Scale Invariant Extension of the Standard Model with a Strongly Interacting Hidden Sector

Taeil Hur and P. Ko*
School of Physics, KIAS, Seoul 130-722, Korea
(Received 11 January 2011; published 4 April 2011)

We present a scale invariant extension of the standard model with a new QCD-like strong interaction in the hidden sector. A scale Λ_H is dynamically generated in the hidden sector by dimensional transmutation, and chiral symmetry breaking occurs in the hidden sector. This scale is transmitted to the SM sector by a real singlet scalar messenger S and can trigger electroweak symmetry breaking. Thus all the mass scales in this model arise from the hidden sector scale Λ_H, which has quantum mechanical origin. Furthermore, the lightest hadrons in the hidden sector are stable by the flavor conservation of the hidden sector strong interaction, and could be the cold dark matter (CDM). We study collider phenomenology, relic density, and direct detection rates of the CDM of this model.

DOI: 10.1103/PhysRevLett.106.141802 PACS numbers: 12.60.−i, 11.15.−q, 11.25.Hf, 95.35.+d

Understanding the origin of electroweak symmetry breaking (EWSB) and the nature of cold dark matter (CDM) are the most important questions in high energy physics in the Large Hadron Collider (LHC) era. In particular, it is an open question whether all the masses of fundamental particles can arise from new strong dynamics [1–3]. In our previous work [4], we considered a model with a strongly interacting hidden sector, where a new strong interaction has such properties as confinement and chiral symmetry breaking like ordinary QCD:

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

plus interactions between the hidden sector and the standard model (SM) sector due to some messengers which were not specified clearly. Using the Gell-Mann–Levy linear sigma model as a low energy effective theory for the hidden sector technicolor interaction, we made two important observations in Ref. [4]. The first point was that dynamical scale Λ_H, which is generated in the hidden sector by dimensional transmutation (analogous to Λ_{QCD}), can play a role of (or contribute to) the Higgs mass parameter in the SM. Another point was that the lightest mesons, the hidden sector pions, can be good candidates for CDM. It is stable due to hidden sector flavor conservation, which is an accidental symmetry of hidden sector strong interaction. Note that we do not impose any *ad hoc* Z_2 symmetry for the stability of CDM. However, in Ref. [4], the mass of the CDM (the hidden sector pion π_h) originated from explicit chiral symmetry breaking from nonzero current quark masses in the hidden sector [$M_{\mathcal{Q}_k}$ in Eq. (1)], and we did not question the origin of those hidden sector current quark masses. It is important and interesting to investigate if the CDM mass can also arise from new strong dynamics through dimensional transmutation [4].

In this Letter, we show that it is in fact possible to show that all the mass scales including the CDM mass arise quantum mechanically through dimensional transmutation and the hidden sector chiral symmetry breaking. For that purpose, we start with the classical Lagrangian without any dimensionful parameters, which then possesses classical scale symmetry. The scale symmetry is broken only in the logarithm, which is related to the trace anomaly. For that purpose, we have to introduce a real singlet scalar S and modify the SM Lagrangian as follows:

$$\begin{aligned}\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} &- \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2}S^2 H_1^\dagger H_1 - \frac{\lambda_S}{8}S^4 \\ &+ (\bar{Q}^i H_1 Y_{ij}^D D^j + \bar{Q}^i \tilde{H}_1 Y_{ij}^U U^j + \bar{L}^i H_1 Y_{ij}^E E^j \\ &+ \bar{L}^i \tilde{H}_1 Y_{ij}^N N^j + S N^{iT} C Y_{ij}^M N^j + \text{H.c.}). \end{aligned} \quad (2)$$

The hidden sector Lagrangian is also modified as follows:

$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{h,f}}(\bar{\mathcal{Q}}_k iD\cdot\gamma - \lambda_k S)\mathcal{Q}_k. \quad (3)$$

Note that all the mass terms are replaced by S or S^2 [including the mass terms for the hidden sector quarks ($M_{\mathcal{Q}_i}$) by Yukawa coupling ($\lambda_i S$)] so that the classical Lagrangian is scale invariant without any mass parameters at tree level. In our model, all the masses will be generated by quantum mechanical effects. Also, S will play a role of a messenger connecting the SM and the hidden sectors.

