# Electroweak symmetry breaking and cold dark matter from strongly interacting hidden sector

Taeil Hur [a], Dong-Won Jung [b,c], P. Ko [d,*], Jae Yong Lee [e]

[a] *Department of Physics, KAIST, Daejon 305-701, Republic of Korea*
[b] *Physics Department and CMTP, National Central University, Jhongli 32054, Taiwan*
[c] *Department of Physics, National Tsing Hua University, Hsinchu 300, Taiwan*
[d] *School of Physics, KIAS, Seoul 130-722, Republic of Korea*
[e] *Department of Physics, Korea University, Seoul 136-701, Republic of Korea*

**ABSTRACT**

We consider a hidden sector with a vectorlike confining gauge theory like QCD with $N_{h,c}$ colors and $N_{h,f}$ light quarks $\mathcal{Q}_h$ in the hidden sector. Then a scale $\Lambda_H$ would be generated by dimensional transmutation, and chiral symmetry breaking occurs in the hidden sector. This scale $\Lambda_H$ can play a role of the SM Higgs mass parameter, triggering electroweak symmetry breaking (EWSB). Furthermore the lightest mesons in the hidden sector is stable by flavor conservation of the hidden sector strong interaction, and could be a good cold dark matter (CDM). We study collider phenomenology, and relic density and direct detection rates of the CDM of this model.

© 2010 Elsevier B.V. All rights reserved.

Understanding the origin of the electroweak symmetry breaking (EWSB) is one of the key issues in particle physics. Experimental searches for it have been made at LEP and Fermilab Tevatron, and are being planned at LHC. We would like to understand why $v \ll M_{Pl}$ at tree level, as well as how to avoid fine tuning of the quadratic divergence to the Higgs (mass)$^2$ parameter at each order of perturbation theory. The latter problem have been a major motivation for many models beyond the standard model (SM). On the other hand the former problem did not receive much attention within the SM. It would be nice if we can understand why the electroweak scale is so small compared to the Planck scale in a similar manner as we understand why proton mass is so small compared with the Planck scale in QCD. Quantum fluctuation of quark and gluon fields makes proton massive, and naturally lighter than Planck scale within QCD: $m_p \sim O(\Lambda_{QCD}) \ll M_{Pl}$. It is a tantalizing question if one can achieve the same for EWSB scale [1,2]. Technicolor (TC) provides an answer for this question, but its naive version is in serious conflict with the electroweak precision test (EWPT) [3].

Another important problem in particle physics and cosmology is to reveal the nature of nonbaryonic cold dark matter (CDM),

which makes $\sim 25\%$ of the total energy density of the universe. Nonbaryonic CDM clearly calls for physics beyond the SM, since there are no good candidates for it within the SM. There are many particle physics models for CDM, among which the lightest supersymmetric particle (LSP) such as neutralino or gravitino is presently the most popular candidate. In many cases, the stability of a CDM is put in by hand by imposing some $Z_2$ symmetries: *e.g.*, $R$-parity in supersymmetry (SUSY) models. It would be nice if the CDM is stable by an accidental symmetry of the underlying local gauge symmetry, like baryon/lepton number conservations in the SM, and not by an ad hoc $Z_2$ symmetry. Within the SM, one can write down all the possible terms that are consistent with global Poincaré and local gauge symmetries with renormalizability. Then the baryon/lepton number conservations follow as accidental symmetries. Another example of an accidental symmetry is the isospin symmetry in QCD due to $(m_u - m_d) \ll \Lambda_{QCD}$.

One can ask if it would be possible to generate EWSB and its scale as one generates proton mass in QCD [1,2], and also accommodate a stable CDM candidate in the same framework. We argue that the answer to this question is affirmative, if there is a new vectorlike confining strong interaction with $N_{h,c}$ colors and $N_{h,f}$ flavors in the hidden sector,

$$\mathcal{L}_{hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{h,f}} \overline{\mathcal{Q}}_k(iD\cdot\gamma - M_{\mathcal{Q}_k})\mathcal{Q}_k. \qquad (1)$$

---

\* Corresponding author.
*E-mail addresses:* dwjung@phys.nthu.edu.tw (D.-W. Jung), pko@kias.re.kr (P. Ko).

