Minimal spontaneously broken hidden sector and its impact on Higgs boson physics at the Large Hadron Collider*

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Abstract
We have studied a hidden sector of the SM with spontaneous symmetry breaking that opens many different scenarios for Higgs physics. We have shown that this hidden sector can affect the SM Higgs detection. In some specific regimes it is still possible to detect the Higgs; in other scenarios the hidden sector would completely eclipse it.

We have performed a study based on the paper by R. Schabinger and J. D. Wells (Physical Review, D72 (2005), p. 093007).

We consider a *hidden* gauge $U(1)$ symmetry, meaning that this sector does not mix with the usual gauge groups of the Standard Model, except, maybe, with the Higgs sector. The Lagrangian under consideration for this case is

$$\mathcal{L}_{Higgs} = |D_\mu H|^2 + |D_\mu \Phi|^2 + m_H^2|H|^2 + m_\Phi^2|\Phi|^2 - \lambda|H|^4 - \rho|\Phi|^4 + \eta|H|^2|\Phi|^2 \ . \tag{1}$$

We are interested in the spontaneous symmetry breaking scenario. Therefore, we write these fields as

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} h + v + iG^0 \\ G^\pm \end{pmatrix}, \quad \Phi = \frac{1}{\sqrt{2}}(\phi + \xi + iG') \tag{2}$$

where $v(\simeq 246\,\mathrm{GeV})$ and ξ are vacuum expectation values; H and Φ are the physical fields. The G fields are Goldstone bosons absorbed by the vector bosons. By just replacing Eq. (2) into Eq. (1) we arrive at the following Lagrangian.

$$\begin{aligned} -\frac{\lambda}{4}h^4 - \frac{\rho}{4}\Phi^4 - \lambda v h^3 - \rho\psi\Phi^3 + \left[-\frac{3}{2}\lambda v^2 + \frac{m_H^2}{2} + \frac{\eta\psi^2}{4}\right]h^2 + \left[-\frac{3}{2}\rho\psi^2 + \frac{m_\Phi^2}{2} + \frac{\eta v^2}{4}\right]\Phi^2 \\ + \left[m_H^2 v - \lambda v^3 + \frac{\eta}{2}v\psi^2\right]h + \left[m_\Phi^2\psi - \rho\psi^3 + \frac{\eta}{2}\psi v^2\right]\Phi + \text{constants}\ . \end{aligned} \tag{3}$$

By looking at the $\{h, \phi\}$ sector, one can write the mass matrix that has to be diagonalized in order to obtain the mass eigenstates. This matrix is given by

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda v^2 & \eta v\xi \\ \eta v\xi & 2\rho\xi^2 \end{pmatrix} \tag{4}$$

and is diagonalized by the mixing angle

$$\tan\omega = \frac{\eta v\xi}{(\rho\xi^2 - \lambda v^2) + \sqrt{(\rho\xi^2 - \lambda v^2)^2 + \eta^2 v^2 \xi^2}} \tag{5}$$

with

$$h \ = \ \cos\omega\, s_1 + \sin\omega\, s_2 \tag{6}$$

*Work performed as a student project under the supervision of A. Zerwekh.

$$\phi \;=\; -\sin\omega\, s_1 + \cos\omega\, s_2\,. \tag{7}$$

The masses of the two eigenstates are then

$$m^2_{s_1,s_2} = (\lambda v^2 + \rho\xi^2) \pm \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \eta^2 v^2 \xi^2}\,. \tag{8}$$

We denote $\Gamma_i^{\rm SM}(m_h)$ the partial decay width of the SM Higgs into a final SM state i, $\Gamma^{\rm SM}$ the total decay width of SM Higgs, and $\Gamma^{\rm hid}(m_\phi)$ the equivalent width of the hidden Higgs. We assume that all final states of $\Gamma^{\rm hid}$ are invisible to particle detectors.

We have focused on the Higgs production via vector boson fusion ($VV \to H$). To first approximation the production cross-section is proportional to the Higgs boson partial width

$$\sigma(VV \to h)(m_h) \propto \Gamma(h \to VV)(m_h)\,. \tag{9}$$

Therefore, the production cross-section of s_1 is related to that of the SM simply by c^2_ω

$$\sigma(VV \to s_1)(m_{s_1}) = c^2_\omega \sigma(VV \to h)(m_{s_1})\,. \tag{10}$$

The branching fractions of the lighter state s_1 into a SM final state i is

$$B_i(s_1) = \frac{c^2_\omega \Gamma_i^{\rm SM}(m_{s_1})}{c^2_\omega \Gamma^{\rm SM}(m_{s_1}) + s^2_\omega \Gamma^{\rm hid}(m_{s_1})}\,. \tag{11}$$

If $\Gamma^{\rm hid}(m_{s_1}) \simeq 0$, the branching fraction would be the same as that of the SM. The overall width would be suppressed by a factor of c^2_ω.

In this case, light and narrow width Higgs bosons ($115\,\text{GeV} \lesssim m_{s_1} \lesssim 160\,\text{GeV}$) are very difficult to find at colliders. If $s_1 \to ZZ \to 4l$ is allowed, a narrow width (above the detector's invariant mass resolution) would be very helpful for the detection.

