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ABSTRACT

We propose a classically scale invariant extension of the Standard Model where the electroweak symmetry breaking and the mass of the Dark Matter particle come from the common scale. We introduce $U(1)_X$ gauge symmetry and X-charged scalar Φ and Majorana fermion N. Scale invariance is broken via Coleman–Weinberg mechanism providing the vacuum expectation value of the scalar Φ. Stability of the dark matter candidate N is guaranteed by a remnant Z_2 symmetry. The Higgs boson mass and the mass of the Dark Matter particle have a common origin, the vacuum expectation value of Φ. Dark matter relic abundance is determined by annihilation $NN \to \Phi\Phi$. We scan the parameter space of the model and find the mass of the dark matter particle in the range from 500 GeV to a few TeV.

1. Introduction

The discovery of the Higgs boson [1,2] is a dramatic confirmation of the Standard Model (SM). Despite finding the last missing piece of SM we are still looking for insight into the detailed mechanism of electroweak symmetry breaking. In particular, within SM, the Higgs mass receives large corrections leading to the hierarchy problem. For several resolutions of the hierarchy problem that have been put forward, like supersymmetry, large extra dimensions or composite structure the LHC found no hints so far.

Given such a scenario where new physics, stemming from e.g. supersymmetry, seems to be absent, one is lead to pursue alternative approaches to the hierarchy problem. Here, we follow an idea first put forward by Bardeen [3] that in classically scale invariant (SI) theories, scale invariance is broken by quantum corrections and quadratic divergence in fundamental scalar masses is a cut-off regularization artefact. All dimensionfull parameters in these theories, including the scalar masses, come from a single renormalization scale. As has been shown by Coleman and E. Weinberg (CW) [4] in order for this mechanism of mass generation to work within perturbation theory at least two bosonic degrees of freedom are needed. A seminal paper by Gildener and S. Weinberg [5] (GW) represents the first cohesive study of the CW mechanism for multiple scalars.

Classical scale invariance breaks by quantum anomaly yielding one pseudo-Goldstone boson, the so-called scalon [5]. The intriguing idea of identifying the scalon with the Higgs particle requires additional bosonic degrees of freedom due to the large top quark mass. Sprung by initial explorations [6] many works have been put forward to realize this scenario. In order to compensate the large top contribution, extra bosons either have large couplings to the Higgs [7–9] or appear in large multiplets [10]. Alternatively, the CW mechanism can be applied in a new gauge sector where the scale gets transmitted to the SM through the Higgs portal [11–16]. For additional work on the SI extensions of SM in different contexts, see [17–21].

Dark matter (DM) is another problem pressing us to extend the SM. Classically SI extensions of the SM with DM have been studied in the inert Higgs doublet model [22], $SU(2)$ vector dark matter [15,16], multiple scalar models [8,23–27] and non-perturbative realizations of the hidden sector [28–30].

SI theories and the CW mechanism offer a possibility of a single origin of the electroweak symmetry breaking and the dark matter mass embodying the paradigm of the WIMP miracle. This attractive picture is the subject of our work. We include SI dark sector consisting of a new $U(1)_X$ gauge group and X-charged scalar Φ and Majorana fermion N. The effective scalar potential is dominated by the contributions of the new gauge boson and leads to the breaking of the dark gauge symmetry. Via the Higgs portal coupling the CW mechanism induces the breaking of electroweak symmetry. Due to the residual Z_2 symmetry the Majorana fermion is stable and represents the DM candidate.

2. The model

We introduce $U(1)_X$ gauge symmetry with doubly X-charged scalar Φ and singly X-charged Majorana fermion N, both singlets under the SM gauge group. The scalar potential and dark Yukawa term are

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$$V(H,\Phi) = \frac{\lambda_H}{2}\left(H^\dagger H\right)^2 + \frac{\lambda_\Phi}{2}\left(\Phi^\dagger\Phi\right)^2 + \lambda_P\left(H^\dagger H\right)\left(\Phi^\dagger\Phi\right), \tag{1}$$

$$\mathcal{L}_y = -\frac{y}{2}\Phi\bar{N}N, \tag{2}$$

where H is an SM Higgs doublet.

The CW mechanism will be studied in the GW framework [5] where quantum corrections are built on top of a flat direction in the tree-level potential giving mass to the scalon. Assuming that both H and Φ acquire vacuum expectation values (*vevs*)

$$H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v_H + h' + iG) \end{pmatrix}, \qquad \Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi' + iJ), \tag{3}$$

the potential (1) has a flat direction when the couplings satisfy

$$\lambda_H(\Lambda)\lambda_\Phi(\Lambda) - \lambda_P^2(\Lambda) = 0. \tag{4}$$

This is a dimensional transmutation, where one dimensionless coupling is traded for the physical scale of the model Λ.

