ON THE POSSIBLE LINKS BETWEEN ELECTROWEAK SYMMETRY BREAKING AND DARK MATTER

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The mechanism behind electroweak symmetry breaking (EWSB) and the nature of dark matter (DM) are currently very important issues in particle physics. Usually, in most models, these two issues are not or poorly connected. However, since a natural dark matter candidate is a weakly interacting massive particle or WIMP, with mass around the electroweak scale, it is clearly of interest to investigate the possibility that DM and EWSB are closely related. In the context of a very simple extension of the Standard Model, the Inert Doublet Model, we show that dark matter could play a crucial role in the breaking of the electroweak symmetry. In this model, dark matter is the lightest component of an inert scalar doublet which can induce dynamically electroweak symmetry breaking at one loop level. Moreover, in a large fraction of the parameter space of this model, the mass of the dark matter particle is essentially determined by the electroweak scale, so that the fact that the WIMP DM mass is around the electroweak scale is not a coincidence.

1 Introduction

If one think about what kind of new physics the Large Hadron Collider could observe, beside elucidating the origin of electroweak symmetry breaking, which is the first goal of this accelerator, there are at least 2 issues which come directly to mind. The first one is the physics which would cure the hierarchy problem(s) related to the scalar sector of the theory. The second one is the particle at the origin of the dark matter in the universe. The reason why one might observe the DM particle at LHC is not as clear at all as for the physics at the origin of EWSB, but it is at least what we expect in the most straightforward explanation for the relic DM density of the universe, which is the WIMP mechanism. If the DM relic density of the universe is due to the

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simple freeze out of the pair annihilation of a stable thermal particle, and if the annihilation cross section is driven by gauge couplings (or more generally couplings of order unity), the DM mass which is e.g. necessary to have the right relic density as observed in the universe ($\Omega_{DM} \simeq 0.22$ [2,3]) turns out to be around the electroweak scale. This leads to a coincidence problem since what sets the DM mass is the observed DM relic density which a priori has nothing to do with the electroweak scale. In most models it is a coincidence.[b] In this talk we consider the following two questions curiously not often considered. First could it be not a coincidence due to some deep reason? Second, if the DM particle is around the electroweak scale, could it play a direct role in the dynamic of EWSB? In the following, focusing on these phenomenological issues of DM and EWSB, we consider an extremely simple model, the inert Higgs doublet model, which shows that DM could have indeed a crucial role in EWSB and that the WIMP scale coincidence above might not be accidental.

2 The inert Higgs doublet model

The model we consider is extremely simple.[4–9] It is based on only 2 assumptions. First it assumes the existence of a second Brout-Englert-Higgs (Higgs for short) doublet, H_2. Second it assumes a discrete symmetry, the simplest one is a Z_2 symmetry, such that all SM particles are even under it, except the second Higgs doublet. To assume such a discrete symmetry has several virtues. It automatically leads to no flavor changing neutral current problems which in more general 2 Higgs doublet model are generic. Moreover if the Z_2 symmetry is not spontaneously broken, which is the case for large fractions of the scalar potential parameters, it leads to a stable DM candidate in the form of the lightest H_2 component. The doublet $H_2 \equiv (H^+ \, (H_0 + iA_0)/\sqrt{2})^T$, since it is complex, has four components, 2 charged, $H^\pm$, one neutral scalar, H_0, and one neutral pseudoscalar, A_0.

The most general scalar potential one can write contains 2 mass and five quartic terms:

$$\begin{aligned} V &= \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 \\ &\quad + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right] \end{aligned} \tag{1}$$

with real quartic couplings. After $SU(2) \times U(1)$ symmetry breaking, from the vacuum expectation value of H_1, $\langle H_1 \rangle = v/\sqrt{2}$ with $v = -\mu_1^2/\lambda_1 = 246$ GeV, we get the following mass spectrum

$$\begin{aligned} m_h^2 &= \mu_1^2 + 3\lambda_1 v^2 \equiv -2\mu_1^2 = 2\lambda_1 v^2 \\ m_{H^+}^2 &= \mu_2^2 + \lambda_3 v^2/2 \\ m_{H_0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5)v^2/2 \\ m_{A_0}^2 &= \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5)v^2/2. \end{aligned} \tag{2}$$

with h the Higgs boson from H_1. To have a dark stable particle, i.e. neutral, H_0 or A_0, we therefore need $\lambda_L \equiv \lambda_3 + \lambda_4 + \lambda_5 < \lambda_3$ and/or $\lambda_S \equiv \lambda_3 + \lambda_4 - \lambda_5 < \lambda_3$.

