Holographic Dark Matter and Higgs

J. Lorenzo Díaz-Cruz

Fac. de Cs. Físico-Matemáticas, BUAP,
Apdo. Postal 1364, Puebla, Pue., C.P. 72000, México,
and Dual CP Institute of High Energy Physics

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We identify possible dark matter candidates within the class of strongly interacting models where electroweak symmetry breaking is triggered by a light composite Higgs boson. In these models, the Higgs boson emerges as a Holographic pseudo-goldstone boson, while dark matter can be identified as a fermionic composite state \( X^0 \), which is made stable through a conserved (“dark”) quantum number. An effective lagrangian description of both the Higgs and dark matter is proposed, that includes higher-dimensional operators suppressed by an scale \( \Lambda_i \). These operators will induce deviations from the standard Higgs properties that could be measured at future colliders (LHC,ILC), and thus provide information on the dark matter scale. The dark matter \( X^0 \), is expected to have a mass of order \( m_{X^0} \lesssim 4\pi f \simeq O(\text{TeV}) \), which is in agreement with the values extracted from the cosmological bounds and the experimental searches for dark matter.

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*Electronic address: jldiaz@fcfm.buap.mx
1.- 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 prefer the existence of a light Higgs boson, with a mass of order of the electroweak (EW) scale \(v \simeq 175\) GeV, that should be tested soon at the LHC \([3]\). Similarly, plenty of astrophysical and cosmological data points towards the existence of a dark matter component, that accounts for about 12% of the matter-energy content of our universe \([4]\). A weakly-interacting massive particle (WIMP) with a mass of the order of the EW scale, seems a most viable option for the dark matter. What is the nature of EWSB and dark matter, and how do 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 SUSY SM (MSSM) \([5]\), 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 combination of the so called Higgsinos and gauginos, which are the SUSY partners of the Higgs and gauge bosons. Thus, in the SUSY case, the fermion-boson symmetry provides the connection between EWSB and Dark Matter. However, many new models have been proposed more recently \([7]\), which provide alternative theoretical foundation to stabilize the Higgs mechanism. Some of these new models assume that EWSB originates in a new strongly interacting sector, and have been originally motivated by the studies of extra dimensions \([8]\). In some of them, candidates for dark matter have been proposed, such as the lightest T-odd particle (LTP) within little Higgs models \([9]\) or the lightest KK particle (LKP) in models with universal extra-dimensions \([10]\).

In this letter, we are interested in searching for possible dark matter candidates, within the so called Holographic Higgs models \([11]\). Here, EWSB is triggered by a light composite Higgs boson, which emerges as a pseudo-goldstone boson. Within this class of strongly interacting models, we shall propose that a stable composite “Baryon”, can account for the dark matter. This particle can be made stable by imposing a conserved (Dark) quantum number, and it will be denoted as the lightest Holographic fermionic particle \((LHP)\). The effective lagrangian description of both the Higgs and dark matter, includes higher-dimensional operators suppressed by an scale \(\Lambda_i (i = H, X)\), which will induce deviations
from the SM predictions for the Higgs properties. Thus, measuring these effects at future colliders (LHC, ILC), could also provide information on the dark matter scale. Furthermore, it is likely that because of compositeness, the Higgs boson will be heavier than in the SM case, as it can be derived from EW precision tests. Having SM interactions, the LHP will share similar characteristics with other WIMP candidates, however the composite nature of $X^0$ will also have important implications for cosmological bounds and the experimental searches for dark matter.

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, namely they appear as two- and three-quark bound states, formed by the action of the strong QCD interaction. In this paper we shall propose models that produce a similar pattern for the Higgs and dark matter, but at a higher energy scale, and with a stable neutral state instead of a charged one. We believe that such scenario is very attractive and unifying, and it could provide further understanding of both EWSB and DM problems. Although we shall formulate our ideas using a generic effective lagrangian approach, we shall also discuss specific models within the known Holographic Higgs models [11].