The hidden sector quarks and gluons are SM singlets, and have no renormalizable interactions with the SM particles. Interactions with the SM sector would occur through exchanges of some messengers, which would be model dependent. Such effects would be described by higher dimensional operators below the messenger scales, and are suppressed by powers of $1/\Lambda_{\text{mess}}$, where $\Lambda_{\text{mess}}$ is a messenger scale, at which interactions between the SM and the hidden sectors are generated. In this Letter, we don't specify the messenger in detail, relegating the discussions to the future works [4].

Since the hidden sector gauge theory is a strongly interacting theory, we have to construct an appropriate effective field theory for given numbers of colors and flavors in the hidden sector. The low energy effective theory of this hidden sector gauge theory will be something similar to (non)linear sigma models of QCD.

There are two key points of this Letter. First of all, a dynamical scale $\Lambda_H$ (naturally smaller than $M_{\text{Pl}}$ like in QCD) is generated quantum mechanically in the hidden sector by dimensional transmutation, and spontaneous chiral symmetry breaking occurs. This scale $\Lambda_H$ can play a role of Higgs mass parameter in the SM, if appropriate conditions are met. Chiral symmetry breaking in the hidden sector is the same as the usual technicolor models, except that the hidden sector quarks are SM singlets, rather than the SM doublets. Therefore the EWPT constraints become milder in our scenario [4]. We can keep nicety of technicolor idea in a new form. Secondly, the lightest mesons and baryons in the hidden sector can be good candidates for CDM, and their stability is guaranteed by accidental chiral symmetry or hidden sector baryon number conservation, rather than by ad hoc $Z_2$ symmetry. This is a clear advantage of our model for CDM compared with many other CDM candidates.

Physics with a hidden sector is by no means a new idea. There are numerous works on physics with a hidden sector [5–9], and also in SUSY and superstring theory. A new ingredient in this Letter compared with earlier literature is that we consider technicolor in the hidden sector, the weak scale of the SM sector is generated in the hidden sector by dimensional transmutation, and the CDM is the lightest hadrons in the hidden sector and is composite.

Our picture is similar to SUSY models, where SUSY is broken spontaneously by hidden sector gaugino condensation. Then SUSY breaking effect is transmitted to the SM sector by messengers. Likewise in our model, a scale is generated in the hidden sector by dimensional transmutation (and chiral symmetry breaking), and its effect is transmitted to the SM sector by messengers.

The SM Lagrangian is given by the usual terms:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} - \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \mu_1^2 H_1^\dagger H_1$$
$$- \left(\overline{Q}^i H_1 Y_{ij}^D D^j + \overline{Q}^i \tilde{H}_1 Y_{ij}^U U^j + \overline{L}^i H_1 Y_{ij}^E E^j + \text{h.c.}\right) \quad (2)$$

where $\mathcal{L}_{\text{kin}}$ is the kinetic term for the SM chiral fermion, Higgs boson and three gauge boson fields. We have suppressed the neutrino mass terms since they are irrelevant to our main points. In the following, we consider Eqs. (1) and (2) and discuss EWSB and DM from the strongly interacting hidden sector.

Far below the hidden sector chiral symmetry breaking scale $\Lambda_{h,\chi} \approx 4\pi \Lambda_H$, the effective field theory of the hidden sector strong interaction would be (non)linear sigma models, similarly to the ordinary QCD. The detailed spectra depend on $N_{h,c}$ and $N_{h,f}$ with approximate $SU(N_{h,f})_L \times SU(N_{h,f})_R$ chiral symmetry. One can choose some $N_{h,f}$ and study the phenomenology, and we assume that $N_{h,f}$ is small enough so that there is chiral symmetry breaking and confinement in the hidden sector.

