could arise in a gauge extension of the electroweak part of the SM where H and S would belong to the same irreducible representation of the enlarged gauge group. We also point out that demanding the Lagrangian be invariant under the exchange of the bilinears $(H^\dagger H)$ and $\frac{1}{2} S^2$ leads to $\mu_H^2 = \mu_S^2$ and $\lambda_H = \lambda_S$. It will be interesting to understand the field theoretic implications of such an exchange symmetry/relation. This may occur, for example, if the Higgs scalars happen to be composite objects (drawing analogy from pions). Clearly, it is the predictive power, testable at the LHC, that makes our Ansatz worth considering. We mention at this stage that we have assumed our Ansatz to be valid at the weak scale, since such relations will in general be scale dependent unless they are protected by some symmetry.

VIII. DEVIATION FROM UNIVERSALITY

A discussion of a possible mild deviation from the Ansatz of strict universality, as expressed in Eq. (4), is now in order. For simplicity of presentation and ease of analytic understanding, let us consider a scenario where $\mu^2 \equiv \mu_H^2$, $\mu_S^2 = \mu^2 + \Delta\mu^2$, and $\lambda \equiv \lambda_H = \lambda_S$, $\lambda_{HS} = \lambda + \Delta\lambda$. We further assume that the deviations are small, i.e. $\alpha \equiv \Delta\mu^2/\mu^2 \ll 1$ and $\beta \equiv \Delta\lambda/\lambda \ll 1$. It immediately follows from Eqs. (2) and (3) that $\tan 2\phi \simeq 1/(3\alpha)$ and $m_2^2 \simeq 3m_1^2(1 + 4\beta/3)$. Indeed, it is quite instructive to observe that under the above assumptions and to the leading approximations, the deviation of the mixing angle (ϕ) from maximality is sensitive to the nonuniversality of mass-dimensional couplings, while the ratio between the heavier and the lighter Higgs bosons is sensitive to the nonuniversality of dimensionless couplings.

IX. CONCLUSIONS

We have presented a simple extension of the Higgs sector of the standard model by adding a real electroweak singlet scalar field, and made an Ansatz of universality of scalar couplings. The model is highly predictive: (i) the mixing between the two Higgs in the model is maximal, and (ii) the mass of the heavier Higgs is $\sqrt{3}$ times that of the lighter Higgs. These and other predictions of the model can be tested at the upcoming LHC. The consequences of a possible mild deviation from a strict universality have also been discussed.

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