2.- Holographic Higgs and Dark Matter. We are thus interested in looking for a dark matter candidate, within the context of strongly interacting models that produce a light composite Higgs boson. Although these models admit a dual AdS/CFT description, we shall discuss its main features from the 4D point of view, ocasionally relaying on the corresponding 5D description to clarify some issues. From the 4D perspective, these models are formulated through an effective lagrangian [12, 13], that 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 an scale $M_R$. This scale can be associated with the mass of the lowest composite resonance, which corresponds to the lightest KK resonance in the dual 5D Ads description; in ordinary QCD it is the mass of the rho meson ($\rho$). The couplings are choosen to satisfy $g_{sm} \lesssim g_* \lesssim 4\pi$. As a result of the dynamics and global symmetries of the strongly interacting sector, a composite Higgs boson emerges as an exactly massless goldstone boson in the limit $g_{sm} \rightarrow 0$. SM interactions then produce a deformation of the theory, and the Higgs boson becomes massive. Thus, radiative effects
induce a Higgs mass, which can be written as: \( m_h \simeq \left( \frac{g_{sm}}{4\pi} \right) M_R \).

Like the Higgs, we propose that dark matter arises as a composite states from the strongly interacting sector; in fact, a whole tower of fermionic states \( X^0, X^\pm, X^\pm, \pm, \ldots \) should appear. Similarly to what happens in ordinary QCD, where the proton is stable because of Baryon number conservation, we shall also assume that the lightest Holographic fermionic particle (LHP) \( X^0 \) will be stable because a new conserved quantum number, that we call “Dark Number” \( (D_N) \). Thus, the SM particles and the “Mesonic” states, like the Higgs boson, will have zero Dark number \( (D_N(SM) = 0) \), while the “baryonic” states like \( X^0 \), will have +1 dark number \( (D_N(X^0) = +1) \). For a deformed \( \sigma \) type model of the strongly interacting sector, one can use NDA to derive a bound on the mass of \( X^0 \), namely \( m_{X^0} \lesssim 4\pi f \), where \( f \) is the analogue of the pion decay constant. It is usually assumed that lightest resonance of the Holographic theory, corresponds to a vectorial resonance, in analogy with ordinary QCD. However, because we lack a detailed quantitative understanding of the strongly interacting theory, we admit the possibility that \( X^0 \) corresponds to the lightest state. Thus, the natural value for \( M_{X^0} \) will be in the TeV range, somehow heavier than the SUSY candidates for dark matter.

The properties of the Holographic Higgs boson can be described in terms of the following effective lagrangian:

\[
\mathcal{L}_H = \mathcal{L}^H_{sm} + \sum \frac{\alpha_i}{(\Lambda_i)^{n-4}} O_{in}
\]

where \( \mathcal{L}^H_{sm} \) denotes the SM Higgs lagrangian. The next term contains higher-dimensional operators \( O_{in} \) \( (n \geq 6) \), that can induce deviations from the SM for the Higgs properties. The coefficient \( \alpha_i \) will depend on gauge/Yukawa couplings, mixing angles and possible loop factor, while the scale \( \Lambda_i \) could be either \( f \) or \( M_R \), depending on the nature of each operator. Examples of such operators include: \( O_W = i(H^\dagger i\sigma^i D^\mu H)(D^\nu W_{\mu\nu})^i \), \( O_B = i(H^\dagger \sigma^i D^\mu H)(\partial^\nu B_{\mu\nu}) \), \( O_{HW} = i(D^\mu H)^i\sigma^i(D^\nu H)W_{\mu\nu}^i \), \( O_{HB} = i(D^\mu H)^i(D^\nu H)B_{\mu\nu}^i \), \( O_T = i(H^\dagger D^\mu H)(H^\dagger D_{\mu} H) \), \( O_H = i\partial^\mu (H^\dagger H)\partial^\mu (H^\dagger H) \), as discussed in ref. [12]. These operators have been studied in the past for the most general effective lagrangian extension of the SM, and they can induce, for instance, modifications to the SM bounds on the Higgs mass obtained from EW precision tests (EWPT) [15]. In particular, the operator \( O_T \) can help to increase the limit on the Higgs mass above 300 GeV, for relatively natural values of parameters, i.e. with \( \alpha_i = O(1) \) and \( \Lambda_H \simeq 1 \) TeV. Furthermore, at LHC it will be possible to measure the corrections to
the Higgs couplings induced by those operators, with a precision that will translate into bounds on the scale $M_R$ of the order 5-7 TeV, while at ILC this range will extend up to about 30 TeV \cite{12}. It is important to stress that such analysis would be re-interpreted as an alternative method to derive indirect constraints on the DM scale.