At the tree level the *vevs* are given by

$$\frac{v_H^2}{v_\Phi^2} = -\frac{\lambda_P}{\lambda_H}. \tag{5}$$

Scalar mass eigenstates are given by

$$\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h' \\ \phi' \end{pmatrix}, \tag{6}$$

with mixing angle θ given by

$$\sin^2\theta = -\frac{\lambda_P}{\lambda_H - \lambda_P}. \tag{7}$$

The tree-level masses of scalars are

$$m_h^2 = (\lambda_H - \lambda_P)v_H^2, \qquad m_\phi^2 = 0, \tag{8}$$

and X-gauge boson and fermion masses are

$$m_X^2 = 4g_X^2 v_\Phi^2, \qquad m_N = \frac{y}{\sqrt{2}}v_\Phi \tag{9}$$

where g_X is the gauge coupling of the $U(1)_X$ gauge symmetry.

To find the scalon mass we need the one-loop corrected potential along the flat direction which takes the following form [5]

$$\delta V(r) = Ar^4 + Br^4\log\left(\frac{r^2}{\Lambda^2}\right), \tag{10}$$

where the radial field r is defined through

$$\begin{pmatrix} v_H + h' \\ v_\Phi + \phi' \end{pmatrix} = r\begin{pmatrix} n_h \\ n_\phi \end{pmatrix}, \tag{11}$$

while the fields n_h, n_ϕ satisfy the constraint $n_h^2 + n_\phi^2 = 1$, with their *vevs* being $\sin\theta$ and $\cos\theta$, respectively. The coefficients A and B are given as [8]

$$\begin{aligned} A = \frac{1}{64\pi^2 v_r^4}\bigg\{ & m_h^4\left(-\frac{3}{2} + \log\frac{m_h^2}{v_r^2}\right) + 6m_W^4\left(-\frac{5}{6} + \log\frac{m_W^2}{v_r^2}\right) \\ & + 3m_Z^4\left(-\frac{5}{6} + \log\frac{m_Z^2}{v_r^2}\right) + 3m_X^4\left(-\frac{5}{6} + \log\frac{m_X^2}{v_r^2}\right) \\ & - 12m_t^4\left(-1 + \log\frac{m_t^2}{v_r^2}\right) - 2m_N^4\left(-1 + \log\frac{m_N^2}{v_r^2}\right)\bigg\}, \end{aligned} \tag{12}$$

$$B = \frac{1}{64\pi^2 v_r^4}\left(m_H^4 + 6m_W^4 + 3m_Z^4 + 3m_X^4 - 12m_t^4 - 2m_N^4\right), \tag{13}$$

where v_r is the *vev* of the field r. The mass of the scalon is given as

$$m_\phi^2 = \frac{\partial^2\delta V}{\partial r^2}\bigg|_{r=v_r} = 8Bv_r^2. \tag{14}$$

The tree-level potential (1) in the mass eigenstate basis reads

$$\begin{aligned} V(h,\phi) = {} & \frac{1}{2}m_h^2h^2 + \frac{1}{2}\sqrt{1 - \frac{\lambda_P}{\lambda_H}}(\lambda_P + \lambda_H)v_H h^3 \\ & + \frac{1}{8}\frac{(\lambda_H + \lambda_P)^2}{\lambda_P}h^4 + \sqrt{-\lambda_P(\lambda_H - \lambda_P)}v_H h^2\phi \\ & + \frac{1}{2}\sqrt{\frac{-\lambda_P}{\lambda_H}}(\lambda_H + \lambda_P)h^3\phi - \frac{1}{2}\lambda_P h^2\phi^2. \end{aligned} \tag{15}$$

Notice that the couplings $h\phi^2$, ϕ^3, $h\phi^3$ and ϕ^4 vanish at the tree level [12,25], independent of the particular value of the Higgs portal coupling λ_P. In particular, the rigorous GW treatment for multiple scalar fields states that in the model studied here there are no Higgs decays to the scalons on the tree level [12,25], contrary to [14]. These points can be understood from the fact that flat direction of the tree-level potential defined by the *vev* of the unit vector field (n_h, n_ϕ) is also an eigenvector of the mass matrix with zero eigenvalue. Therefore, if a term in the tree-level potential has more than two physical ϕ fields, or two ϕ fields and a dimensionfull coupling, the respective coefficient will be zero by construction.

