PHENOMENOLOGY FROM A U(1) GUAGED HIDDEN SECTOR*

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We consider the phenomenological consequences of a hidden Higgs sector extending the Standard Model (SM), in which the matter content are uncharged under the SM gauge groups. We consider a simple case where the hidden sector is gauged under a U(1) with one Higgs singlet. The only couplings between SM and the hidden sector are through mixings between the neutral gauge bosons of the two respective sectors, and between the Higgs bosons. We find signals testable at the LHC that can reveal the existence and shed light on the nature of such a hidden sector.

1. The shadow U(1)s model

It has been recently pointed out that hidden sectors which commonly extend the Standard Model (SM), need not be associated with a very high energy scale, and renormalizable interactions with the SM fields through mixing are possible which provide portals to new physics accessible at the Large Hadron Collider (LHC) 1.

We consider here a simple case where the hidden sector contains a single complex scalar φs gauged under the hidden sector gauge group, which we take to be a single “shadow” U(1)s. The complete Lagrangian of our model

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takes the form

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} X^\mu\nu X_{\mu\nu} - \frac{\epsilon}{2} B^\mu\nu X_{\mu\nu} + \left( \partial_\mu - \frac{1}{2} g_s X_\mu \right) \phi_s \right) - V_0(\Phi, \phi_s), \tag{1}$$

where $B^\mu\nu$ and $X^\mu\nu$ are the field strength tensors of the SM $U(1)_Y$ and $U(1)_s$, respectively, $\Phi$ is the SM Higgs field, and $g_s$ is the gauge coupling constant of the $U(1)_s$. The tree level scalar potential is given by

$$V_0(\Phi, \phi_s) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + \mu_s^2 \phi_s^* \phi_s + \lambda_s (\phi_s^* \phi_s)^2 + 2 \kappa (\Phi^\dagger \Phi) (\phi_s^* \phi_s). \tag{2}$$

The hidden sector couples to the SM only through the two mixing terms, the kinetic mixing between the two $U(1)$'s parameterized by $\epsilon$, and the mixing between the scalar fields controlled by $\kappa$.

The spontaneous symmetry breaking (SSB) of the symmetry $SU(2)_L \times U(1)_Y \times U(1)_s$ down to $U(1)_{EM}$ is triggered once the scalars acquire nonzero VEVs:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \phi_s \rangle = \frac{v_s}{\sqrt{2}}. \tag{3}$$

2. Mixing in the gauge sector

Because of the kinetic mixing term, a $GL(2)$ transformation is needed to recast the Lagrangian in Eq. (1) to canonical form, which mixes the gauge fields of the $U(1)_Y$ and $U(1)_s$:

$$\begin{pmatrix} X' \\ B' \end{pmatrix} = \begin{pmatrix} c_\epsilon & 0 \\ -s_\epsilon & 1 \end{pmatrix} \begin{pmatrix} X \\ B \end{pmatrix}, \quad s_\epsilon = \frac{\epsilon}{\sqrt{1 - \epsilon^2}}, \quad c_\epsilon = \sqrt{1 - s_\epsilon^2}. \tag{4}$$

A further mass mixing happens after SSB between the SM $Z$ and the extra “shadow” $Z_s$ bosons, with the mixing angle given by

$$\tan(2\eta) = \frac{2 s_W s_\epsilon}{c_W^2 (M_3/M_W)^2 + s_W^2 s_\epsilon^2}, \quad M_3 = \frac{g_s v_s}{2}, \tag{5}$$

where $s_W$ denotes the weak-mixing angle $\sin \theta_W$, $c_W = \sqrt{1 - s_W^2}$, and $M_W = g_W v/2$ is the $W$ mass with $g_W = e/s_W$.

These mixings modify couplings of $Z$ and introduce new ones to $Z_s$ which directly affect electroweak precision tests (EWPTs) that stringently constrain any model with extra $Z$ bosons, which in turn constrain the kinetic mixing parameter $\epsilon$. The results of a systematic study of all the currently available EWPT observables are summarized by Fig. 1. Here, $\chi_2(s_\epsilon, M_3)$ measures the deviation between the model and the experiments, and $\Delta \chi_2 = \chi - \chi_2^{SM}$ with $\chi_2^{SM} = \chi(0, M_3) = \chi_2(s_\epsilon, \infty)$.  

*aSee 2 for more details.*
As seen from Fig. 1, $\epsilon$ need not be vanishingly small as is usually assumed; it can be of order $10^{-3} \sim 10^{-2}$, in agreement with the general expectation from string theory $^3$.

