Composite Higgs models, Dark Matter and $\Lambda$

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Abstract. We suggest that dark matter can be identified with a stable composite fermion $X^0$, that arises within the holographic AdS/CFT models, where the Higgs boson emerges as a composite pseudo-goldstone boson. The predicted properties of $X^0$ satisfies the cosmological bounds, with $m_{X^0} \sim 4\pi f \simeq O(\text{TeV})$. Thus, through a deeper understanding of the mechanism of electroweak symmetry breaking, a resolution of the Dark Matter enigma is found. Furthermore, by proposing a discrete structure of the Higgs vacuum, one can get a distinct approach to the cosmological constant problem.

Keywords: Electroweak symmetry breaking, Higgs models, dark matter

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INTRODUCTION

The notion of spontaneous symmetry breaking (SSB) [1] has been an important ingredient for the development of modern particle physics, with applications that range from the description of chiral symmetry breaking in the strong interactions [2], to the generation of masses in the electroweak model [3, 4], including as well the development of inflationary models [5]. However, the effective description of the Higgs mechanism still lacks a fundamental understanding. Thus, explaining the nature of electroweak symmetry breaking (EWSB) is one of the most important questions in particle physics today. Within the standard model (SM), electroweak precision tests (EWPT) prefer a Higgs boson mass of the order of the electroweak (EW) scale $v \simeq 175 \text{ GeV}$ [6]. Plenty of phenomenological studies have provided us with an understanding of the expected properties of the Higgs boson (mass, decay rates and production cross sections), which should be tested soon at the LHC.

On the other hand, from the cosmology side, there are also big problems, one of them being the enigma of dark matter (DM) [7]. Plenty of astrophysical and cosmological data requires the existence of a DM component, that accounts for about 10-20% of the matter-energy content of our universe [8]. 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. What is the nature of DM and how does it fit into our current understanding of elementary particles, is however not known.

Given the similar requirements on masses and interactions for both particles, Higgs boson and DM, one can naturally ask whether they could share a common origin. Within the minimal SUSY SM [9], which has become one of the most popular extensions of the SM, there are several WIMP candidates (neutralino, sneutrino, gravitino) [10]. 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 [11], which provide alternative theoretical foundation to stabilize the Higgs mechanism. Some of these models, which have been originally motivated by the studies of extra dimensions [12], include new DM candidates, such as the lightest T-odd particle (LTP) within little Higgs models [13] or the lightest KK particle (LKP) in models with universal extra-dimensions [14].

Here, we summarize the results of our search for possible dark matter candidates, within the Holographic Higgs models [15]. In these constructions, EWSB is triggered by a light composite Higgs boson, which emerges as a pseudo-goldstone boson [16, 17]. Within this class of models, we propose that a stable composite “Baryon”, tightly bounded by the new strong interactions, can account for the 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 paper we shall 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.

However, even if the Higgs bosons is found at the LHC, and even if one could identify the Dark matter candidate, there will be some issues left open. One of them, probably the most difficult one, is the cosmological constant problem. Namely, we would like to understand why the Higgs vacuum does not produce the large curvature that one would expect with naive estimates. Many efforts have been devoted to this problem, but so far no solution has been found. This issue would probably need an understanding of the structure of space-time [18].

Here, we also present our discrete model of the Higgs vacuum [19], which departs from the usual continuum model. Namely we shall assume that the Higgs vacuum has a structure, and it consists of small size regions (droplets) where the vacuum expectation value is different from zero, while in the true empty regions it vanishes. For simplicity we shall consider that these regions form spherical droplets, and it will be shown that this model allows to solve the cosmological constant problem, for a certain relation between the density and size of the spherical droplets. The model is not distinguishable from the SM at the energies of current accelerators, however interesting deviations can be expected to occur at the coming LHC or higher energies.

**HOLOGRAPHIC HIGGS MODELS AND DARK MATTER**

The Holographic Higgs models of our interest, admit a dual 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 [16, 17]. From the 4D perspective, the effective lagrangian that describes these models [20, 21], 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 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 ($\rho$). The couplings are chosen here to satisfy $g_{sm} \sim g_\ast \sim 4\pi$, 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: $m_h \sim (g_{sm}/\pi)M_R$.

