Holographic Dark Matter and Higgs Models

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We propose a dark matter candidate within the class of models where electroweak symmetry breaking is triggered by a light composite Higgs boson. In these dual anti–de Sitter/conformal field theory models, the Higgs boson emerges as a holographic pseudo-Goldstone boson, while dark matter can be identified with a stable composite fermion X^0. The effective Lagrangian description of the Higgs and X^0-multiplets, including higher-dimensional operators, can be tested at future colliders (LHC, ILC) and through astrophysical signals (ultrahigh-energy cosmic rays). The expected mass of X^0, $m_{X^0} \lesssim 4\pi f \simeq O\,(\text{TeV})$, satisfies the bounds extracted from the cosmological relic density, while the experimental searches for dark matter further constrains the possible models.

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Introduction.—Explaining the nature of electroweak symmetry breaking (EWSB) and dark matter (DM) have become two of the most important problems in modern elementary particle physics and cosmology today [1,2]. Within the standard model (SM), electroweak precision tests (EWPT) prefer a Higgs boson mass of the order of the electroweak scale $v \simeq 175$ GeV, which should be tested soon at the LHC [3]. Similarly, plenty of astrophysical and cosmological data requires the existence of a DM component, that accounts for about 11% of the matter-energy content of our Universe [4]. A weakly interacting massive particle (WIMP), with a mass also of the order of the EW scale, seems a most viable option for the DM. The nature of EWSB and DM and how they fit in our current understanding of elementary particles is, however, not known.

Given the similar requirements on masses and interactions for both particles, Higgs and DM, one can naturally ask whether they could share a common origin. Within the minimal supersymmetric (SUSY) SM [5], which has become one of the most popular extensions of the SM, there are several WIMP candidates (neutralino, sneutrino, gravitino) [6]. Among them, the neutralino has been most widely studied; it is a combinations of SUSY partners of the Higgs and gauge bosons, the Higgsinos and gauginos. Thus, in SUSY models the fermion-boson symmetry provides a connection between the Higgs boson and DM. However, many new models have been proposed more recently [7], which provide an alternative theoretical foundation to stabilize the Higgs mechanism. Some of these models, which were originally motivated by the studies of extra dimensions [8], include new DM candidates, such as the lightest T-odd particle within little Higgs models [9] or the lightest Kaluza-Klein (KK) particle in models with universal extra dimensions [10].

In this Letter, we are interested in searching for possible dark matter candidates, within the holographic Higgs models. Here EWSB is triggered by a light composite Higgs boson, which emerges as a pseudo-Goldstone boson [11,12]. Within this class of models, we propose that a stable composite "baryon," tightly bounded by the new strong interactions, can account for the DM. The effective Lagrangian description of both the Higgs and DM includes higher-dimensional operators suppressed by a scale Λ_i ($i = H, X$), which will induce deviations from the SM predictions for the Higgs properties. Measuring these effects at future colliders (LHC, ILC) could provide information on the DM scale. Although our DM candidate could share similar characteristics with other WIMPs, its composite nature will have important implications for cosmological bounds and the experimental searches for DM. This picture, where strong interactions produce a light pseudo-Goldstone boson and a heavier stable fermion, is not strange at all in nature. This is precisely what happens in ordinary hadron physics, where the pion and the proton play such roles. In this Letter we discuss models that produce a similar pattern for the Higgs and DM, but at a higher energy scale, and with a stable neutral state instead of a charged one. We believe that such a scenario is very attractive and unifying, and it provides further understanding of both EWSB and DM problems.

Holographic Higgs and dark matter.—The holographic Higgs models of our interest admit a dual anti–de Sitter/conformal field theory (AdS/CFT) description; however, we shall discuss its features mainly from the 4D point of view, using first a generic effective Lagrangian approach, and then presenting specific realizations within the known holographic Higgs models [11,12]. From the 4D perspective, the effective Lagrangian that describes these models [13,14] includes two sectors: (i) the SM sector that contains the gauge bosons and most of the quarks and leptons, which is characterized by a generic coupling g_{SM} (gauge or Yukawa) and (ii) a new strongly interacting sector, characterized by another coupling g_* and a scale M_R. This scale can be associated with the mass of the lowest composite resonance, which in the dual AdS/CFT picture corresponds to the lightest KK mode; in ordinary QCD M_R can be taken as the mass of the rho meson (ρ). The couplings are chosen here to satisfy $g_{SM} \lesssim g_* \lesssim 4\pi$, and as a result of the dynamics of the strongly interacting sector, a composite Higgs boson emerges. It behaves as an exactly massless Goldstone boson because of the global symmetries that hold in the limit $g_{SM} \to 0$. SM interactions then produce a deformation of the theory, and the Higgs boson becomes a pseudo-Goldstone boson. Radiative effects induce a Higgs mass, which can be written as $m_h \simeq (\frac{g_{SM}}{4\pi})M_R$.