In fact, the Lagrangian (2) was considered in Ref. [5], where the radiative EWSB was studied using the methods of Coleman and Weinberg [6]. In Ref. [7], Meissner and Nicolai showed that this Lagrangian is renormalizable in a sense that the counterterm structure is the same as the classically scale invariant Lagrangian when dimensional regularization and mass-independent renormalization schemes such as the $\overline{MS}$ scheme are used. Our approach is different from Ref. [5] in that we include a hidden sector with new strong QCD-like interaction, so that we can discuss CDM and dynamical mass generation even without radiative corrections to the effective potential.

Note that the hidden sector has exact global $SU(N_{h,f})_L \times SU(N_{h,f})_R$ chiral symmetry in the limit $\lambda_k = 0$ for $k = 1, 2, \ldots, N_{h,f}$, which will break into diagonal $SU(N_{h,f})_V$ with massless Nambu-Goldstonte (NG) bosons. Because of strong interaction in the hidden sector, hidden sector quarks will condense with $\langle \mathcal{Q}_k \mathcal{Q}_k \rangle \neq 0$, and a linear term in S will develop, leading to a nonzero vacuum expectation value (VEV) for S. After S gets a VEV, one has $M_{\mathcal{Q}_i} = \lambda_i \langle S \rangle$. The hidden sector quarks are light if $M_{\mathcal{Q}_j} \equiv \lambda_j \langle S \rangle \ll \Lambda_{h\chi} \equiv 4\pi\Lambda_H$, where $\Lambda_{h\chi}$ is the hidden sector chiral symmetry breaking scale. If there are N_f light hidden sector quarks, there would be approximate $SU(N_{h,f})_L \times SU(N_{h,f})_R$ global chiral symmetry. This chiral symmetry is explicitly broken, so that the resulting hidden sector pions become massive with $m_{\pi_h}^2 = \mu_h M_{\mathcal{Q}} \ll \Lambda_{h\chi}$. If $n_{h,f}$ of λ_i's are approximately equal, the $SU(n_{h,f})_V$ will be a good approximate global symmetry to categorize the pseudo-NG bosons.

This picture is similar to supersymmetry (SUSY) models, where SUSY is broken spontaneously by hidden sector gaugino condensation. The SUSY breaking effect is transmitted to the minimal supersymmetric standard model (MSSM) sector by messengers. Likewise, in our model, classical scale symmetry is broken in the hidden sector by dimensional transmutation in our model, and its effect is transmitted to the SM sector by messenger (real singlet scalar S in our model). 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 SM doublets, thereby the constraints from S and T become milder in our scenario. We still do have a fundamental Higgs scalar H_1 in the SM sector, but its mass parameter is determined by the hidden sector chiral symmetry breaking scale, and thus naturally suppressed relative to the Planck scale, as the proton mass in QCD is naturally smaller than Planck scale by dimensional transmutation.

To illustrate our main points, let us consider $N_{h,f} = 2$ with small current quark masses $M_{\mathcal{Q}_{i=1,2}}$ and $N_{h,c} = 3$, as in the ordinary QCD with two light flavors. In this case, the low energy degrees of freedom would be the hidden sector pions (π_h) with decay constant $v_h \approx \Lambda_H$, its scalar partner σ_h, and the hidden sector nucleons $N_h = (p_h, n_h)$. To simplify our discussions, we assume that both hidden sector scalar σ_h and nucleons N_h are much heavier than the hidden sector pions, or the hidden sector scale Λ_H, and integrate them out. Then the low energy dynamics of the hidden sector can be described entirely in terms of the hidden sector pions. This description is sufficient for calculating the relic density and the direct detection of π_h's, since π_h's are almost at rest in these calculations. However, we will keep in mind that the hidden sector baryons would also be stable by hidden sector baryon number conservation, and make another CDM. Their relic density and direct detection rate are more difficult to calculate than those of hidden sector pions, and so we do not include them in this Letter.