Simultaneous to the Higgs appearance, a whole tower of fermionic composite states $X^0, X^\pm, X^{\pm\pm}...$ 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 for short). 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, that we call “Dark Number” ($D_N$). Thus, the SM particles and the “Mesonic” states, like the Higgs boson, will have zero stable because a new conserved quantum number, that we call “Dark Number” ($D_N$). The formation of such “baryonic” states, including a conserved number of topological origin, has been derived recently using the Skyrmion model in the RS geometry [22]. For a strongly interacting sector that corresponds to a deformed $\sigma$ type model, the mass of $X^0$ satisfies: $M_{X^0} \sim 4\pi f$, where $f$ is the analogue 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 $\Lambda_H \simeq M_R$, then the EWPT analysis can be reinterpreted as an indirect method to obtain constraints on the dark matter scale.

There are several alternatives to accommodate our proposed LHP candidate, within the Holographic Higgs models proposed so far [16], 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 $G = SU(3) \times U(1)_X$ [16]. $U(1)_X$ 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. $Q \equiv 3^*_1/3, D \equiv 3_0$. The SM up-type singlet ($U$) is defined as a TeV-brane singlet field, i.e. $U \equiv 1_{1/3}$. The hypercharge is obtained from: $Y = \frac{T_3}{\sqrt{3}} + X$, 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 $X = 1/3$: $\Psi_1 = (N^0_1, C^+_1, N^0_2)^T$, there are two options for the LHP: i) Model 1 (active): the LHP belongs to a SM doublet $\psi_1 = (N^0_1, C^+_1)$, i.e. $X^0 = N^0_1$, and ii) Model 2...
(sterile): the LHP is a SM singlet, i.e. $X^0 = N^0_2$. Similar pattern is obtained for $X = -1/3$. Choosing instead a $SU(3)$ triplet with $X = \pm 2/3$, i.e. $\Psi_2 = (N^0_3, C^+_3, C^+_3)^T$, only allows the LHP to be $X^0 = N^0_3$ (Model 3). Allowing the inclusions 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).

On the other hand, LHP candidates can also arise within the minimal composite Higgs model (MCHM) with global symmetry $G = SO(5) \times U(1)_X$ [23], which incorporates a custodial symmetry. The SM hypercharge is defined now by $Y = X + T^R_3$, where $T^R_3$ denotes the R-isospin obtained from the breaking chain: $SO(5) \times U(1)_X \rightarrow SO(4) \times U(1)_X \rightarrow SU(2)_L \times U(1)_Y$, 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 accomodate the LHP in SM doublets or singlets, similar to the pattern obtained for 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 an LHP within a $Y = \pm 1$ triplet.

The effective lagrangian description of both the Higgs and DM, is given by:

$$\mathcal{L}_H = \mathcal{L}^H_{sm} + \mathcal{L}_{DM} + \sum \frac{\alpha_i}{(\Lambda_H)^{n-4}} O_{in},$$

(1)

where $\mathcal{L}^H_{sm}$ denotes the SM Higgs lagrangian. The higher-dimensional operators $O_{in}$ ($n \geq 6$) can induce corrections to the SM Higgs properties; measuring these effects at future colliders (LHC, ILC), could provide information on the DM scale. The coefficient $\alpha_i$ and the scale $\Lambda_H$ will depend on the nature of each operator. The leading operators are: $O_W = i(H^\dagger D^\mu H)(D^\nu W_{\mu\nu})^i$, $O_B = i(H^\dagger D^\mu H)(\partial^\nu B_{\mu\nu})$, $O_{HW} = i(D^\mu H)^\dagger \sigma^\nu(D^\nu H) W_{\mu\nu}^i$, $O_{HH} = i(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}^i$, $O_T = i(H^\dagger D^\mu H)(H^\dagger D^\nu H)$, $O_H = i\partial^\mu (H^\dagger H) \partial^\nu (H^\dagger H)$ [20]. At 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 [20]. These operators can also modify the SM bounds on the Higgs mass obtained from EWPT. In particular, $O_T$ can increase the limit on the Higgs mass above 300 GeV, for $\alpha_i = O(1)$ and $\Lambda_H \approx 1$ TeV.