3.- **Holographic Dark Matter models.** Our proposed dark matter candidate ($LHP$) can arise in any of the Holographic Higgs models proposed so far; we shall argue that it is a generic feature of this class of strongly interacting theories \cite{11}. However, its specific realization will depend on the particular model under consideration, which will fix the quantum numbers of the LHP. In this paper, we shall consider the simplest possibilities for the LHP, within the models discussed in \cite{11,14}. From the 4D perspective, each model is defined by imposing a global symmetry $G$ on the strongly interacting sector, of which only the SM subgroup $H = SU(2) \times U(1)$ will be gauged. Thus, the DM model will be defined by specifying a $G$-multiplet, which is composed of an $H$-multiplet that has SM gauge interactions, plus some extra singlets. 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 that can be constructed with $G = SU(3) \times U(1)_X$. The extra $U(1)_X$ is needed in order to get the correct assignment for SM hypercharges. Under $SU(3) \times U(1)_X$ the SM doublets and d-type singlets are included in $SU(3)$ triplets, namely: the SM quark doublet appears in: $Q \simeq 3^*_{1/3}$, while the d-type singlet is contained in: $D \simeq 3_0$. The SM up-type singlet is contained in a TeV-brane field that transforms as a singlet: $U \simeq 1_{1/3}$. The SM hypercharge for the fermions is obtained from the relation: $Y = T_8 \sqrt{3} + X$, while the electric charge arises from the usual relation: $Q_{em} = T_3 + \frac{Y}{2}$. The additional composite fermions (“Baryons”), which shall contain the LHP, must also appear in complete multiplets of $SU(3)$, in order to keep under control their radiative contributions to the Higgs mass \cite{16}. Furthermore, admitting only the lowest dimensional representations under $SU(3)$ (triplets and singlets) to accomodate an electrically neutral LHP candidate, requires: $X = \pm 1/3, \pm 2/3$, which admit SM singlets and doublets. A classification of the corresponding active and sterile Holographic dark matter models is listed in Table 1. It includes, for instance, the case of an $SU(3)$ anti-triplet with $X = 1/3$, which can be written as: $\Psi = (N_1^0, C_1^+, N_2^0)^T$. Therefore, we can have two options for the LHP: i) Model 1 (active) where the LHP is part of the SM doublet $\psi = (N_1^0, C_1^+)$, i.e. $X^0 = N_1^0$, similar to a heavy neutrino, and ii) Model 2 (sterile) where the LHP is a SM singlet, i.e. $X^0 = N_2^0$. In this case
$X^0$ does not have SM couplings at tree-level, but they could appear through the inclusion of higher-dimensional operators. Allowing the inclusions of SU(3) octets leads to the possibility of having also SM triplets with $Y = 0$ (model 7). On the other hand, when one considers the Higgs model with $G = SO(5) \times U(1)_X$ [16], there is number of other posibilities for the quantum numbers of the $G$– and $H$–multiplets. In particular, one could have a DM neutral state belonging to SM Doublet, SM triplet, SM singlet, etc. A detailed study of these DM option will be carried in a forthcoming publication [17]. Here we shall only determine the viability of the $SU(3)$ models listed in table 1.

