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Dark chiral symmetry breaking and the origin of the electroweak scale

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ABSTRACT

We study a classically scale-invariant model in which strong dynamics in a dark sector sets the scale of electroweak symmetry breaking. Our model is distinct from others of this type that have appeared in the recent literature. We show that the Higgs sector of the model is phenomenologically viable and that the spectrum of dark sector states includes a partially composite dark matter candidate.

1. Introduction

The Lagrangian of the standard model has precisely one dimensionful parameter, the squared mass of the Higgs doublet field. This mass sets the scale of electroweak symmetry breaking, which is communicated to the standard model fermions via their Yukawa couplings. The origin and stability of the hierarchy between the electroweak scale and the Planck scale have motivated many of the leading proposals for physics beyond the standard model. In this Letter, we study the phenomenology of a specific model in which the Higgs mass squared arises as a result of strong dynamics in a dark sector. Other models of this type have been discussed in the recent literature [1,2]; we explain how our model differs from those proposals below.

It is well known that the Yukawa coupling between a scalar ϕ and fermions can lead to a linear term in the scalar potential if the fermions condense. Such a term alters the potential so that the scalar develops a vacuum expectation value (vev). If the scalar squared mass term is absent, then the scale of the scalar vev is set entirely by that of the strong dynamics that produced the condensate. If these fields carry electroweak quantum numbers, then electroweak symmetry will be spontaneously broken. A simple model based on this idea was proposed by Carone and Georgi in Ref. [3]. In this Letter, we consider a similar theory in which the scalar and fermions in question do not carry electroweak charges. The vev of ϕ does not break electroweak symmetry, but provides an origin for the Higgs squared mass via the Higgs portal coupling $\lambda_p \phi^\dagger \phi H^\dagger H$. As long as λ_p has the appropriate sign, electroweak symmetry breaking is triggered at a scale set by the strong dynamics of the dark sector.

The choice of a classically scale-invariant scalar potential can be justified by various arguments. We place them in two categories:

1. *The model is tuned.* Dimensionful parameters might not assume natural values as a consequence of the probability distribution over the string landscape, which is poorly understood. If one takes this point of view, it is not unreasonable to consider extensions of the standard model that are designed to address its deficiencies (for example, extensions that provide for viable dark matter physics) that appear tuned but are parametrically simple and can be easily tested in experiment. Our model is of this type and could easily be ruled out (or supported) by upcoming dark matter searches.

2. *The model is not tuned.* If there are no physical mass scales between the weak and Planck scales, then the only possible source of a Higgs quadratic divergences is from the cut off of the theory. Although field theoretic completions to low-energy effective theories lead generically to quadratic divergences proportional to the square of the cutoff [4], this may not be the case for quantum gravitational physics at the Planck scale [5]. As argued in Ref. [6], a spacetime description itself may break down at this scale and one's intuition based on quantum field theories may be flawed. If one takes this point of view, it is not unreasonable to assume that a Higgs mass generated via dimensional transmutation in the infrared is only multiplicatively renormalized [7] and to explore the phenomenological consequences. A significant number of recent papers have adopted this perspective [1,2,8,9].

The model we propose has a dark sector $SU(2)_L \times SU(2)_R$ chiral symmetry that is spontaneously broken by a fermion condensate triggered by strong dynamics. An $SU(2)_D$ subgroup of the global symmetry is gauged, and the dark fermions have Yukawa couplings to a scalar that is a doublet under this gauge symmetry. The

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dark sector would be an electroweak neutral clone of the model in Ref. [3], except that a U(1) gauge factor is replaced by a discrete subgroup to avoid a massless dark photon. The presence of an $SU(2)_D$-doublet scalar immediately distinguishes the model from most related ones in the literature which employ a dark singlet to communicate dark sector strong dynamics through the Higgs portal [1]. We note that the model of Ref. [2] has the same dark sector global chiral symmetry as ours, but does not gauge any subgroup. This leads to a different particle spectrum and phenomenology. We also utilize a non-linear chiral Lagrangian approach, familiar from the study of technicolor and QCD, which provides a convenient framework for the systematic description of dark sector phenomenology at low energies.

Our paper is organized as follows. In the next section we define the model. In Section 3, we consider phenomenological constraints. In Section 4, we study the relic density and direct detection of the dark matter candidate in the model, which is a partially composite dark sector state. In Section 5, we present our conclusions.

2. The model

The gauge group of the model is $G_{SM} \times SU(N) \times SU(2)_D$. The first factor refers to the standard model gauge group, while the second is responsible for confinement in the dark sector. The G_{SM} singlet fields (which we will call the dark sector, henceforth) are: a complex $SU(2)_D$-doublet scalar ϕ, a left-handed $SU(2)_D$-doublet fermion $\Upsilon_L \equiv (p_L, m_L)^T$ and two right-handed singlet fermions p_R and m_R. The fermions transform in the fundamental representation of the SU(N) group. The field content is analogous to that of the technicolor model in Ref. [3] with $SU(2)_W$ replaced by $SU(2)_D$ and $U(1)_Y$ replaced by a Z_3 factor. As we will see below, the latter choice is the simplest way to preserve a convenient analogy between the two theories while also eliminating an unwanted massless gauge field. The dark sector has a global $SU(2)_L \times SU(2)_R$ chiral symmetry that is spontaneously broken when the dark fermions condense