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:

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

(2)

where $D_\mu = \partial_\mu - i g_T T^i W^i_\mu - g_T g_Y B_\mu$. 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 $\alpha_X$ should be of order $O(1)$ ($b_i/16\pi^2$) for operators induced at tree- (loop-) level.

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:
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:

\[
\Omega_{X}h^{2} = \frac{2.57 \times 10^{-10}}{\langle \sigma v \rangle} = \frac{2.57 \times 10^{-10}M_{X}^{2}}{C_{T,Y}}
\]

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. \( \Omega_{X}h^{2} = 0.11 \pm 0.066 \) \([24]\), models 1,3 require \( M_{X} = 1.3 \) TeV, while model 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: \( O_{1}^{4} = \frac{1}{2}(\bar{f}Y_{\mu}F)(\bar{X}Y_{\mu}X) \), \( O_{1}^{4} = \frac{1}{2}(\bar{f}Y_{\mu}F)(\bar{X}Y_{\mu}X) \), \( O_{1}^{4} = \frac{1}{2}(\bar{F}Y_{\mu}F)(\bar{X}Y_{\mu}X) \), \( O_{1}^{4} = \frac{1}{2}(\bar{F}Y_{\mu}F)(\bar{X}Y_{\mu}X) \), ii) fermion-scalar operator: \( O_{X\Phi} = (\Phi^{\dagger}\Phi)(\bar{X}X) \), and iii) Fermion-vector-scalar operator: \( O_{DX} = (\Phi^{\dagger}D^{\mu}\Phi)(\bar{X}Y_{\mu}X) \). 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 \( ZX^{0}X^{0} \) of the form: \( \Gamma_{ZX\Phi} = \frac{\eta_{\mu}}{2\sqrt{w}} \), with \( \eta = 2c_{b}g_{s}w^{2}/M_{R}^{2} \), and \( c_{b} \) being the coefficient of \( O_{DX} \). Then, requiring \( \Omega_{X}h^{2} \simeq \Omega_{DM}h^{2} = 0.11 \pm 0.006 \) \([24]\), 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 \([25]\). 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 it was discussed in ref. \([26]\), vector-like 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. \([21]\), we notice that by admitting a mixing between the composite LHP and a set of elementary fields with the same quantum numbers, then the vertex \( ZX\Phi \) 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, \( |\psi_{1} = (\eta_{0},C_{1}^{+})^{T} \), one includes an elementary copy of these fields, which then allows to write the vertex \( ZX\Phi \) as: \( \Gamma_{ZX\Phi} = \frac{\eta_{\mu}}{2\sqrt{w}} \), with \( \eta' < 0 \). 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 \([25]\) requires 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 [25], provided that
the factor $\eta$ 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.

A DISCRETE MODEL OF THE HIGGS VACUUM

Our presentation of the Higgs mechanism starts by considering an scalar field that
interacts with gauge bosons and fermions. The lagrangian for the scalar and gauge
sectors is written as:

$$\mathcal{L} = (D^\mu \Phi)^\dagger D_\mu \Phi - V(\Phi)$$

where the covariant derivative is given by: $D_\mu \Phi = (\partial_\mu - ig T^a \mathcal{V}_\mu^a) \Phi$, and $T^a$ are the gen-
erators for the representation that $\Phi$ belongs to. The Higgs potential takes the “Sombrero
Mexicano” form, which has a minimum at a value of the Higgs field $< \Phi >= v$, which
is assumed to occur everywhere.