For illustration purpose, let us consider $N_{h,f} = 2$ with small current quark masses $M_{Q_{i=1,2}} \ll \Lambda_H$, and $N_{h,c} = 3$, like ordinary

QCD with two light flavors. In this case, the low energy effective theory is the Gell-Mann–Levy (GML)'s linear $\sigma$ model, or nonlinear $\sigma$ model with approximate global $SU(2)_L \times SU(2)_R$ symmetry. The relevant degrees of freedom would be the hidden sector pions ($\pi_h$) and it scalar partner $\sigma_h$, which forms $SU(2)_L \times SU(2)_R$ bidoublet $H_2$, transforming as

$$H_2(x) \equiv \left(\sigma_h(x) + i\pi_h^a(x)\tau^a\right) \rightarrow L_h H_2(x) R_h^\dagger$$

under the hidden sector global $SU(2)_L \times SU(2)_R$ symmetry. Here $\tau^a$'s are the Pauli matrices. There are also the hidden sector nucleons $N_h = (p_h, n_h)$, which is rather heavy $M_{N_h} \sim N_{h,c} \Lambda_H$. In this Letter, we ignore the hidden sector nucleons for simplicity, and consider physics related with $\pi_h$'s and $\sigma_h$, since we do not have good theoretical tools to calculate the $N_h \overline{N_h} \rightarrow$ (SM particles), which is relevant to thermal relic density of the hidden sector baryons. For the case of hidden sector pions which, the low energy effective theory of the hidden sector below the hidden sector chiral symmetry breaking scale $\Lambda_{h,\chi} \sim 4\pi v_2$ (where $v_2 \equiv \langle \sigma_h \rangle \sim \Lambda_H$) would be the Gell-Mann–Levy's linear $\sigma$ model, or its nonlinear version if $m_{\sigma_h} \gg v_2$. For the sake of simplicity, we assume that the low energy effective theory of the hidden sector is just renormalizable GML $\sigma$ model defined in terms of a scalar doublet $H_2$, postponing the discussions of the higher dimensional operators and the nonlinear sigma model version in the future publication [4].

Then, the potential for $H_1$ and $H_2$ is given by

$$V(H_1, H_2) = -\mu_1^2\left(H_1^\dagger H_1\right) + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 - \mu_2^2\left(H_2^\dagger H_2\right)$$
$$+ \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \frac{av_2^3}{2}\sigma_h \quad (3)$$

where $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$. This potential looks exactly the same as the ordinary two-Higgs doublet model, except for the $a$ term that generates nonzero masses for the hidden sector pions.

Since $H_2$ does not have renormalizable couplings to the SM fermions, there is no Higgs-mediated FCNC problem. Due to the chiral symmetry breaking in the hidden sector, $H_2$ develops a VEV $v_2$. Then the $\lambda_3$ term will contribute to the effective Higgs mass parameter: $m_{H_1}^2 = \mu_1^2 - \lambda_3 v_2^2$. In particular, one can imagine an interesting possibility that $\mu_1^2 = 0$, and the SM has classical scale symmetry. Then the entire Higgs mass parameter arises quantum mechanically due to dimensional transmutation in the hidden sector. In this Letter, we concentrate on the scenario with $\mu_1^2 = 0$. General case with $\mu_1^2 \neq 0$ will be discussed in Ref. [4].