The holographic Higgs boson is described by the effective Lagrangian: $\mathcal{L}_H = \mathcal{L}_{SM}^H + \sum \frac{\alpha_i}{(\Lambda_H)^{n-4}} O_{in}$, where $\mathcal{L}_{SM}^H$ denotes the SM Higgs Lagrangian. The next term contains higher-dimensional operators O_{in} ($n \geq 6$) that can induce corrections to the SM Higgs properties; the coefficient α_i and the scale Λ_H will depend on the nature of each operator. The leading operators are $O_W = i(H^\dagger \sigma^i D^\mu H) \times (D^\nu W_{\mu\nu})^i$, $O_B = i(H^\dagger D^\mu H)(\partial^\nu B_{\mu\nu})$, $O_{HW} = i(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$, $O_{HB} = i(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$, $O_T = i(H^\dagger D^\mu H)(H^\dagger D_\mu H)$, $O_H = i\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H)$ [13]. At the LHC it will be possible to measure the corrections to the Higgs couplings, with a precision that will translate into a bound $\Lambda_H \geq 5$–7 TeV, while at ILC it will extend up to about 30 TeV [13]. These operators can also modify the SM bounds on the Higgs mass obtained from EWPT [15]. In particular, O_T can increase the limit on the Higgs mass above 300 GeV, for $\alpha_i = O(1)$ and $\Lambda_H \simeq 1$ TeV.

Simultaneous to the Higgs appearance, a whole tower of fermionic composite states $X^0, X^\pm, X^{\pm\pm}, \ldots$ should also appear. Our dark matter candidate is identified with the lightest neutral state (X^0) within this fermionic tower, and we call it the lightest holographic fermionic particle (LHP). Similarly to what happens in ordinary QCD, where the proton is stable because of baryon number conservation, we also assume that X^0 is stable because of a new conserved quantum number, which we call "dark number" (D_N). Thus, the SM particles and the "mesonic" states, like the Higgs boson, will have zero dark number [$D_N(\text{SM}) = 0$], while the "baryonic" states like X^0, will have $+1$ dark number [$D_N(X^0) = +1$]. The formation of such "baryonic" states, including a conserved number of topological origin, has been derived recently using the Skyrmion model [16]. For a strongly interacting sector that corresponds to a deformed σ-type model, the mass of X^0 satisfies $M_{X^0} \lesssim 4\pi f$, where f is the analog of the pion decay constant, thus $m_{X^0} \simeq M_R$. In analogy with ordinary QCD, it is usually assumed that lightest resonance corresponds to a vector meson; however, X^0 itself could be the lightest state. In any case, the natural value for M_{X^0} will be in the TeV range, somehow heavier than the SUSY candidates for DM. It is important to stress that because $\Lambda_H \simeq M_R$, the EWPT analysis can be reinterpreted as an indirect method to obtain constraints on the dark matter scale.

Holographic dark matter models.—There are several alternatives to accommodate our proposed LHP candidate, within the holographic Higgs models proposed thus far [11], and it is one of the purposes of our work to identify the most favorable models. From the 4D perspective, each model is defined by imposing a global symmetry G on the new strongly interacting sector, then a subgroup H of G will be gauged; here we shall consider the case when the SM group is gauged, i.e., $H = SU(2)_L \times U(1)_Y$. Furthermore, in order to fix the LHP quantum numbers, one needs to specify a particular representation (G-multiplet) that will contain it. Then, this G-multiplet can be decomposed in terms of an H-multiplet plus some extra states. We call *active DM* those cases when the LHP belongs to the H-multiplet, while *sterile DM* will be used for models where the LHP is a SM singlet.