As we discussed in our paper [19], the continuum Higgs v.e.v. will be replaced by
a distribution, i.e. we shall assume that the Higgs v.e.v. is different from zero only
in some small regions (droplets), elsewhere the v.e.v. will be zero. Thus, we take the
view that the Higgs vacuum is really a Bose condensate. Such condensates have been
studied in condensed matter, where certain compounds are made of certain atoms, e.g.
Helium, that favor the emergence of such phenomena. Therefore, one could be tempted
to extrapolate that such “molecular” or “atomic” structures should also exist in order to
explain the true nature of the Higgs mechanism. In this paper, we shall consider that this
may be a possibility, but will leave open the possibility that our “droplets” are indeed
those “atoms” or a “molecule” or a larger collection of such atoms, which will define a
hierarchy of scales.

If the vacuum energy (v.e.v.) were spread continuously, it would contribute to the
cosmological constant, with a value of the order $\Lambda \sim 10^9$ GeV$^4 = 10^{49}$ GeV/cm$^3$.
However if the droplets, of finite size $r_d$ and inter-distance $l_d$, are distributed uniformly
with a density $\rho_d$, then their contribution to the cosmological constant would be $\Lambda = \rho_d v \tau_d$, where the volume of the droplets is given by $\tau_d \approx r^3_d$. Thus, by saturating the
observed value for the cosmological constant ($\approx 10^{-4}$ GeV/cm$^3$), we obtain $\rho_d \tau_d \approx 10^{-56}$. Furthermore, by considering that the distance between the droplets should be
smaller than the shortest distance being tested at current colliders, i.e. $l_d \leq 10^{-15}$ cm,
then the resulting size of the droplets is of the order of the Planck length, i.e. $r_d \approx 10^{-33}$ cm.

One may wonder why current experiments have not detected the structure of the Higgs
vacuum. The reason is that current probes (photons, electrons, protons) have an energy or
momentum that corresponds to a wave-length that is large than the distance between the
spheres with v.e.v. different from zero. Thus, with current probes the vacuum “looks”
continuum. However, one one gets an energy that is if the order of the inverse of the
distance between the spheres, the vacuum will start to show its structure.

In order to identify possible test of our model that can be carried at the LHC, we shall
focus on Higgs phenomenology. Let us consider the standard Higgs interaction with a
fermion $\psi$, which is described by the Yukawa lagrangian. After SSB we get the mass of the fermion and its interaction with the Higgs. However, this will be valid only at low energies, but at high-energies the fermion will “see” less v.e.v., therefore the coupling will be not be given just by the fermion mass, but rather we need to include an energy-dependent factor for the vertex and the mass:

$$\mathcal{L}_{\text{new}} = x(q^2) \frac{m}{v} h \bar{\psi}_L \gamma_5 \psi_R + m(q^2) \bar{\psi}_L \psi_R + h.c. \quad (5)$$

These effect can be probed at the LHC by looking at the Higgs production. For instance we can study the gluon fusion production, which depends on the Higgs coupling with the top. Now the cross-section needs to include the form factor $x(q^2)$, which will affect the shape of the $p_T$ distributions. At lower momenta the result will be similar to the SM, but at higher momenta, we will observe a deviation from the SM result.

**CONCLUSIONS**

We have proposed a 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 $m_{X^0} \sim 4\pi f$, 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 couplings receive potentially large corrections, which could be tested at the coming (LHC) and future colliders (ILC). Measuring these deviations, could also provide information on the dark matter scale. We have verified that the LHP relic abundance is satisfied for masses of $O(\text{TeV})$, which is the range expected in Holographic Higgs models. Furthermore, the current bounds on experimental searches for DM based on LHP-nucleon scattering, provides further constraints on the possible models. Overall, we conclude that most favorable models are the active ones with $Y = 0$. It could be interesting to compare our model with other approaches tha predict a composite dark matter candidate [28].

Here, we have also presented a model of the Higgs vacuum, which assumes that the Higgs vacuum has an structure, it consists of small size regions where the vacuum expectation value is different from zero, while in the true empty regions it vanishes. For simplicity we shall consider that these regions form spherical droplets, and it will be shown that this model allows to solve the cosmological constant problem, for a certain relation between the density and size of the sherical droplets. The model is not distinguishable from the SM at the energies of current accelerators, however interesting deviations can be expected to occur at the coming LHC or at higher energies.

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