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Natural electroweak symmetry breaking in generalised mirror matter models

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Abstract

It has recently been pointed out that the mirror or twin Higgs model is more technically natural than the standard model, thus alleviating the "little" hierarchy problem. In this Letter we generalise the analysis to models with an arbitrary number of isomorphic standard model sectors, and demonstrate that technical naturalness increases with the number of additional sectors. We consider two kinds of models. The first has N standard model sectors symmetric under arbitrary permutations thereof. The second has p left-chiral standard model sectors and p right-chiral or mirror standard model sectors, with p-fold permutation symmetries within both and a discrete parity transformation interchanging left and right. In both kinds of models the lightest scalar has an invisible width fraction $1/N$, which will provide an important means of experimentally testing this class of models.

1. Introduction

One simple way to explain non-baryonic dark matter is to postulate the existence of a mirror sector (for an up-to-date review, see Ref. [1]). In this theory, each type of ordinary particle (other than the graviton) has a distinct mirror partner. The ordinary and mirror particles form parallel sectors each with gauge symmetry $G_{\mathrm{SM}} \equiv SU(3)_c \otimes SU(2) \otimes U(1)_Y$, so that the overall gauge group is $G_{\mathrm{SM}} \otimes G_{\mathrm{SM}}$ [2]. The interactions of each sector are governed by a Lagrangian of exactly the same form, except with left- and right-chiral fermions interchanged. In other words, the Lagrangian has the form

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}(e_L, e_R, q_L, q_R, W_\mu, B_\mu, \ldots) + \mathcal{L}_{\mathrm{SM}}(e'_R, e'_L, q'_R, q'_L, W'_\mu, B'_\mu, \ldots) + \mathcal{L}_{\mathrm{mix}}. \tag{1}$$

There are just two renormalisable gauge invariant interactions which can couple the ordinary and mirror sectors together [2]:

$$\mathcal{L}_{\mathrm{mix}} = \epsilon F^{\mu\nu} F'_{\mu\nu} + 2\lambda \phi^\dagger \phi \phi'^\dagger \phi', \tag{2}$$

where $F^{\mu\nu} \equiv \partial^\mu B^\nu - \partial^\nu B^\mu$ [$F'^{\mu\nu} \equiv \partial^\mu B'^\nu - \partial^\nu B'^\mu$] is the $U(1)$ [mirror $U(1)$] field strength tensor and ϕ, ϕ' are the ordinary and mirror Higgs doublets. (If singlet neutrinos are added to both sectors, then mass-mixing terms like $\bar{\nu}_R \nu'_L$ are also allowed in $\mathcal{L}_{\mathrm{mix}}$.)

An interesting effect of the Higgs–mirror-Higgs mixing term (in $\mathcal{L}_{\mathrm{mix}}$) is to cause each of the two weak eigenstate Higgs fields (ϕ, ϕ') to be maximal mixtures of the mass eigenstates, h_+, h_-. Each of $h_\pm$ can be produced in colliders, but with production cross sections suppressed by a factor of $1/2$ compared to the standard model Higgs [3]. Furthermore, each mass eigenstate will decay into the mirror sector half of the time—giving another characteristic prediction of the theory [3]. The Higgs–mirror-Higgs coupling can also be reconciled with standard big bang nucleosynthesis in low reheat temperature scenarios [4].

Another interesting feature of the Higgs sector in these models is that it can [5,6] alleviate the hierarchy problem because there is a limit in which the Higgs is, in part, a pseudo-Goldstone boson [7]. This can most readily be understood if the Higgs potential is

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written in the form

$$V = -\mu^2\big(\phi^\dagger\phi + \phi'^\dagger\phi'\big) + \lambda\big(\phi^\dagger\phi + \phi'^\dagger\phi'\big)^2 + \delta\big[\big(\phi^\dagger\phi\big)^2 + \big(\phi'^\dagger\phi'\big)^2\big]. \tag{3}$$

The Higgs potential preserves a $U(4)$ symmetry in the limit $\delta \to 0$, with the ϕ, ϕ' transforming as the 4 representation of $U(4)$. There are two non-trivial vacua, depending on whether $\delta < 0$ or $\delta > 0$. The symmetric vacuum occurs for $\delta > 0$ and this is the case to be considered in this Letter.[1] In this case $\langle\phi\rangle = \langle\phi'\rangle \equiv u$, with $u^2 = \mu^2/(4\lambda + 2\delta)$.

