Hiding the Higgs Boson from Prying Eyes

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Abstract

There are two simple ways that the Higgs boson $H$ of the Standard Model (SM) may be more difficult to observe than expected at the Large Hadron Collider (LHC) or the Tevatron. One is well-known, i.e. $H$ decays invisibly, into dark-matter scalar particles for example. The other is that $H$ mixes with a heavy singlet scalar $S$ which couples to new colored fermions and scalars. Of the two mass eigenstates, the light one could (accidentally) have a suppressed effective coupling to two gluons, and the heavy one could be kinematically beyond the reach of the LHC.
The one Higgs boson $H$ of the Standard Model (SM) of particle interactions is expected to be produced by gluon-gluon fusion at the Large Hadron Collider (LHC) and be observed through its decay into $ZZ$, $WW$, and other channels. Recent reported data [2, 3, 4] have excluded the following mass ranges at 95% confidence level:

\[
\begin{align*}
\text{ATLAS} & : & 146 - 232, & 256 - 282, & 296 - 466 \text{ GeV} \\
\text{CMS} & : & 145 - 216, & 226 - 288, & 310 - 340 \text{ GeV} \\
\text{TEVATRON} & : & 156 - 177 \text{ GeV}
\end{align*}
\]

Combined with the LEPII bound [5] of $m_H > 114.4$ GeV, this leaves only a small window for its observation. Whereas more data could eventually find $H$ through its rare decay mode to two photons, it is perhaps a good time now to consider how $H$ may be hidden from view because of either its decay or its production.

A first possibility is that $H$ decays significantly into invisible channels, thereby diminishing its branching fractions into observable final states. This is a very old idea [6] and has many different model realizations. One recent example is the model of a dark (inert) scalar doublet [7], where the Standard Model is extended to include a second scalar doublet, which is odd under an exactly conserved $Z_2$ symmetry [8]. If the neutral member $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$ of this doublet is split so that $m_R < m_I$ by at least the order of 100 keV, then $\eta_R$ is a good dark-matter candidate [9, 10]. For the latest discussion on this model, see Ref. [11]. If $2m_R < m_H$, then the invisible decay of $H$ into these dark-matter scalars will suppress its branching fractions to other particles, as already discussed in detail a few years ago [12]. The effect is especially significant below the $WW$ threshold and could suppress the $\gamma\gamma$ branching fraction by as much as a factor of three.

A second possibility is a new proposal. The idea is very simple. Suppose there is a scalar singlet $S$ which couples to new colored fermions and scalars. In that case, both $H$ and $S$ will couple to two gluons through loops. Let the $Hgg$ amplitude be $A_H$ and the $Sgg$ amplitude be
$A_S$, then $A_H$ is dominated by the $t$-quark loop, and $A_S$ comes from the new colored fermions and scalars. Take for example $A_S = 3A_H$. Now if $H$ mixes with $S$, the linear combination $H' = (3H - S)/\sqrt{10}$ would not couple to two gluons, and would not be produced at the LHC by gluon-gluon fusion. If $H'$ also happens to be a mass eigenstate, then it could hide from being seen at the LHC even if its mass is 170 GeV (above the $WW$ threshold). The orthogonal combination $S' = (3S + H)/\sqrt{10}$ has an enhanced coupling to two gluons, but it is presumably heavy because it is mostly a singlet, and could be kinematically beyond the reach of the LHC.

Consider the scalar potential of the SM doublet $\Phi = (\phi^+, \phi^0)$ and a real singlet $S$:

$$V = \mu_1^2 \Phi^\dagger \Phi + \frac{1}{2} \lambda_1 (\Phi^\dagger \Phi)^2 + \frac{1}{2} \mu_2^2 S^2 + \frac{1}{3} \mu_3 S^3 + \frac{1}{4} \lambda_2 S^4 + \mu_4 S \Phi^\dagger \Phi + \frac{1}{2} \lambda_3 S^2 \Phi^\dagger \Phi. \quad (4)$$

Let $\langle \phi^0 \rangle = v$ and $\langle S \rangle = u$, then the minimum of $V$ is determined by

$$0 = v(2\mu_1^2 + 2\lambda_1 v^2 + \lambda_3 u^2 + 2\mu_4 u), \quad (5)$$
$$0 = u(\mu_2^2 + \lambda_2 u^2 + \lambda_3 v^2 + \mu_3 u) + \mu_4 v^2. \quad (6)$$