If $\Gamma^{\rm hid}(m_{s_1}) \neq 0$, the decay is predominantly into undetectable particles. The invisible branching fraction is

$$B_{\rm inv}(s_1) = \frac{s^2_\omega \Gamma^{\rm hid}(m_{s_1})}{c^2_\omega \Gamma^{\rm SM}(m_{s_1}) + s^2_\omega \Gamma^{\rm hid}(m_{s_1})}\,, \tag{12}$$

which approaches 1 when $s^2_\omega \Gamma^{\rm hid} \gg c^2_\omega \Gamma^{\rm SM}$. In this case, one has the double problem of suppressed production plus invisible decays. This scenario would lead to an invisibly decaying Higgs boson, which will be very very hard to detect at a hadron collider. A high-energy e^+e^- collider would have relatively little trouble with the invisible decay aspect.

What happens with s_2? The same formula applies, except by an obvious change in the mixing factor, and that one has to consider the new possibility of $s_2 \to s_1 s_1$ decays. Thus one has

$$B_i(m_{s_2}) = \frac{s^2_\omega \Gamma_i^{\rm SM}(m_{s_2})}{s^2_\omega \Gamma_i^{\rm SM}(m_{s_2}) + c^2_\omega \Gamma_i^{\rm SM}(m_{s_2}) + \Gamma(s_2 \to s_1 s_1)}\,, \tag{13}$$

$$B_{\rm inv}(s_2) = \frac{c^2_\omega \Gamma^{\rm hid}(m_{s_2})}{c^2_\omega \Gamma^{\rm SM}(m_{s_2}) + s^2_\omega \Gamma^{\rm hid}(m_{s_2}) + \Gamma(s_2 \to s_1 s_1)}\,, \tag{14}$$

$$\text{and } B(s_2 \to s_1 s_1) = \frac{\Gamma(s_2 \to s_1 s_1)}{c^2_\omega \Gamma^{\rm SM}(m_{s_2}) + s^2_\omega \Gamma^{\rm hid}(m_{s_2}) + \Gamma(s_2 \to s_1 s_1)}\,. \tag{15}$$

The whole phenomenology of the s_1 dectectability is determined by three parameters:

$$m_{s_1},\; s^2_\omega,\; \text{and } r_{s_1} \equiv \frac{\Gamma^{\rm hid}(m_{s_1})}{\Gamma^{\rm SM}(m_{s_1})}\,. \tag{16}$$

Two interesting observables are

a) The total rate of Higgs-mediated events at a hadron collider, such as $gg \to h \to \gamma\gamma,\ ZZ,\ WW,\ t\bar{t}, \ldots$ is related to the SM rate by

$$\frac{\sigma_i B_j}{\sigma_i^{\rm SM} B_j^{\rm SM}} = \frac{(1-s_\omega^2)^2}{1-(1-r_{s_1})s_\omega^2} \, , \tag{17}$$

where i refers to the initial state that created the Higgs boson, and j refers to the final states.

b) The total width of the s_1 Higgs boson, which determines the broadness of the reconstructed invariant mass peak, is related to the SM width by

$$\frac{\Gamma(m_{s_1})}{\Gamma^{\rm SM}(m_{s_1})} = 1-(1-r_{s_1})s_\omega^2 \, . \tag{18}$$

In Figs. 1 and 2 we plot for various values of r_{s_1} the two observables $\sigma_i B_j/(\sigma_i B_j)_{\rm SM}$ and $\Gamma/\Gamma^{\rm SM}$ In Fig. 1 we see that the rate for Higgs-boson-induced observables never exceeds that of the SM. This obviously makes detection of the s_1 Higgs boson in the standard channels much more difficult than detection of the SM Higgs boson.

In Fig. 2 we see that the width can be larger than the SM Higgs boson. Combining this with the rate supression, it implies that discovering the s_1 in the LHC is harder than in the SM case. If $r < 1$, as s_ω^2 increases, the observable rate into standard channels goes down (bad for detection) whereas the width decreases (good for detection).

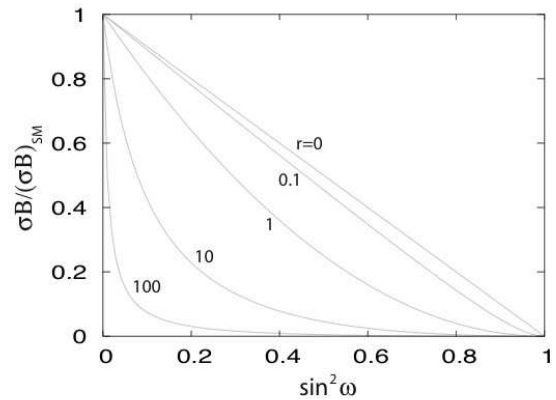

Fig. 1: The rate of $\sigma_i B_j$ relative to that of the SM for various values of r

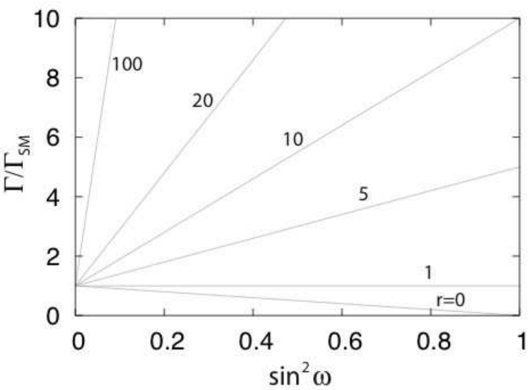

Fig. 2: The total width compared to that of the SM total width for various values of r

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