The couplings of $X^0$ with the SM sector will include both renormalizable and effective interactions. The renormalizable interactions will be fixed by the quantum numbers of $X^0$, while the effective lagrangian will include higher-dimensional operators, which would represent both the effects from the integration of heavy fermions that belong to the $G$–multiplet, as well as the composite nature of LHP. Thus, we write the full lagrangian for DM as follows:

$$\mathcal{L}_{DM} = X^0 (\gamma^\mu D_\mu - M_X) X^0 + \sum \frac{\alpha_i}{(A_i)^{n-4}} O_{in}$$

where $D_\mu = \partial_\mu - ig_\mu T^i W^i_\mu - g'_\mu Y B_\mu$. For the case with $Y = 0$, we have $g_\mu (g'_\mu) = g_2 (g_1)$, while for $Y = 1$ it can be a different story, as it will be discussed next.

4.- Holographic Dark Matter constraints. We would like to discuss possible effects from the dark matter LHP, including its composite nature. Namely, we are interested in studying how to constrain the effective lagrangian (2), using both cosmology and the experimental searches for DM. Three cases of models shown in table 1 will be analyzed here. Namely: i) Active LHP models with $Y \neq 0$, ii) Active LHP models with $Y = 0$, and iii)
Sterile LHP models. We shall discuss first the calculation for the relic density of DM. After including the interaction with SM gauge bosons, the result for the relic density calculation can be written in terms of the thermal averaged cross-section $\langle \sigma v \rangle$ as:

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

where the constant $C_{T,Y}$ depends on the isospin (T) and hypercharge (Y) of the LHP candidate. Numerical values for $C_{T,Y}$ for the lowest-dimensional representations are: $C_{1/2,1/2} = 0.004$, $C_{1,0} = 0.01$ In order to have agreement with current data on relic DM density, i.e. $\Omega_X h^2 = 0.11 \pm 0.066$ [18], model 1 requires $M_X = 1.3$ TeV, while model 7 requires $M_X = 2.1$ TeV. It is quite remarkable that these are precisely the right mass values expected in the strongly interacting theory!

Constraints on the LHP candidates can also be derived from the interpretation of experimental searches for dark matter signals. We shall discuss here the direct search for DM based on the nucleon-LHP scattering [19]. Again, we can calculate the cross-section for this reaction, taking into account the LHP interactions with SM fields. We find that the cross section can be expressed as: $\sigma_{T,Y} = \frac{G_F^2 f_N Y^2}{2 \pi}$, where $f_N$ is a factor that depends on the type of nucleus used in the reaction. As it was discussed in ref. [20], vector-like dark matter with $Y = 1$ is severely constrained by the direct search, 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 dark matter models. For this, we follow ref. [13], and admit a possible mixing between the composite LHP and some elementary fields having the same SM quantum numbers. Then, the vertex $ZXX$ will be suppressed by the mixing angles needed to go from the weak eigenstates to the physical mass eigenstates. To discuss an specific model, we shall consider model 1 from Table 1, i.e. the active DM appears in a doublet $\psi_1 = (N_1^0, C_1^+)$. Including the elementary copy of these fields, allows to suppress the vertex $ZXX$, which can be written as: $\Gamma_{ZXX} = \frac{G_F^2}{2\pi} f_N Y^2$, with $\eta < 1$ taking into account the mixing between the elementary and composite sectors. In this case the cross-section for $DM + N \rightarrow DM + N$ can be written as: $\sigma = \frac{G_F^2}{2\pi} f_N \eta^2$. Then, agreement with current bounds [19] requires to have $|\eta| \leq 10^{-4}$, which in turn translates into a bound $\Lambda_i > 10$ TeV.