Within this picture, physics of the hidden sector pions and its interactions with the SM sector and the real scalar S can be described by the following effective Lagrangian:

$$\begin{aligned}
\mathcal{L}_{\text{hidden}}^{\text{eff}} &= \frac{v_h^2}{4} \text{Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2} \text{Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)], \\
\mathcal{L}_{\text{mixing}} &= -v_h^2 \Lambda_{h\chi}^2 \bigg[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_{h\chi}^2} + \kappa_S \frac{S^2}{\Lambda_{h\chi}^2} + \kappa_S' \frac{S}{\Lambda_{h\chi}} \\
&\qquad + O\bigg(\frac{S H_1^\dagger H_1}{\Lambda_{h\chi}^3}, \frac{S^3}{\Lambda_{h\chi}^3} \bigg) \bigg], \\
\mathcal{L}_{\text{full}} &= \mathcal{L}_{\text{hidden}}^{\text{eff}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mixing}}.
\end{aligned} \tag{4}$$

In deriving $\mathcal{L}_{\text{mixing}}$, we used the naive dimensional analysis and ignored operators that are suppressed by powers of $v_h/\Lambda_{h\chi}$. Dimensionless couplings κ_H, κ_S, etc. are of $O(1)$ according to the naive dimensional analysis.

Since we have to use an effective Lagrangian for the hidden sector strong interaction, it is mandatory for us to discuss the effects of higher dimensional operators and power counting rules. Here one can adopt the naive power counting rule proposed by Manohar and Georgi [8]. We have already shown some terms that connect the SM Higgs boson and S to the hidden sector pions. We can also consider interactions involving the hidden sector pions and the SM fermions and gauge fields. The basic principle is exactly the same as that in the chiral Lagrangian.

The tree level scalar potential in the present model is given by

$$\begin{aligned}
V &= \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 + \frac{\lambda_S}{8} S^4 \\
&\quad + \mu_{H_1}^2 H_1^\dagger H_1 + \frac{1}{2} \mu_S^2 S^2 + \rho^3 S,
\end{aligned} \tag{5}$$

where $\mu_{H_1}^2$, μ_S^2, and ρ^3 are defined in terms of the parameters in the Lagrangian:

$$\mu_{H_1}^2 = v_h^2 \kappa_H, \tag{6}$$

$$\mu_S^2 = 2 v_h^2 \kappa_S, \tag{7}$$

$$\rho^3 = v_h^2 \{ \Lambda_{h\chi} \kappa_S' - \mu_h (\lambda_u + \lambda_d) \}. \tag{8}$$

We are interested in the phase

$$H_1 = \bigg(0, \frac{(v_1 + h_{\text{SM}})}{\sqrt{2}} \bigg)^T, \qquad S = (v_S + S).$$

The scalar mass matrix is given by (EWSB condition $M_{11} + M_{22} > 0$, $M_{11} M_{22} > M_{12}^2$)

$$\mathcal{L} \supset -\frac{1}{2} \big(h_{\text{SM}} \quad S \big) \begin{pmatrix} \lambda_1 v_1^2 & \lambda_{1S} v_1 v_S \\ \lambda_{1S} v_1 v_S & \lambda_S v_S^2 - \rho^3 / v_S \end{pmatrix} \begin{pmatrix} h_{\text{SM}} \\ S \end{pmatrix}. \tag{9}$$

The mass eigenstates h and H are defined as

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_{\rm SM} \\ S \end{pmatrix}, \tag{10}$$

which diagonalizes the scalar mass matrix. The hidden sector pions get masses if S develops a VEV: $m_{\pi_h}^2 = v_S \mu_h (\lambda_u + \lambda_d)$.