The $\lambda_3$ coupling is important in our scenario, since it transmits the scale $\Lambda_H$ to the SM Higgs sector. Let us comment on a possible origin of such term. We can include a real singlet scalar $S$ as a messenger, which has the following interactions with the SM Higgs doublet and the hidden sector quarks:

$$\mathcal{L}_{\text{int}} = -\frac{1}{2}m_S^2 S^2 + \mu_S S^3 + \lambda_S S^2 H_1^\dagger H_1$$
$$+ \sum_{k=1}^{N_{h,f}} \overline{Q}_k\left[iD \cdot \gamma - (M_{Q_k} + \lambda_k S)\right]Q_k. \quad (4)$$

In general, the real singlet scalar $S$ can develop nonzero VEV. Integrating out the scalar field $S$, one can obtain

$$\mathcal{L}_{\text{eff}} \sim \langle S \rangle H_1^\dagger H_1 \sum_k \bar{Q}_k Q_k / M_S^2$$

which in turn becomes the $\lambda_3$ term, after hidden sector chiral symmetry breaking.

Let's look into the interaction more detail. Around the vacuum we can write the scalar fields as $S = \langle S \rangle + \tilde{S}$. In the visible sector, three vertex $\tilde{S} - H_1 - H_1^\dagger$ is generated with coupling $\lambda_S \langle S \rangle$ For the hidden sector, we can write down the low energy effective Lagrangian which contains the three-vertex $\tilde{S} - H_2 - H_2^\dagger$ with coupling $8 \frac{\Lambda_{h,\chi}^3}{v_2^2} \lambda_k$. Then the effective vertex $\lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2)$ is derived with

$$\lambda_3 = 8 \lambda_S \langle S \rangle \frac{\Lambda_{h,\chi}^3}{v_2^2 M_S^2} \lambda_k.$$

More detailed analysis based on the nonlinear realization will be studied in [4].

The Higgs sector of our model is similar to the usual two-Higgs doublet model, but there are two important differences. First of all, the hidden sector Higgs $H_2$ is a singlet under the SM gauge group in our model, and EW gauge bosons $W^\pm$ and $Z^0$ get masses only from the SM Higgs VEV $\langle H_1 \rangle$. The charged Higgs boson $H^\pm$ and the pseudoscalar $A^0$ in the usual two-Higgs doublet model become dark matter candidates $\pi_h^{\pm,0}$ in our model, since these particles cannot decay into the SM particles. Note that the charge of $\pi_h^{\pm,0}$ is not electric charge, but is the 3rd component of the isospin $SU(2)_V$ in the hidden sector. Secondly, we added the last term $\propto a \sigma_h$ term in order to accommodate explicit chiral symmetry breaking in the hidden sector from nonzero hidden sector quark masses $M_{\mathcal{Q}_i}$. The resulting hidden sector pions become massive and no cosmological problem arises from massless DM in addition to three light neutrinos.

We consider a phase of $V(H_1, H_2)$ where both $H_1$ and $H_2$ develop the nonzero VEV's:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i \pi_h^0}{\sqrt{2}} \end{pmatrix}. \tag{5}$$

In order to achieve a correct EWSB in the SM sector, we have to satisfy an inequality $\lambda_1 (\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$.

The mass matrix of $h_{SM}$ and $\sigma_h$ is given by

$$\mathcal{M}^2 = \begin{pmatrix} \lambda_1 v_1^2 & \lambda_3 v_1 v_2 \\ \lambda_3 v_1 v_2 & \lambda_2' v_2^2 \end{pmatrix} \tag{6}$$

in the $(h_{SM}, \sigma_h)$ basis. The mass eigenstates $(h, H)$ are linear combination of $h_{SM}$ and $\sigma_h$ that diagonalizes the above mass matrix:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_{SM} \\ \sigma_h \end{pmatrix}. \tag{7}$$

There are 4 independent parameters, $\tan\beta$, $m_{\pi_h}$, $\lambda_1$ and $\lambda_2$, and we can trade the latter two by $m_h$ and $m_H$ with $m_h \leqslant m_H$. In order to demonstrate the main points of this Letter, we fix $\tan\beta = 1$ ($v_1 = v_2$) and scan over other parameters with $m_{\pi_h} \lesssim 0.5 \Lambda_H \sim 5 v_2$, so that the hidden sector pions can be still regarded as pseudo Goldstone bosons. For $\lambda_1$ and $\lambda_2$, we scan upto $\sim 4\pi$, and check if the perturbative unitarity for $W_L W_L$ scattering is satisfied or not. The most important constraint on our model comes from the Higgs boson search and the relic density of the DM, which are calculated by modifying the micromegas [10].