The DM properties of this model have been studied in a series of papers which show that this model is perfectly viable and moreover testable. There are 4 types of processes which drive the relic density:[8] annihilation to a pair of gauge bosons, to a pair of Higgs boson, to a pair of fermion via a Higgs boson, and coannihilation to a fermion pair of the DM particle with the other neutral H_2 component via a Z boson or with $H^\pm$ via a $W^\pm$. The cross sections are exactly the same for H_0 and A_0 so that both DM candidates are equally good. Annihilations

[b] For example in the MSSM neutralino scenario there is no direct link between these 2 scales, due to the μ problem. There exists however models where such link exists as in the NMSSM.

to a pair of gauge bosons tend to be too fast to give the right relic density, except in 2 mass regimes. A low mass regime where the DM mass is below the W and Z mass thresholds; it requires [8,6] $40\,\mathrm{GeV} < m_{DM} < 75$ GeV (in this case the relic density is determined by the 2 processes with light fermions in the final state). And a high mass regime [8] (also possible because asymptotically, for large DM mass, the annihilation to a pair of gauge bosons drops as $1/m_{DM}^2$); it requires $600\,\mathrm{GeV} \lesssim m_{DM} \lesssim 100$ TeV.

For direct detection the main process is elastic scattering of DM with a nucleon via a Higgs boson. For the low mass regime most of the parameter space cannot be probed by present experiments but will be by the future ones, see [8,6]. Similarly in this regime, and for usual Navarro-Frank-White DM galactic density profile, most of the parameter space will be covered by the GLAST satellite experiment, see [8,9]. This model is therefore testable. The high mass regime, on the other hand, leads to more suppressed rates.

3 Electroweak Symmetry Breaking induced by Dark Matter

Although EWSB can be perfectly induced in the SM by the scalar potential of the Higgs boson without the need of any additional particle, the inert Higgs doublet model offers the possibility to have a dynamical origin for the EWSB. It provides an example of DM model where due to the fact that DM is around the electroweak scale, it can easily have an important role for EWSB, by driving it at one loop through the Coleman-Weinberg mechanism.[10,11] Consider a regime where μ_1^2 would be positive, vanishing or more generally much less negative than its ordinary value in the SM $-\lambda v^2$. In this case there is no or very little EWSB at tree level. There is not either EWSB at one loop in the SM. This is due to the well-known fact that the one loop effective potential is dominated in the SM by the top loops which have the wrong sign for EWSB. These loops can lead to a potential with an extremum in v but only to a maximum, i.e. they destabilize the Higgs vacuum. However in the inert Higgs doublet model the situation is totally different. There are additional scalar loops involving H_2. Neglecting gauge bosons loops as well as fermion loops other than top ones, using the $\overline{MS}$ prescription, we get the following effective Higgs potential

$$V_{\text{eff}}(h) = \mu_1^2 \frac{h^2}{2} + \lambda_1 \frac{h^4}{4} + \frac{1}{64\pi^2} \sum_i n_i m_i^4 \big(ln \frac{m_i^2}{\mu^2} - 3/2\big) \tag{3}$$