Our main point can be best illustrated for the simplest case, $\kappa_H = \kappa_S = \kappa_S' = 0$. In this case a reduction in the number of parameters occurs, and we obtain λ_{1S} and λ_S in terms of λ_1 and v_S:

$$\lambda_{1S} = -\frac{\lambda_1 v_1^2}{v_S^2}, \qquad \lambda_S = \frac{\lambda_1 v_1^4 + 2 m_{\pi_h}^2 v_h^2}{v_S^4}. \tag{11}$$

Trading λ_1 with m_h, we use the following set as input parameters: $\tan\beta \equiv v_S/v_1, v_h, m_{\pi_h}, m_h$. For numerical analysis, we consider two cases: (a) $v_h = 500$ GeV and $\tan\beta = 1$ and (b) $v_h = 1000$ GeV and $\tan\beta = 5$, and scan over other two parameters with $m_{\pi_h} \lesssim 0.5 \Lambda_{h\chi} \sim 5 v_2$, so that the hidden sector pions can still be regarded as a pseudo-Goldstone bosons. For λ_1, we scan up to $\sim 4\pi$, and check if the perturbative unitarity for $W_L W_L$ scattering is satisfied. The most important constraints on our model come from the Higgs boson search and the relic density of the DM, the latter of which is calculated by modifying MICROMEGA [9] to suit our model.

In the low energy, there are two scalars h and H which are linear combinations of $h_{\rm SM}$ and S, and both are assumed to be fundamental scalar bosons. Note that $h_{\rm SM}$ 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. On the other hand, the scalar S couples to the SM Higgs boson, the right-handed Majorana neutrino through the Majorana mass term, and most importantly to the hidden sector pions. In particular, its coupling to the hidden sector pion increases as the hidden sector pion mass increases, which is characteristic of the model with classical scale symmetry. It is easy to copy the results from the SM case, with a few important things to be emphasized in our case. $h(H) \to \pi_h \pi_h$ will open up the invisible decay channel of Higgs bosons h and H, whose decay rates depend on the π_h masses and other parameters. This will make it more difficult to observe the Higgs bosons h or H using the visible final states. If $m_H > 2m_h$, then a new channel $H \to hh$ can open up, and the decay width of h_2 will be increased. The production cross sections of h and H at the Tevatron or LHC are the same as the SM Higgs boson production rate, except that the rates are scaled by the $h(H) - t - t$ 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. 1, we show the branching ratio for h with $m_h = 120$ GeV for (a) $v_h = 500$ GeV and $\tan\beta = 1$ and (b) $v_h = 1$ TeV and $\tan\beta = 2$. As in Ref. [4], the invisible decay width of h is large as long as $h \to \pi_h \pi_h$ is kinematically allowed ($m_{\pi_h} < m_h/2 = 60$ GeV). Otherwise h decay follows that of the SM predictions.

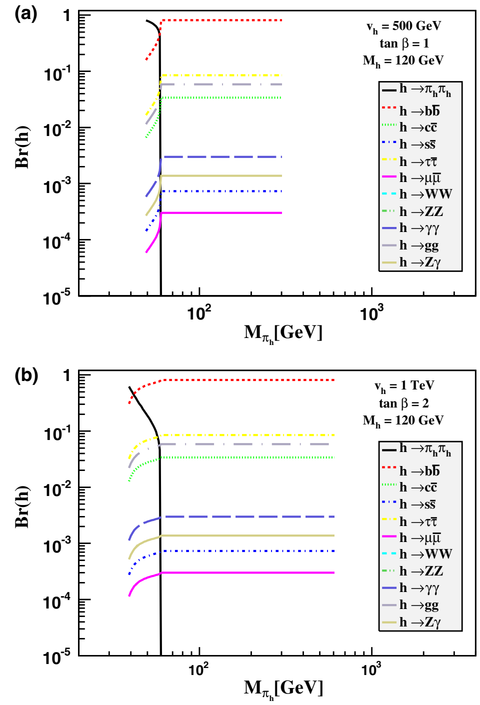

FIG. 1 (color online). Branching ratios of h of $m_h = 120$ GeV as functions of m_{π_h} for (a) $v_h = 500$ GeV and $\tan\beta = 1$ and (b) $v_h = 1$ TeV and $\tan\beta = 2$.