In the low energy, there are two scalars $h_{SM}$ and $\sigma_h$ which mix through $\lambda_3$ term, and make two Higgs bosons $h_1$ and $h_2$. Note that only $h_{SM}$ couples to the SM gauge bosons and SM fermions. Therefore the couplings of $h$ and $H$ are modified by $\cos\alpha$ and $\sin\alpha$ of the SM couplings, and it is straightforward to calculate their decay rates and branching ratios with a few notable differences from the SM. Invisible decay channels of neutral scalars $h$, $H$ can open up through $h, H \to \pi_h \pi_h$, whose decay rates depend on the $\pi_h$
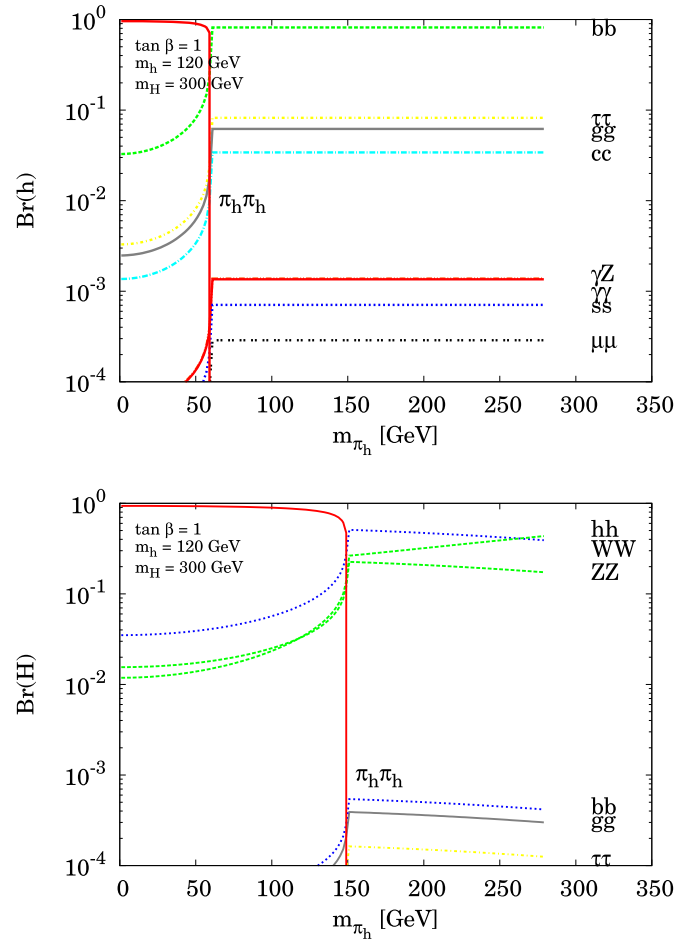


**Fig. 1.** Branching ratios of (top) $h$ and (bottom) $H$ as functions of $m_{\pi_h}$ for $\tan\beta = 1$, $m_h = 120$ GeV and $m_H = 300$ GeV.

masses and other parameters. This will make more difficult to observe the Higgs bosons $h$ or $H$ using the visible final states, such as $b\bar{b}$ or $t\bar{t}$, and $W^{(*)}W$ or $Z^{(*)}Z$. If $m_H > 2m_h$, then a new channel $H \to hh$ can open up, and the decay width of $H$ will increase. In Fig. 1, we show the branching ratios for two body decays of $h$ of 120 GeV and $H$ with 300 GeV for $\tan\beta = 1$. Note that the invisible branching ratios of $h$ and $H$ into $\pi_h \pi_h$ could be substantial if $\pi_h$ is light.