where $n_i = \{1, 1, 1, 1, 2, 2, -12\}$ is the number of degrees of freedom for each species $i = \{h, H_0,$ $G_0, A_0, h^\pm, H^\pm, t\}$ which couples to the Higgs boson with tree level masses given in Eq. (2), $m_{G_0}^2 = m_{h^\pm}^2 = \mu_1^2 + \lambda_1 v^2$, $m_t^2 = g_t^2 v^2/2$ (with G_0, $G^\pm$, the 3 would-be Goldstone bosons in H_1 and g_t the top Yukawa coupling). Since they are scalar loops, the H_2 loops have the right sign, i.e. they restabilize the potential and can lead to a minimum in v, so that EWSB is driven by the DM inert Higgs doublet. Imposing that the effective potential has an extremum in $v = 246$ GeV, the Higgs mass at one-loop is given by

$$\begin{aligned} M_h^2 \;\; &= \;\; \frac{d^2 V_{\text{eff}}}{dh^2} = m_h^2 + \frac{1}{32\pi^2} \Big[6\lambda_1 f(m_h^2) + \lambda_L f(m_{H_0}^2) + 2\lambda_1 f(m_{G_0}^2) + \;\lambda_S f(m_{A_0}^2) \\ &+ \;\; 4\lambda_1 f(m_{h^+}^2) + 2\lambda_3 f(m_{H^+}^2) + 36\lambda_1^2 h^2 \log \frac{m_h^2}{\mu^2} + \lambda_L^2 h^2 \log \frac{m_{H_0}^2}{\mu^2} \\ &+ \;\; 4\lambda_1^2 h^2 \log \frac{m_{G_0}^2}{\mu^2} + \lambda_S^2 h^2 \log \frac{m_{A_0}^2}{\mu^2} + 8\lambda_1^2 h^2 \log \frac{m_{h^+}^2}{\mu^2} + 2\lambda_3^2 h^2 \log \frac{m_{H^+}^2}{\mu^2} \\ &- \;\; 36 g_t^2 h^2 f(m_t^2) - 12 g_t^4 h^2 \Big] \Big|_{\langle h \rangle = v} \end{aligned} \tag{4}$$

with $f(m^2) = m^2(\log(m^2/\mu^2) - 1)$.

Since H_2 has no vacuum expectation value, there is no mixing between the scalars and it is straightforward to compute the contribution of one-loop corrections to the mass of the other scalars from the second derivative of the effective potential around the Higgs *vev*. This still requires to keep track of the dependence of the propagators on h, H_0, A_0 and $H^\pm$ though. The fact that there is no mixing also means that the extremum is necessarily a minimum if all masses are positive. The result is

$$\begin{aligned} M_{H_0}^2 &\equiv \frac{\partial^2 V_{\text{eff}}}{\partial H_0^2} = m_{H_0}^2 + \frac{1}{32\pi^2}\Big[\lambda_L f(m_h^2) + 6\lambda_2 f(m_{H_0}^2) \\ &+ \lambda_S f(m_{G_0}^2) + 2\lambda_2 f(m_{A_0}^2) + 2\lambda_3 f(m_{h^+}^2) + 4\lambda_2 f(m_{H^+}^2) \\ &- 2\lambda_L^2 v^2 g(m_h^2, m_{H_0}^2) - 2\lambda_5^2 v^2 g(m_{G_0}^2, m_{A_0}^2) - (\lambda_4+\lambda_5)^2 v^2 g(m_{h^+}^2, m_{H^+}^2)\Big]\Big|_{\langle h\rangle = v} \\ M_{A_0}^2 &\equiv \frac{\partial^2 V_{\text{eff}}}{\partial A_0^2} = m_{A_0}^2 + \frac{1}{32\pi^2}\Big[\lambda_S f(m_h^2) + 2\lambda_2 f(m_{H_0}^2) \\ &+ \lambda_L f(m_{G_0}^2) + 6\lambda_2 f(m_{A_0}^2) + 2\lambda_3 f(m_{h^+}^2) + 4\lambda_2 f(m_{H^+}^2) \\ &- 2\lambda_S^2 v^2 g(m_h^2, m_{A_0}^2) - 2\lambda_5^2 v^2 g(m_{G_0}^2, m_{H_0}^2) - (\lambda_4-\lambda_5)^2 v^2 g(m_{h^+}^2, m_{H^+}^2)\Big]\Big|_{\langle h\rangle = v} \\ M_{H^\pm}^2 &\equiv \frac{\partial^2 V_{\text{eff}}}{\partial H^+ \partial H^-} = m_{H^\pm}^2 + \frac{1}{32\pi^2}\Big[\lambda_3 f(m_h^2) + 2\lambda_2 f(m_{H_0}^2) + \lambda_3 f(m_{G_0}^2) \\ &+ 2\lambda_2 f(m_{A_0}^2) + 2(\lambda_3+\lambda_4) f(m_{h^+}^2) + 8\lambda_2 f(m_{H^+}^2) - \frac{1}{2}(\lambda_4+\lambda_5)^2 v^2 g(m_{h^+}^2, m_{H_0}^2) \\ &- 2\lambda_3^2 v^2 g(m_h^2, m_{H^+}^2) - \frac{1}{2}(\lambda_4-\lambda_5)^2 v^2 g(m_{h^+}^2, m_{A_0}^2)\Big]\Big|_{\langle h\rangle = v}. \end{aligned}$$