Quadratically divergent corrections to the Higgs potential come from 1-loop top quark, gauge boson and scalar Feynman diagrams. The top quark loop corrections have the form

$$\mu^2 = \mu_0^2 + a_t\Lambda_t^2, \tag{4}$$

where μ_0^2 is the bare parameter, $a_t = 3\lambda_t^2/8\pi^2$ and $\lambda_t \sim 1$ is the top quark Yukawa coupling. The parameter Λ_t is the ultraviolet cutoff in the naive cut-off regularisation approach. The quadratic divergence in the mirror sector is of exactly the same form, *so the quadratic divergences preserve the $U(4)$ symmetry*. In the $\delta \to 0$ $U(4)$ symmetry limit, the spontaneous breaking is $U(4) \to U(3)$. This implies seven Goldstone bosons, six of which are eaten by the $W^\pm$, Z and $W'^\pm$, Z', leading to one massless Higgs boson. In other words, in the $U(4)$ symmetry limit, one of the two physical scalars becomes massless. Of course, we do not expect $U(4)$ to be an exact symmetry of the potential: It is not a symmetry of the rest of the Lagrangian, and we know from experiments that $m_{h_+}, m_{h_-} \gtrsim 114$ GeV. But it is an approximate symmetry when $\delta \lesssim \lambda$.

The hierarchy problem due to top quark loops is alleviated in the mirror model, because the correction becomes

$$\frac{\delta\mu^2(\text{top})}{\mu^2} = \frac{3\lambda_t^2}{4\pi^2}\frac{\Lambda_t^2}{m_{h_+}^2}, \tag{5}$$

which is the same formula as in the standard model except with $m_{\text{higgs}} \to m_{h_+}$. In the standard model, the bound from precision electroweak measurements is $m_{\text{higgs}} < M_{\text{EW}}$, where $M_{\text{EW}} \approx 186$ GeV (which is the 95% C.L. limit given by the Particle Data Group [9]). However, in the mirror model, this bound becomes [6]

$$m_{h_+}m_{h_-} < M_{\text{EW}}^2. \tag{6}$$

Evidently, a heavy h_+ can be compensated by a relatively light h_-. In fact the bound, Eq. (6), implies a limit of $m_{h_+} \lesssim 300$ GeV (given that $m_{h_-} \gtrsim 114$ GeV). Because of the larger m_{h_+} limit, the fine tuning in the μ^2 parameter due to top quark loops is alleviated.

Recently, the mirror matter model has been generalised to incorporate N sectors [10]. The minimal standard model corresponds to $N = 1$, the mirror model corresponds to $N = 2$, but in general there can be N sets of particles. These generalised mirror models can also be motivated by the dark matter problem and are therefore of significant interest. In this general case there are N physical scalars, one for each sector. How the Higgs physics generalises in this N-sector case is an interesting question, and the purpose of this Letter is to answer that question. We consider two physically distinct, but related models. First, we consider having the N sectors exactly identical, so that a discrete S_N (permutation symmetry of N objects) is preserved. In this case there is no exact parity symmetry. In the second case, an exact parity symmetry is required to exist, which means that there are p ordinary isomorphic sectors and p isomorphic mirror sectors (so that $N = 2p$ is necessarily even in this case). The ordinary and mirror sectors are related to each other by interchanging the left- and right-handed chiral fermions, but are otherwise identical. Both types of models alleviate the hierarchy problem in a similar way.

2. The SM generalised to N isomorphic sectors

The SM generalised to N isomorphic sectors is described by the Lagrangian

$$\mathcal{L} = \sum_{i=1}^{N} \mathcal{L}_{\text{SM}}\big(e_{iL}, e_{iR}, q_{iL}, q_{iR}, W_i^\mu, B_i^\mu, \ldots\big) + \mathcal{L}_{\text{mix}}, \tag{7}$$

where we use the integer subscripts to label the particles from the N sectors. Clearly the Lagrangian has gauge symmetry G_{SM}^N and discrete symmetry S_N. The $\mathcal{L}_{\text{mix}}$ part describes the interactions coupling ordinary and mirror particles together which are consistent with these symmetries. In general, $\mathcal{L}_{\text{mix}}$ has the form

$$\mathcal{L}_{\text{mix}} = \epsilon \sum_{k,l=1}^{N} F_k^{\mu\nu}F_{l\mu\nu} + 2\lambda \sum_{k,l=1}^{N} \phi_k^\dagger\phi_k\phi_l^\dagger\phi_l, \tag{8}$$

where $k \neq l$ in the sums and $F_i^{\mu\nu} \equiv \partial^\mu B_i^\nu - \partial^\nu B_i^\mu$.

[1] The mirror model with asymmetric vacuum ($\delta < 0$) has been studied in Ref. [8].