Finally, we discuss the sterile LHP case, considering the model 2. In this case, the couplings of the LHP with SM fields, only appear through higher-dimensional operators.
The whole tower of dim-6 operators, includes, for instance, the following operator:

\[ O_6 = \frac{ic_x}{f^2} (H \bar{D}_\mu H) \bar{X} \gamma^\mu X \]  

(4)

where \( D_\mu \) denotes the SM covariant derivative, with \( c_x \) parametrizing the strength of this contribution; this operator will induce the vertex \( ZX^0 X^0 \). Including the effect from those operators that do not modify the Lorentz vectorial structure of the vertex \( ZX^0 X^0 \), allows us to write it as: \( \Gamma_{ZX^0 X^0} = \frac{g}{2c_w} \gamma^\mu \), with \( \eta' \) being a parameter that measures the strength of those new effects associated with the whole tower of such operators; if only the operator (3) is included we have: \( \eta' = 2c_x g_c w^2 / f^2 \). Then, requiring \( \Omega h^2 \simeq \Omega_{DM} h^2 = 0.11 \pm 0.006 \) [18], one obtains a constraint of order: \( \eta' \simeq O(0.1) \). On the other hand, we find that the corresponding cross section for nucleon-LHP scattering is suppressed enough to satisfy the experimental limits [19].

Other experimental searches can be discussed similarly, such as the annihilation into photon pairs, i.e. \( XX \rightarrow \gamma \gamma \). Even more exotic signatures of this model, can be obtained by considering the extra particles appearing in the G-multiplets, i.e. we can look for effects from the G- or H-partners of the LHP. Within the Holographic \( SU(3) \) model 1, the LHP appears in a weak doublet, with an extra charged state \( X^- \). Because of EWPT, in particular their contribution to the \( \rho \) parameter, the masses of both particles \( X^0 \) and \( X^- \) should not differ by much. Thus, it should be possible to produce pairs \( X^- X^+ \) at the LHC, which will decay predominantly into \( X^\pm \rightarrow W^\pm + X^0 \). Furthermore, in a strongly interacting theory there should be resonances of these states, which could be searched at LHC too. Turning now to Astrophysical signals, we could imagine that \( X^- \) and other resonances, could be produced at places with high concentrations of dark matter, where we would observe high-energy activity. Good candidates for such places, are the AGN. The high-energy signals arising from the decays of \( X^- \) into \( X^0 + W^- \), would lead to the prediction of cosmic rays with energies in the multi-TeV range. An extensive discussion of these searches, including the whole tower of dim-6 operators, will be presented in an extended version of this letter [17].

5.- Conclusions. We have proposed new dark matter candidates, within the context of strongly interacting Holographic Higgs models. These 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. 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 boson couplings receive potentially large corrections, which could be tested at the coming (LHC) and future colliders (ILC). Measuring these deviations from SM predictions, will not only constrain the Higgs properties, but it could also provide information on the dark matter scale. In particular, LHC could provide indirect evidence of dark matter for masses of order 5-7 TeV, while ILC will be able to reach masses of order 30 TeV. A correlated dark matter signal with these masses should be also observed at LHC. A list of some of the models that can appear within the $SU(3)$ Holographic Higgs model are shown in table 1.

We have verified that the calculation of the LHP relic abundance, including the corrections to its couplings, satisfies the astrophysical observations. Furthermore, the current bounds on dark matter experimental searches, such as those based on LHP-nucleon scattering, provides stringent constraints on the parameters of the model. We conclude that most favorable models are the sterile ones with $Y = 0$, like model 7 of table 1. Although models with $Y \neq 0$ are less favored, we identified a possible mechanisms within the Holographic approach, which can help to improve their consistency. Additional astrophysical signals from these models, can be discussed too; for instance, one can look for the production of excited states or the G- or H-partners of $X^{-}$, which could produce TeV-scale High energy cosmic rays that could be searched in future experiments[21].

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