3. $Z_s$ signal at the LHC

The phenomenology of the $Z_s$ is expected to be very different from scenarios where the extra $Z$ couples directly to the SM, such as in the familiar $SO(10)$ or $E_6$ based grand unified theories (GUTs) models. One immediate example is the narrowness of the $Z_s$ width. In the large $Z_s$ mass limit, say $M_{Z_s} > 1$ TeV,

$$\Gamma_{Z_s} \simeq 2.37 \frac{g_2^2 M_{Z_s} s^2}{24 \pi c_{W}^2} = 0.1742 \left( \frac{M_{Z_s}}{1 \text{ TeV}} \right) \left( \frac{s^2}{0.01} \right) \text{GeV}. \quad (6)$$

Another distinguishing feature is the $Z_s$ branching ratios, as shown in Fig. 2. The $Z_s$ decays preferentially into $u$-type quarks and charge leptons, which is very different from the SM $Z$ decay. Also for a sufficiently heavy $Z_s$, the branching ratio into charge leptons and $t$ quarks is relatively large and almost equal. This can be used to distinguish between different extra $Z$ models and may also be used as a diagnostic tool at the LHC.
Figure 2. Branching ratio for the $Z_s$ decays as functions of $M_{Z_s}$. The mass of the Higgs is taken to be $M_{h_1} = 120$ GeV. The parameter $s_\epsilon$ is set to be $10^{-3}$.

4. A classically conformal Higgs sector

Motivated by the idea that very light hidden sector scalars may be candidates for dark matter $^4$, we consider here a special case where our model is classically conformal (setting $\mu = \mu_s = 0$ in Eq. 2). The SSB is induced radiatively via Coleman-Weinberg (CW) mechanism $^5$, which naturally generates a small mass scale without further assumption or fine tuning.

Applying the perturbative multiscalar effective potential analysis of Gildener and S. Weinberg $^6$, two physical scalar states arise. One is a heavy SM-like Higgs boson, $H_2$, and the other a light “shadow” Higgs, $H_s$, whose mass arise entirely from radiative corrections and is given by

$$M^2_{H_s} = \frac{3\epsilon_r^2}{64\pi^2(1+r)} \left[ \frac{3g^4_W}{2} + \frac{g^2_Y}{2} + \frac{g^4_Y}{v_r^4} + \frac{8M^4_{Z_s}}{v_r^4} \right] + \frac{M^4_{H_2} - 12M^4_{W}}{8\pi^2v_r^2(1+r)}, \quad (7)$$

where $r = \sqrt{\lambda/\lambda_s} = 4M^2_{Z_s}/(v^2_r g^2_s)$, and $v_r = v/\sqrt{1+r} = 4M^2_{W}/g^2_s$ is fixed by the physical $W$ mass.

5. Search for the light shadow Higgs at the LHC

The Yukawa couplings of the shadow Higgs to the SM fields is simply that of the SM Higgs scaled by a factor of $1/\sqrt{1+r^2}$. Applying the bounds from the LEP direct Higgs search to the shadow Higgs case, which is most stringent at $M_{H_1} \simeq 20$ GeV $^8$, we have $\xi^2 \equiv (g_{HZZ}/g^SM_{HZZ})^2 = 1/(1+r) \lesssim 2 \times 10^{-2}$ implying that $r \gtrsim 49$. From the expression of $r$, this bound can be
easily satisfied for appropriate choices of $M_Z$ and $g_s$, and a light shadow Higgs is not ruled out.

Since the shadow Higgs couples like the SM Higgs, one way to search for it at the LHC, is to studying the $t \to H_1 b W^+$ decay just like for the SM Higgs. Suppose $M_{H_1} = 30 \text{ GeV}$, taking the top-Higgs Yukawa coupling to be $y_t \sim 1$, the decay width is

$$
\Gamma(t \to H_1 b W^+) \sim \frac{2 \times 10^{-3}}{1 + r} \text{GeV}.
$$

(8)

This is to be compared with that in the SM, $\Gamma_{t \to H_1 b W^+}^{SM} = 1.37 \text{ GeV}$. With $r \gtrsim 49$, a search for the shadow Higgs in the $t \to H_1 b W^+$ decay is likely to require the LHC to operate at high luminosity for extended periods of time.

6. Summary

Renormalizable mixing between the hidden and the SM sectors are portals through which new physics can be discovered using the LHC. One distinct signature of a hidden $U(1)$ sector is the existence of an extra $Z$ with a very narrow width. To distinguish it from that of the other extra $Z$ models, precise measurement of its branching ratios is needed, although the International Linear Collider would provide a much cleaner environment for doing so than the LHC.

In the special case where our model is classical conformal, a light shadow Higgs can be generated from the SSB of the scale-invariance through CW mechanism. It is viable under the current direct search limit, and can be searched for at the LHC in the $t \to H_1 b W^+$ decay. However, to achieve the required detection sensitivity, high luminosity runs would likely be needed.

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