Let us consider first the models based on the group $G = SU(3) \times U(1)_X$ [11]. $U(1)_X$ is needed in order to get the correct SM hypercharges. Under $SU(3) \times U(1)_X$ the SM doublets (Q) and d-type singlets (D) are included in $SU(3)$ triplets, i.e., $Q \equiv \mathbf{3}^*_{1/3}$, $D \equiv \mathbf{3}_0$. The SM up-type singlet (U) is defined as a TeV-brane singlet field, i.e., $U \equiv \mathbf{1}_{1/3}$. The hypercharge is obtained from $Y = \frac{T_8}{\sqrt{3}} + X$, while the electric charge arises from $Q_{em} = T_3 + Y$, and $T_{3,8}$ denote the diagonal generators of $SU(3)$. Then, admitting only the lowest dimensional $SU(3)$ representations (triplets and singlets), one can obtain the electrically neutral LHP by requiring $X = \pm 1/3, \pm 2/3$. Thus, for an $SU(3)$ antitriplet with $X = 1/3$, $\Psi_1 = (N_1^0, C_1^+, N_2^0)^T$, there are two options for the LHP. (i) Model 1 (active): the LHP belongs to a SM doublet $\psi_1 = (N_1^0, C_1^+)$, i.e., $X^0 = N_1^0$. (ii) Model 2 (sterile): the LHP is a SM singlet, i.e., $X^0 = N_2^0$. A similar pattern is obtained for $X = -1/3$. Choosing instead a $SU(3)$ triplet with $X = \pm 2/3$, i.e., $\Psi_2 = (N_3^0, C_2^+, C_3^+)^T$, only allows the LHP to be $X^0 = N_3^0$ (model 3). Allowing the inclusion of $SU(3)$ octets leads to the possibility of having LHP candidates that belong to SM triplets with $Y = 0, \pm 1$ (models 4, 5). This classification of active and sterile holographic $G = SU(3)$ DM models is summarized in Table I.

On the other hand, LHP candidates can also arise within the minimal composite Higgs model (MCHM) with global symmetry $G = SO(5) \times U(1)_X$ [17], which has better agreement with EWPT [18]. The SM hypercharge is defined now by $Y = X + T_3^R$, where T_3^R denotes the R isospin obtained from the breaking chain: $SO(5) \times U(1)_X \to SO(4) \times U(1)_X \to SU(2)_L \times U(1)_Y$, and with $SO(4) \simeq SU(2)_L \times SU(2)_R$. In the model MCHM$_5$, the SM quarks and leptons are accommodated in the fundamental representations (5) of $SO(5)$, while in the option named MCHM$_{10}$, the SM matter is grouped in the antisymmetric (10-dimensional) representation of $SO(5)$. For the DM candidates one can use either of these possibilities. DM models using the 5 of $SO(5)$ can accommodate the LHP in SM doublets or singlets, similar to the pattern obtained for

TABLE I. LHP candidates within the $SU(3) \times U(1)_X$ holographic Higgs models

$U(1)_X$	G-multiplets	H-multiplets	LHP models
$+\frac{1}{3}$	$\mathbf{3}^*$: $\Psi_1 = (N_1^0, C_1^+, N_2^0)^T$	$\mathbf{2}^*$: $\psi_1 = (N_1^0, C_1^+)^T$	(1) $X^0 = N_1^0$ (active) (2) $X^0 = N_2^0$ (sterile)
$+\frac{2}{3}$	$\mathbf{3}^*$: $\Psi_2 = (N_3^0, C_2^+, C_3^+)^T$	$\mathbf{2}^*$: $\psi_2 = (N_3^0, C_2^+)^T$	(3) $X^0 = N_3^0$ (active)
0	$\mathbf{8}$: Ψ_3 = full octet mult.	$\mathbf{3(Y=0)}$: $\psi_3 = (C_4^+, N_4^0, C_5^-)^T$	(4) $X^0 = N_4^0$ (active)
1	$\mathbf{8}$: Ψ_4 = full octet mult.	$\mathbf{3(Y=1)}$: $\psi_4 = (C_1^{++}, C_6^+, N_5^0)^T$	(5) $X^0 = N_5^0$ (active)

the $SU(3)$ models. On the other hand, in models that employ the 10 representation of $SO(5)$, the LHP can also appear in SM triplets. For instance, taking $X = 0$ allows X^0 to fit in a $Y = 0$ triplet, while the option $X = \pm 1$ offers the possibility of having a LHP within a $Y = \pm 1$ triplet. Thus, a broad spectrum of possible holographic DM candidates appearing in more elaborate models is already included in the classification shown in Table I.