with $g(m_1^2, m_2^2) = [f(m_1^2) - f(m_2^2)]/(m_2^2 - m_1^2)$.

4 Constraints

In order that this dynamical mechanism of EWSB, driven by the DM doublet, does work, there are essentially 3 constraints:

1) <u>EWSB</u>. The general strategy is simple. The contribution of at least some of the loops with H_2 particles must be large enough to compensate the large, negative, contribution of the top quark. This requires that at least one of the λ_{3-5} couplings must be large and positive. This will inevitably drive some of the scalar particle masses in the few hundred GeV range. Imagine that EWSB is driven by loop corrections of $H^\pm$ and A_0, with $\lambda_3 \simeq \lambda_S$. In this case the $\lambda_{3,S}$ contribution is relevant with respect to the top loop one provided $\lambda_{3,S} \gtrsim 2g_t^2$. Asking that their contribution is large enough for the Higgs mass to be above $\sim$ 115 GeV requires $\lambda_{3,S} \gtrsim 5g_t^2$, approximately, i.e. fairly large but still perturbative quartic couplings. This gives $M_{H^\pm,A_0} \gtrsim 380$ GeV.

2) <u>DM mass</u>. Calculating the H_0 relic density using the one loop induced coupling $\lambda_L^{eff} = \frac{1}{v}\partial^3 V_{eff}/\partial h \partial^2 H_0 \equiv \frac{1}{v}\partial M_{H_0}^2/\partial v$, the low mass regime turns out to be still perfectly viable. Since at least one of the components of the inert Higgs doublet must be very heavy to break the electroweak symmetry while, in this case, the DM candidate must be lighter than M_W, this leads to large mass splittings between at least 2 of the inert Higgs components.

As for the large DM mass regime, it can be shown that it can work only for less phenomenologically interesting special cases. In the following we will consider only the low mass regime.

3) <u>Electroweak precision measurements</u>. The most important constraints on the model from electroweak precision measurements comes from the ρ parameter or equivalently the Peskin-Takeuchi T parameter.[3] A doublet with large mass splitting gives a contribution

$$\Delta T = \frac{1}{32\pi^2 \alpha v^2}\left[f(M_{H^\pm}, M_{H_0}) + f(M_{H^\pm}, M_{A_0}) - f(M_{A_0}, M_{H_0})\right] \tag{5}$$

	λ_1	λ_2	λ_3	λ_4	λ_5	M_h	M_{H_0}	M_{A_0}	$M_{H^\pm}$	h_{BR}	W_{BR}
I	-0.11	0	5.4	-2.8	-2.8	120	12	405	405	100%	0%
I	-0.11	-2	5.4	-2.7	-2.7	120	43	395	395	100%	0%
I	-0.11	-3	5.4	-2.6	-2.6	120	72	390	390	94%	6 %
I	-0.30	0	7.6	-4.1	-4.1	180	12	495	495	100%	0 %
I	-0.30	-2.5	7.6	-3.8	-3.8	180	64	470	470	100%	0 %
II	-0.29	-5	-0.07	5.5	-5.53	150	54	535	63	0%	100 %