The production cross sections of $h$ and $H$ at Tevatron, LHC or ILC are the same as the SM Higgs boson production rates, except that the rates are scaled by the $h(H) - t - t$ or $h(H) - V - V$ (with $V = W, Z$) couplings, which are $\cos^2\alpha$ and $\sin^2\alpha$, respectively. Therefore the production rates of $h$ and $H$ are always suppressed relative to the SM Higgs production of the same mass.

In Fig. 2, we show the relic densities of $\pi_h$ in the $(m_h, m_H)$ plane for $\tan\beta = 1$ with different colors for $\log_{10}(\Omega_{\pi_h} h^2)$ between $-6$ and $8$. We imposed only $\Omega_{\pi_h} h^2 < 0.122$ (the WMAP bound), since there could be additional DM's, namely the lightest hidden sector nucleons or axions. The white region is excluded by direct search limit on Higgs boson and the correct EWSB vacuum for the SM sector. In a certain parameter space, the relic density is too large. This would be cured if we include nonrenormalizable interactions between the SM and the hidden sector [4]: for example, $\bar{f} f H_2^\dagger H_2$, and other operators. However we may lose predictability because of new couplings for these operators.

In Fig. 3, we show the spin-independent dark matter scattering cross section with proton $\sigma_{SI}$ for $\tan\beta = 1$, with the current
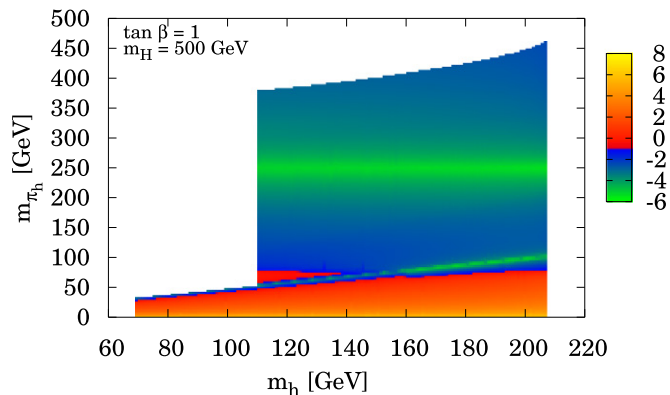
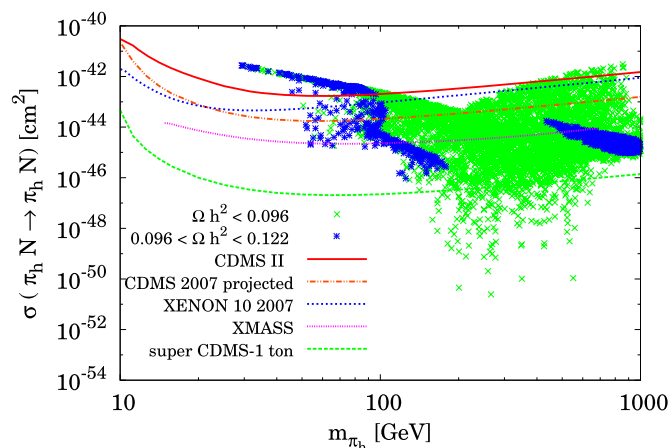**Fig. 2.** $\Omega_{\pi_h} h^2$ in the $(m_{h_1}, m_{\pi_h})$ plane for $\tan\beta = 1$ and $m_H = 500$ GeV.



**Fig. 3.** $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of $m_{\pi_h}$ for $\tan\beta = 1$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this Letter.)

bounds from CDMS-II and XENON as well as the projected sensitivities of XMASS and SuperCDMS. Blue and green dots denote the relic density $0.096 < \Omega_{DM} h^2 < 0.122$ and $\Omega_{DM} < 0.122$. Note that our model predicts $\sigma_{SI}$ in a very interesting range, partially excluded by the current CDMS-II and XENON data, and also could be tested by the near future experiments.