The renormalizable interactions of X^0 with the SM are fixed by its quantum numbers, while the complete effective Lagrangian includes higher-dimensional operators; namely,

$$\mathcal{L}_{\rm DM} = \bar{X}^0(\gamma^\mu D_\mu - M_X)X^0 + \sum \frac{\alpha_i}{(\Lambda_X)^{n-4}} O_{in}, \quad (1)$$

where $D_\mu = \partial_\mu - i g_x T^i W_\mu^i - g_x' \frac{Y}{2} B_\mu$. For those operators that describe composite effects, one expects that $\Lambda_X \simeq f$, while for operators that result from the integration of the G partners of X^0, one expects $\Lambda_X \simeq M_R > M_X$. Similarly, the coupling α_X should be of order $O(1)$ ($b_i/16\pi^2$) for operators induced at tree (loop) level.

Holographic dark matter constraints.—We are interested in constraining the LHP models, using both cosmology (relic density) and the experimental searches for DM. We shall consider the three types of models shown in Table I: (i) active LHP models with $Y \neq 0$, (ii) active LHP models with $Y = 0$, and (iii) sterile LHP models. Let us discuss first the active LHP models. The corresponding relic density can be written in terms of the thermal averaged cross section $\langle\sigma v\rangle$ as follows:

$$\Omega_X h^2 = \frac{2.57 \times 10^{-10}}{\langle\sigma v\rangle} = \frac{2.57 \times 10^{-10} M_X^2}{C_{T,Y}}, \quad (2)$$

where $C_{T,Y}$ depends on the isospin (T) and hypercharge (Y) of the LHP. Numerical values of $C_{T,Y}$ for the lowest-dimensional representations are $C_{1/2,1/2} = 0.004$, $C_{1,0} = 0.01$, $C_{1,1} = 0.011$. Then, in order to have agreement with current data, i.e., $\Omega_X h^2 = 0.11 \pm 0.066$ [19], models 1, 3 require $M_X = 1.3$ TeV, while models 4 (5) require $M_X = 2.1$ ($M_X = 2.2$) TeV, respectively. It is quite remarkable that these values are precisely of the right order expected in the strongly interacting Higgs model.

In order to discuss the relic density constraint for the sterile LHP DM (model 2), we notice that the couplings of X^0 with the SM gauge and Higgs bosons, come from the higher-dimensional operators, which include (i) 4-fermion operators, $O_{FX}^1 = \frac{1}{2}(\bar{F}\gamma^\mu F)(\bar{X}\gamma_\mu X)$, $O_{fX}^1 = \frac{1}{2}(\bar{f}\gamma^\mu f) \times (\bar{X}\gamma_\mu X)$, $O_{FX}^V = \frac{1}{2}(\bar{F}\gamma^\mu X)(\bar{X}\gamma_\mu F)$, $O_{fX}^V = \frac{1}{2}(\bar{f}\gamma^\mu X) \times (\bar{X}\gamma_\mu f)$, $O_{FX}^S = \frac{1}{2}(\bar{F}X)(\bar{X}F)$, $O_{fX}^S = \frac{1}{2}(\bar{f}X)(\bar{X}f)$, (ii) fermion-scalar operator, $O_{X\phi} = (\Phi^\dagger\Phi)(\bar{X}X)$, and (iii) fermion-vector-scalar operator, $O_{DX} = (\Phi^\dagger D^\mu \Phi) \times (\bar{X}\gamma_\mu X)$, where $F(f)$ denote the SM fermion doublet (singlet). The full analysis should include all these operators, which depends on many parameters; however, to obtain a simplified estimate, we shall only consider the operator O_{DX}. This operator induces an effective vertex ZX^0X^0 of the form $\Gamma_{ZXX} = \frac{g}{2c_W}\eta\gamma^\mu$, with $\eta = 2c_x g c_w v^2/M_R^2$, and c_x being the coefficient of O_{DX}. Then, requiring $\Omega_X h^2 \simeq \Omega_{\rm DM} h^2 = 0.11 \pm 0.006$ [19] implies $M_X \simeq 0.8\eta$ TeV. Thus, for M_X of order TeV, one would need to have $\eta \geq 1$, which could be satisfied in some region of parameter space, although one usually expects $\eta \leq 1$ within a strongly interacting scenario.