The hidden sector pion π_h can be a good candidate for the CDM of the Universe. In Fig. 2, we show the relic densities of π_h in the (m_{π_h}, m_h) plane for (a) $v_h = 500$ GeV and $\tan\beta = 1$ and (b) $v_h = 1$ TeV and $\tan\beta = 2$, with different colors for $\log_{10}(\Omega_{\pi_h} h^2)$ between -4 and 0.5. We imposed only $\Omega_{\pi_h} h^2 < 0.122$ (the Wilkinson Microwave Anisotropy Probe bound), since there could be additional DMs, namely, the lightest hidden sector nucleons or axions. The white region is excluded by the direct search limit on the Higgs boson and the correct EWSB vacuum for the SM sector. In a certain parameter space, the relic density is somewhat large, but not so large as in our previous paper [4] where the hidden quark masses are given by hand, and not by scalar VEV.

In Fig. 3, we show the spin-independent dark matter scattering cross section with proton $\sigma_{\rm SI}$ for $(v_h, \tan\beta) = (500\ {\rm GeV}, 1)$, and $(1\ {\rm TeV}, 2)$, with the current bounds from CDMS-II and XENON as well as the projected sensitivities of XMASS and SuperCDMS. Within particular parameter space with all κ's equal to zero, there is an approximate linear relationship between $\log\sigma_{\rm SI}$ and $\log M_{\pi_h}$. Green and blue dots denote the relic density $0.096 < \Omega_{\rm DM} h^2 < 0.122$ and $\Omega_{\rm DM} h^2 < 0.096$. Note that our model predicts $\sigma_{\rm SI}$ just below the recent bound from the XENON-10 experiment, and could be tested by experiments in the near future.

In this Letter, we presented a renormalizable and scale invariant extension of the SM with new QCD-like strong interaction in the hidden sector. The scale generated in the

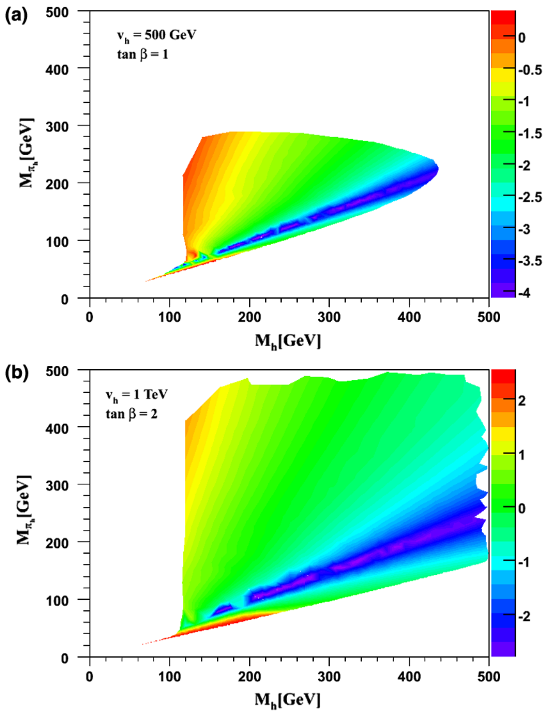

FIG. 2 (color online). $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for (a) $v_h = 500$ GeV and $\tan\beta = 1$ and (b) $v_h = 1$ TeV and $\tan\beta = 2$.

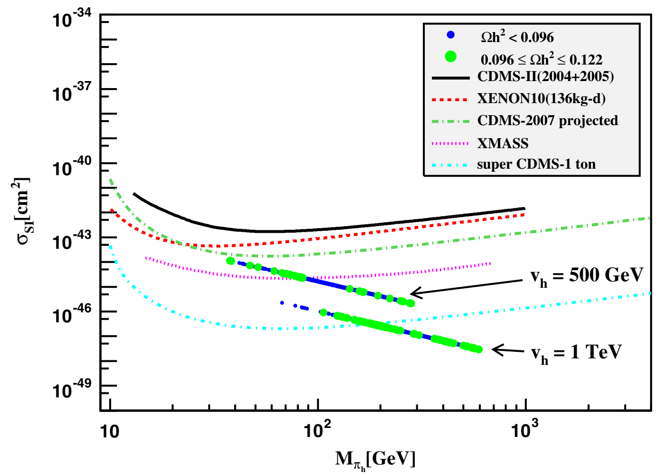

FIG. 3 (color online). $\sigma_{\rm SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}. The upper line is for $v_h = 500$ GeV and $\tan\beta = 1$, and the lower line is for $v_h = 1$ TeV and $\tan\beta = 2$.