$$\langle \bar{p}p + \bar{m}m \rangle \approx 4\pi f^3 \ , \tag{2.1}$$

where f is the dark pion decay constant. We refer to the unbroken SU(2) subgroup of the global symmetry as dark isospin. Spontaneous chiral symmetry breaking results in an isotriplet of dark pions

$$\Pi = \sum_{a=1}^{3} \pi^a \frac{\sigma^a}{2} \ , \tag{2.2}$$

where σ^a are the Pauli matrices. As in the chiral Lagrangian approach of Ref. [3], we adopt a nonlinear representation

$$\Sigma = \exp(2i\Pi/f) \ , \tag{2.3}$$

which transforms under the global chiral symmetry as $\Sigma \to L\Sigma R^\dagger$, where L and R are the transformation matrices for $SU(2)_L$ and $SU(2)_R$, respectively. It will be convenient to define the following four-by-four matrix field

$$\Phi \equiv \left(i\sigma^2\phi^* \middle| \, \phi \right) \ , \tag{2.4}$$

and the nonlinear field redefinition

$$\Phi = \frac{\sigma + f'}{\sqrt{2}} \Sigma' \tag{2.5}$$

with $\Sigma' = \exp(2i\Pi'/f')$. The kinetic terms for Φ and Σ are

$$\begin{aligned} \mathcal{L}_{KE} &= \frac{1}{2}\,\mathrm{tr}\left(D_\mu \Phi^\dagger D^\mu \Phi\right) + \frac{f^2}{4}\,\mathrm{tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \\ &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{f^2}{4}\,\mathrm{tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right) \\ &\quad + \frac{(\sigma+f')^2}{4}\,\mathrm{tr}\left(D_\mu \Sigma'^\dagger D^\mu \Sigma'\right) \ . \end{aligned} \tag{2.6}$$

Here $D_\mu = \partial_\mu - i g_D A^a_\mu \frac{\sigma^a}{2}$, where A^a_μ is the $SU(2)_D$ gauge field. Study of the terms quadratic in the fields allows one to identify an unphysical linear combination of fields Π_u that becomes the longitudinal component of A^a_μ, and an orthogonal state π_p that is physical:

$$\pi_u = \frac{f\Pi + f'\Pi'}{\sqrt{f^2 + f'^2}}, \tag{2.7}$$

$$\pi_p = \frac{-f'\Pi + f\Pi'}{\sqrt{f^2 + f'^2}}. \tag{2.8}$$

The π_p multiplet will later be identified as the dark matter candidate in the theory.

Explicit breaking of the chiral symmetry originates from the Yukawa couplings. Assuming that the fields transform under the Z_3 symmetry as

$$\Upsilon_L \to \Upsilon_L \, , \quad \phi \to \omega\phi \, , \quad p_R \to \omega p_R \, , \quad m_R \to \omega^2 m_R \, , \tag{2.9}$$

where $\omega^3 = 1$, we find that the Yukawa couplings are given as in Ref. [3] by

$$-\mathcal{L}_y = y_+ \overline{\Upsilon}_L \tilde{\phi}\, p_R + y_- \overline{\Upsilon}_L \phi\, m_R + \text{h.c.} \tag{2.10}$$

Defining $\Upsilon_R \equiv (p_R, m_R)$ and the matrix $Y \equiv \mathrm{diag}(y_+, y_-)$ this may be re-expressed as

$$-\mathcal{L}_y = \bar{\Upsilon}_L \Phi Y \Upsilon_R + \text{h.c.} \ , \tag{2.11}$$

which implies that we may treat (ΦY) as a chiral-symmetry-breaking spurion with the transformation property

$$(\Phi Y) \to L(\Phi Y)R^\dagger \ . \tag{2.12}$$

The lowest order term in the chiral Lagrangian that involves (ΦY) is

$$\mathcal{L} = c_1 4\pi f^3\, \mathrm{tr}(\Phi Y \Sigma^\dagger) + \text{h.c.} \tag{2.13}$$

where c_1 is expected to be of order unity by naive dimensional analysis [10]. This term determines the physical dark pion mass

$$m_\pi^2 = 2c_1\sqrt{2}\frac{4\pi f}{f'}(f^2 + f'^2)\, y \ , \tag{2.14}$$

where $y \equiv (y_+ + y_-)/2$, as well as a linear term in the scalar potential

$$V_y(\sigma) = -8\sqrt{2}\pi c_1 f^3 y\sigma \ . \tag{2.15}$$

This term sets the scale of the dark scalar vev, which determines the induced mass term for the standard model Higgs doublet H via a coupling in the potential $V = V_0 + V_y$, where V_0 represents the scale-invariant terms:

$$V_0(\phi, H) = \frac{\lambda}{2}(H^\dagger H)^2 - \lambda_p (H^\dagger H)(\phi^\dagger\phi) + \frac{\lambda_\phi}{2}(\phi^\dagger\phi)^2. \tag{2.16}$$

In the ultraviolet (UV), before the dark fermions have condensed, vacuum stability of Eq. (2.16) requires that

$$\lambda > 0 \quad \text{and} \quad \lambda\lambda_\phi > \lambda_p^2. \tag{2.17}$$