Constraints on the LHP models can also be derived from the direct experimental search for DM, such as the one based on the nucleon-LHP elastic scattering [20]. The corresponding cross section can be expressed as $\sigma_{T,Y} = \frac{G_F^2}{2\pi} f_N Y^2$, where f_N depends on the type of nucleus used in the reaction. As was discussed in Ref. [21], vectorlike dark matter with $Y = 1$ is severely constrained by the direct searches, unless its coupling with the Z boson is suppressed with respect to the SM strength. A suppression of this type can be realized in a natural manner for holographic DM models. Namely, following Ref. [14], we notice that by admitting a mixing between the composite LHP and a set of elementary fields with the same quantum numbers, the vertex ZXX will be suppressed by the mixing angles needed to go from the weak- to the mass-eigenstate basis. For model 1, with active DM appearing in a doublet $\psi_1 = (N_1^0, C_1^+)^T$, one includes an elementary copy of these fields, which then allows one to write the vertex ZXX as $\Gamma_{ZXX} = \frac{\eta' g_2}{2c_W}\gamma^\mu$, with $\eta' < 1$. The cross section for DM + $N \rightarrow$ DM + N can be written then as $\sigma = \frac{G_F^2}{2\pi} f_N \eta'^2$. Agreement with current bounds [20] requires one to have $|\eta'|^2 \leq 10^{-2}$–10^{-4}, which seems reasonable. On the other hand, DM with $Y = 0$ automatically satisfies this bound, i.e., $\sigma(Y = 0) = 0$. While for sterile dark matter, the corresponding nucleon-LHP cross section satisfies the current limits [20], provided that the factor η also satisfies $|\eta|^2 \leq 10^{-2}$–10^{-4}, which is in contradiction with the bound derived from the cosmological relic density, i.e., $\eta \geq 1$; therefore, we find that the sterile dark matter candidate (model 2) seems disfavored.

Conclusions.—We have proposed new DM candidates (LHP) within the context of strongly interacting holographic Higgs models. LHP candidates are identified as composite fermionic states (X^0), with a mass of order $m_{X^0} \lesssim 4\pi f$, which is made stable by assuming the existence of a conserved "dark" quantum number. This scenario can be justified using the Skyrme model, as shown recently in [16]. Thus, we suggest that there exists a connection between two of the most important problems in particles physics and cosmology: EWSB and DM. In these models, the Higgs couplings receive potentially large corrections, which could be tested at the coming (LHC) and future (ILC) colliders. Measuring these deviations could also provide information on the dark matter scale. In particular, LHC (ILC) could provide a bound $\Lambda_H \simeq 5$–7 ($\simeq 30$) TeV. Such a DM signal, with O (TeV) masses, should be correlated with the observation of its charged $G-$ partners ($X^\pm$) at the LHC (similar to the "custodians" discussed in Ref. [18]). A list of some of the models that can appear within the $SU(3) \times U(1)_X$ holographic Higgs model are shown in Table I; models based on the group $SO(5) \times U(1)_X$ are also contained in that list.

We have verified that the LHP relic abundance is satisfied for masses of O (TeV), which is the range expected in holographic Higgs models. Furthermore, the current bounds on experimental searches for DM based on LHP-nucleon scattering provide further constraints on the possible models. In particular, models with sterile dark matter seem excluded by recent data from the CDMS Collaboration [20]. Although models with $Y \neq 0$ are less favored, we have identified a possible mechanism within the holographic approach, which can help to improve their consistency. Overall, we conclude that most favorable models are the active ones with $Y = 0$, such as model 4 of Table I. Additional astrophysical signals from these models can be discussed along similar lines. For instance, the annihilation into photon pairs, i.e., $XX \rightarrow \gamma\gamma$, will receive contributions from SM and effective interactions, which could enhance the signal. We can also identify a mechanism by which the LHP DM can be converted into ultrahigh-energy cosmic rays (UHECR). Namely, it is possible that at places with large concentrations of DM, such as the galactic centers, the LHP annihilate into charged pairs, i.e., $X^0X^0 \rightarrow X^+X^-$. Then, the charged partners of $X^0, X^\pm$ would be accelerated up to very high energies by action of the strong electromagnetic fields, which are suspected to exist in the active galactic nuclei, especially if a charged, rotating black hole exists there. Thus, the $X^\pm$ decay products will contribute to the spectrum of UHECR, and its direction will show the correlations suggested by the recent observations of the AUGER Collaboration [22].

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