In summary, we proposed a new possibility that there is a hidden sector with a new vectorlike confining strong interaction like QCD. A scale $\Lambda_H$ is generated quantum mechanically through dimensional transmutation, and it is naturally smaller than the Planck scale. This scale is transmitted to the SM sector Higgs mass parameter through some messengers. The lightest hadrons in the hidden sector, $\pi_h^{\pm,0}$, can make good candidates for the CDM. Stability of CDM in our model is guaranteed by flavor symmetry which is an accidental symmetry of the hidden sector gauge theory, and not by ad hoc $Z_2$ symmetry in many other models for DM's. Direct rate for the DM is around the current or near-future DM scattering experiments, and our model predicts detectable rates in a sizable parameter space. There are two Higgs bosons, one ($h_{SM}$) fundamental in the SM sector and the other ($\sigma_h$) composite from

the hidden sector. These two mix with each other, making two mass eigenstates $h$ and $H$, and they can decay into the CDM pair. Their invisible branching ratio could be substantial depending on the masses of Higgs bosons and the DM particle.

We can extend the current work in various directions. One can study cosmological consequences of the lightest hidden sector baryons, baryogenesis and the relation between baryon and DM densities. Or we can consider different values of $N_{h,f}$. Further, if there is an additional weakly interacting gauge symmetry in the hidden sector, such as $SU(2)_L$ or $SU(2)_R$, the weak gauge bosons will get massive by eating up the hidden sector pions, and could be a spin-one CDM. If we impose classical scale symmetry in the hidden sector, we need additional real singlet scalar $S$ scalar that can provide the masses for the hidden sector quarks. Then the whole theory becomes classically scale invariant and all the mass scales could be generated quantum mechanically by dimensional transmutation. More detailed discussions on these topics will be presented elsewhere [4]. Still we hope that this Letter is enough to convey the underlying ideas on the role of hidden sector technicolor interaction on the EWSB and the DM physics, and open a new possibility in the model building with dynamical EWSB such as technicolor.

While we were completing this work, we came to know that F. Wilczek considered the idea of EWSB from hidden sector strong interaction with $a = 0$ in Eq. (3) [11]. The basic ideas and the qualitative features of the present and related models were presented by P. Ko at the 3rd conference on "Dark Side of the Universe," University of Minnesota, USA (June 5–10, 2007) and at KIAS particle physics journal club (July 4, 2007).

## Acknowledgements

## References

[1] C.T. Hill, E.H. Simmons, Phys. Rept. 381 (2003) 235;
C.T. Hill, E.H. Simmons, Phys. Rept. 390 (2004) 553, Erratum.
[2] F. Wilczek, Int. J. Mod. Phys. A 21 (2006) 2011.
[3] M.E. Peskin, T. Takeuchi, Phys. Rev. Lett. 65 (1990) 964;
M.E. Peskin, T. Takeuchi, Phys. Rev. D 46 (1992) 381.
[4] Works in preparation.
[5] A.Y. Ignatiev, R.R. Volkas, Phys. Lett. B 487 (2000) 294;
R. Foot, H. Lew, R.R. Volkas, JHEP 0007 (2000) 032;
R. Foot, arXiv:0706.2694 [hep-ph].
[6] Z. Berezhiani, Int. J. Mod. Phys. A 19 (2004) 3775.
[7] R. Barbieri, T. Gregoire, L.J. Hall, arXiv:hep-ph/0509242.
[8] M.J. Strassler, K.M. Zurek, Phys. Lett. B 651 (2007) 374, arXiv:hep-ph/0604261.
[9] B. Patt, F. Wilczek, arXiv:hep-ph/0605188.
[10] G. Belanger, F. Boudjema, A. Pukhov, A. Semenov, Comput. Phys. Commun. 176 (2007) 367.
[11] F. Wilczek, Plenary talk at SUSY07, Karlsruhe, Germany, July 26–August 1, 2007, and arXiv:0708.4236.