Table 1: Instances of parameters with WMAP DM abundance. Also given are the relative contribution of Higgs mediated annihilation (h_{BR}) and gauge processes (W_{BR}).

with $f(m_1, m_2) = (m_1^2 + m_2^2)/2 - m_1^2 m_2^2/(m_1^2 - m_2^2)\ln(m_1^2/m_2^2)$.[6] To give an idea of what is going on, the contribution from $M_{H^\pm} \sim 450$ GeV and $M_{DM} \sim 75$ GeV tree level masses gives $\Delta T \sim 1$, while electroweak precision measurements impose $|\Delta T| \lesssim 0.2$. There is however a nice and painless cure to this problem: as a quick inspection of Eq. (5) reveals, if either H_0 or A_0 is degenerate with $H^\pm$, the contribution of the inert doublet to the ΔT parameter vanishes identically. Physically, this is due to the existence of a custodial symmetry in the limit $M_{H^\pm} = M_{A_0}$ or $M_{H^\pm} = M_{H_0}$ (i.e. $\lambda_4 = \pm\lambda_5$). Technically, an exact or approximate custodial symmetry does not only avoid large corrections to the T parameter. It also implies that it is no fine tuning to take, for instance, the DM particle to be much lighter than the other components of the inert doublet (i.e. λ_L or λ_S much different from the other quartic couplings) as required by the EWSB and DM constraints.

From the three constraints above, we can now consider four cases, see the numerical examples of Table 1. Case I corresponds to a light H_0 and to two heavy, nearly degenerate A_0 and $H^\pm$ (*i.e.* $m_{H_0} << m_{A_0} \simeq m_{H^+}$ or $\lambda_L << \lambda_S \simeq \lambda_3$). Case II has a reversed hierarchy, *i.e.* $m_{H_0} \lesssim m_{H^+} << m_{A_0}$ or $\lambda_L \lesssim \lambda_3 << \lambda_S$). The two last corresponds to A_0 as the DM candidate, with $m_{A_0} << m_{H_0} \simeq m_{H^+}$ (case III) and $m_{A_0} \lesssim m_{H^+} << m_{H_0}$ (case IV). Cases III and IV can be obtained from cases I and II simply by switching H_0 with A_0. This leaves the relic density unchanged, so that Table 1 is relevant for these cases too.

All the examples of Table 1 have a DM abundance in agreement with WMAP data. As announced, we observe that some of the quartic couplings must be large. Also, in all the working cases the DM mass is below M_W. In Case I (similarly case III), the DM abundance is determined by its annihilation through the Higgs particle only and thus depends on M_h and the effective trilinear hH_0H_0 coupling, *i.e.* λ_L^{eff} above. For various, albeit large, couplings we found the correct abundance for DM masses in the range $M_{H_0} \sim (10-72)$ GeV. Below this range, the Higgs mediated annihilation is too suppressed. For this calculation the one-loop contribution to λ_L^{eff} is important in some cases. In case II (resp. case IV) coannihilation through the W^+ can play a role if the $H^+ - H_0$ (resp. $H^+ - A_0$) splitting is not too large. Notice that the masses of $H^\pm$ quoted in Table 1 are consistent with collider data because the H^+ does not couple to fermions, is short lived and, if $M_{H^\pm} > M_Z/2$, does not contribute to the width of the Z boson.

Imposing the perturbativity condition that the quartic couplings $\lambda_{3,L,S}$ are smaller than *e.g.* 2π or 4π gives $M_h \lesssim 80$ GeV or $M_h \lesssim 175$ GeV in Cases II and IV while for Cases I and III we have $M_h \lesssim 150$ GeV or $M_h \lesssim 350$ GeV. We have checked that these M_h bounds can be saturated, keeping $\Omega_{DM} \sim 0.22$.