hidden sector by dimensional transmutation is transmitted not only to the EWSB scale, but also to the hidden sector pion mass through $\lambda\langle S\rangle$. Therefore all the mass scales (except for the cosmological constant) have their origin in a single scale Λ_H in the hidden sector strong interaction. A new element of the present work compared with our previous work [4] was that the hidden sector quark masses also arise from scale invariant interaction and its breaking due to $\langle S\rangle \neq 0$. Further, the present model is renormalizable, with S being a messenger connecting the hidden sector and the SM sector. As a concrete example to show this idea really works, we considered the $SU(2)_L \times SU(2)_R$ chiral symmetry breaking and dynamics of the resulting two scalar bosons and the CDM (π_h's) using the effective chiral Lagrangian technique. The details would depend on the number of hidden sector quark flavors, but the qualitative features must be similar to our example based on two flavors in the hidden sector. Since we have assumed that $\langle S\rangle \lesssim 4\pi v_h$, its scale is $\sim$ TeV. Therefore neutrinos get masses through a TeV scale seesaw mechanism, and the Majorana masses for M_R's are $\langle S\rangle$ dependent. Interest in low energy seesaw models is being renewed these days for various reasons.

We can extend this work in various directions. The lightest hidden sector baryons could be additional dark matter candidates, and its phenomenology and relic density are interesting subjects. We can consider an extra $U(1)_X$ gauge boson as a messenger, by introducing a new $U(1)_X$ under which both SM and hidden sector matters are charged [10,11]. Finally, one can study the one loop radiative corrections using the methods of Coleman and Weinberg [6]. Such calculations have been done recently for the SM plus right-handed neutrinos by Meissner and Nicolai [5], and it was shown that the realistic EWSB could be possible. In their scenario, there is no CDM candidate, and it would be interesting to extend their calculations to our model with vectorlike confining gauge theory in the hidden sector. More detailed discussions on the topics presented here will be presented elsewhere [11].

P. K. is grateful to W. Bardeen, M. Drees, C. Hill, D. W. Jung, J. Y. Lee, C. S. Lim, A. Masiero, S. Rudaz, and F. Wilczek for discussions. P. K. is supported in part by National Research Foundation (NRF) through Korea Neutrino Research Center (KNRC) at Seoul National University.

*pko@kias.re.kr

[1] C. T. Hill and E. H. Simmons, Phys. Rep. **381**, 235 (2003); **390**, 553(E) (2004).
[2] F. Wilczek, Int. J. Mod. Phys. A **21**, 2011 (2006).
[3] F. Wilczek, Int. J. Mod. Phys. A **23**, 1791 (2008).
[4] T. Hur, D. -W. Jung, P. Ko, and J. Y. Lee, Phys. Lett. B **696**, 262 (2011).
[5] K. A. Meissner and H. Nicolai, Phys. Lett. B **648**, 312 (2007).
[6] S. R. Coleman and E. J. Weinberg, Phys. Rev. D **7**, 1888 (1973).
[7] K. A. Meissner and H. Nicolai, Phys. Lett. B **660**, 260 (2008).
[8] A. Manohar and H. Georgi, Nucl. Phys. **B234**, 189 (1984).
[9] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, Comput. Phys. Commun. **176**, 367 (2007).
[10] M. J. Strassler and K. M. Zurek, Phys. Lett. B **651**, 374 (2007).
[11] S. Baek, Taeil Hur, and P. Ko (to be published).