The $2 \times 2$ mass-squared matrix spanning the physical scalars $H$ and $S$ is given by

$$M^2 = \begin{pmatrix} 2\lambda_1 v^2 & \sqrt{2}(\lambda_3 u + \mu_4) v \\ \sqrt{2}(\lambda_3 u + \mu_4) v & 2\mu_2^2 u^2 + \mu_3 u - \mu_4 v^2/u \end{pmatrix}. \quad (7)$$

Let the mass eigenstates of the above be $H' = H \cos \theta - S \sin \theta$ and $S' = S \cos \theta + H \sin \theta$, with eigenvalues $m_1^2$ and $m_2^2$, then Eq. (7) may be rewritten as

$$M^2 = \begin{pmatrix} m_1^2 \cos^2 \theta + m_2^2 \sin^2 \theta & (m_2^2 - m_1^2) \sin \theta \cos \theta \\ (m_2^2 - m_1^2) \sin \theta \cos \theta & m_1^2 \sin^2 \theta + m_2^2 \cos^2 \theta \end{pmatrix}. \quad (8)$$

As an example, let $\sin \theta = 1/\sqrt{10}$, $\cos \theta = 3/\sqrt{10}$, $u = 2\sqrt{2}v = 492.4$ GeV, where $v = 174.1$ GeV, we then obtain $m_1 = 170$ GeV and $m_2 = 500$ GeV for the choice $\lambda_1 = 0.84$, $\lambda_2 = 0.47$, $\lambda_3 = 0.55$, and $\mu_3 = \mu_4 = 0$. This demonstrates the numerical viability of this proposal.

It has been assumed that $S$ couples to new colored fermions and scalars. This is of course model-dependent, but a necessary condition is to have $A_S = A(S \to gg)$ a few times larger
than $A_H = A(H \to gg)$. Now $A_H$ is dominated by the $t$ quark which is a fundamental triplet under $SU(3)_C$ and is proportional to $(\sqrt{2} v)^{-1}$. Suppose $A_S$ comes from a colored fermion octet $Q$ with the coupling $S\bar{Q}Q$, then it is proportional to $u^{-1}$ but its color factor of 3 is 6 times that of the $t$ quark. Hence for the above choice of $u = 2\sqrt{2} v$, $A_S \simeq 3 A_H$ is realized. The allowed mass term $\bar{Q}Q$ would change the details of the above, but may be forbidden by a $Z_2$ symmetry under which $S$ and $Q_L$ are odd, but $Q_R$ is even.

More realistically, $H'$ is unlikely to decouple from $gg$ entirely. In that case, the suppression (or enhancement if $\sin \theta < 0$) factor in $H'$ production at the LHC is $(\cos \theta - (A_S/A_H) \sin \theta)^2$. On the other hand, depending on the choice of new colored fermions and scalars, there is also a contribution from $A(S \to \gamma\gamma)$ to $H'$ decay. This means that the branching fraction of $H'$ to $\gamma\gamma$ would also not be the same as in the SM. If a particle is discovered at the LHC in the $\gamma\gamma$ channel below 145 GeV, but with a branching fraction different from what is expected from the SM, especially if it is greater, it may be due to this effect. The presence of the octet $Q$ may also be relevant in gauge-coupling unification [13] without supersymmetry.

In conclusion, the existence of the Higgs boson may be hidden from view at present because of a variety of scenarios, some of which have been discussed recently [14, 15, 16, 17]. In this paper, two simple ways are considered: the presence of light dark-matter scalars which affects the decay or an accidental cancellation between $A(H \to gg)$ and $A(S \to gg)$ in $H - S$ mixing which affects the production. In the latter case, an increase from the present $E_{cm} = 7$ TeV to 14 TeV at the LHC in the future would produce $S'$ easily, and the decay $S' \to H'H'$ would be a spectacular signature for discovering $H'$.

I thank Bohdan Grzadkowski and Maria Krawczyk for a stimulating “Scalars 2011” Conference in Warsaw (August 2011) which led to this work. My research is supported in part by the U. S. Department of Energy under Grant No. DE-AC02-06CH11357.
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