In the Table we considered only the case $\mu_1 = \mu_2 = 0$ because it is a particularly clear and intriguing case. It shows an example of model where starting from no scale at all, through dimensional transmutation, one can generate all scales of the SM. This cannot be realized in the SM but can work adding to the SM the DM particle, which anyway has to be added to the SM, as in the inert Higgs doublet model. Moreover it shows clearly that it is possible to work in a regime where both DM mass scale and electroweak scale are directly related to a small unique scale. The later feature holds more generally as long as $\mu_{1,2}$ are small with respect to the electroweak scale. In view of the hierarchy problem it is however difficult to justify the strict $\mu_1 = \mu_2 = 0$ conformal case. Note also that this scenario of EWSB driven by DM can be realized over a large parameter range beyond the case μ_1, $\mu_2 = 0$. In particular in the case $\mu_1^2 > 0$.

The existence of a second Higgs doublet has several consequences for colliders.[12] The main ones is that if $m_{DM} < m_h/2$, the Higgs can decay invisibly to a pair of DM particles. This leads to a smaller branching ratio of $h \to b\bar{b}$, and thus to a slightly lower bound on the Higgs mass from LEP data: $M_h > 105$ GeV instead of 114.4 GeV.[3] Similarly the suppression of the visible branching ratios render more difficult but not impossible the search for the Higgs boson at LHC. Possibility of tests at LHC, by producing the inert Higgs doublet components, do exist.[12]

5 Summary

We have shown that Dark Matter in the form of the lightest neutral component of a single inert scalar doublet could be responsible for EWSB. As a result of all constraints we get the bound on the mass of the Higgs $M_h \lesssim 350$ GeV while the mass of dark matter is in the range $M_{DM} \sim (10 - 72)$ GeV. Such a DM candidate is in a range of couplings that makes it accessible to both direct (ZEPLIN, Xenon,...) and indirect (GLAST) future searches (cf Figure 5 of [8]). Another interesting feature of our framework is that it provides a hint for why the DM mass would be around the electroweak scale, as required by the WIMP paradigm, *i.e.* $M_{DM} \propto v$ in our scenario in a large part of the parameter space.

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References

1. T. Hambye and M. Tytgat, Phys. Lett. **B659** (2008) 651.
2. D. N. Spergel *et al.*, arXiv:astro-ph/0603449.
3. W.M. Yao *et al.* [Particle Data Group], J. Phys. G **33** (2006) 1.
4. N.G. Deshpande and E. Ma, Phys. Rev. **D18** (1978) 2574.
5. E. Ma, Phys. Rev. **D73** (2006) 077301.
6. R. Barbieri, L.J. Hall and V.S. Rychkov, Phys. Rev. **D74** (2006) 015007.
7. D. Majumdar and A. Ghosal, arXiv:hep-ph/0607067.
8. L. Lopez Honorez, E. Nezri, J.F. Oliver and M.H.G. Tytgat, JCAP **0702** (2007) 028.
9. M. Gustafsson, E. Lundstrom, L. Bergstrom and J. Edsjo, Phys. Rev. Lett. **99** (2007) 041301.
10. S. R. Coleman and E. Weinberg, Phys. Rev. **D7** (1973) 1888.
11. E. Gildener and S. Weinberg, Phys. Rev. **D13**, 3333 (1976); M. Sher, Phys. Rept. **179**, 273 (1989); J.P. Fatelo, J.-M. Gérard, T. Hambye and J. Weyers, Phys. Rev. Lett. **74** (1995) 492; "T. Hambye, Phys. Lett. **B371**, 87 (1996); R. Hempfling, Phys. Lett. **B379** (1996) 153; W.F.S. Chang, J.N. Ng and J.M.S. Wu, Phys. Rev. **D75** (2007) 115016; K.A. Meissner and H. Nicolai, Phys. Lett. **B648**, 312 (2007); J.R. Espinosa and M. Quiros, Phys. Rev **D76** (2007) 076004; R. Foot, A. Kobakhidze and R.R. Volkas, Phys. Lett. **B655** (2007) 75; R. Foot, A. Kobakhidze, K.L. McDonald, R.R. Volkas, Phys.Rev. **D77** (2008) 035006.
12. Q. H. Cao, E. Ma and G. Rajasekaran, Phys. Rev. **D76** (2007) 095011.