Due to the remnant Z_2 symmetry the Majorana fermion N is a DM candidate [31]. Our DM scenario assumes that N is heavier than the scalar ϕ. In the early Universe DM annihilates dominantly through the t-channel to $\phi\phi$ pair, while contributions suppressed by a small mixing arise from $NN \to hh$ and $NN \to h\phi$ processes. At the time of the decoupling of the DM, scalar ϕ is in the thermal equilibrium with the thermal bath of the SM particles through the Higgs portal interaction. While our numerical analysis covers all the mentioned annihilation processes, it is instructive to show the dominant one. The thermally averaged p-wave annihilation cross section for $NN \to \phi\phi$ is

$$\begin{aligned} & \langle\sigma(NN \to \phi\phi)v\rangle \\ & \quad = \frac{y^4\cos^4\theta}{96\pi}\sqrt{1 - \frac{m_\phi^2}{m_N^2}}\frac{m_N^2(9m_N^4 - 8m_N^2m_\phi^2 + 2m_\phi^4)}{(2m_N^2 - m_\phi^2)^4}v^2. \end{aligned} \tag{16}$$

In our calculations we use the observed value for the DM relic density of the Universe, $\Omega_{DM}h^2 = 0.1187(17)$ [32].

3. Results

The model introduces four new parameters: gauge coupling g_X, Yukawa coupling y and quartic scalar couplings λ_P and λ_Φ. The two constraints given by the Higgs boson mass and the dark matter relic abundance leave two undetermined parameters chosen to be m_X and m_ϕ. The mass of the X-boson has to be larger than $\sim$600 GeV to overcome the top quark contribution in order to have positive mass for the scalon. Higgs searches at LEP exclude scalon masses under 114 GeV in our model. Global fit to the current LHC data [25] gives an upper bound of $\sin\theta < 0.37$. We scan the parameter space of the model from the initial values $m_X = 600$ GeV, $m_\phi = 114$ GeV, up to $m_X = 2000$ GeV, $m_\phi = 400$ GeV.

We give our results as prediction for various quantities in the m_X–m_ϕ plane. On Fig. 1 we give mass of the DM candidate m_N and dark sector gauge coupling g_X. On Fig. 2 we give the mixing angle $\sin\theta$ and *vev* of Φ, v_Φ. Holding m_ϕ fixed while increasing m_X increases the *vev* v_ϕ naturally leading to a smaller mixing angle θ.

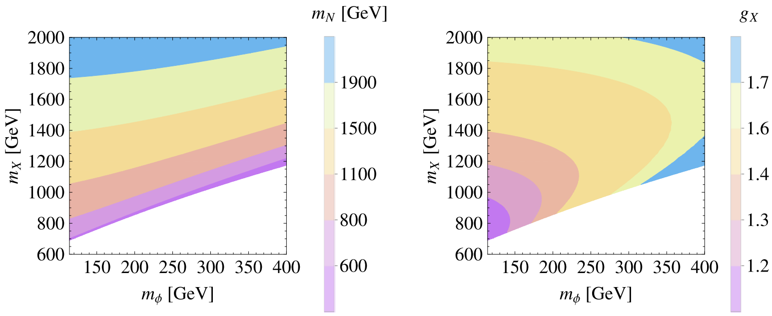

Fig. 1. Mass of the DM candidate m_N (left) and dark sector gauge coupling g_X (right) as a function of dark gauge boson mass m_X and the scalon mass m_ϕ. The lower region on the plot is excluded by the LHC bound on $\sin\theta$. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

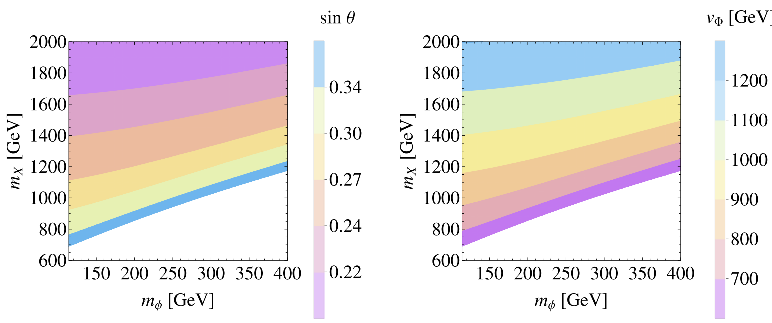

Fig. 2. Mixing angle $\sin\theta$ (left) and the *vev* of Φ, v_Φ (right) as a function of dark gauge boson mass m_X and the scalon mass m_ϕ. The lower region on the plot is excluded by the LHC bound on $\sin\theta$. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

From (16) we see that the scale v_Φ dominates the DM annihilation cross section

$$\langle \sigma v\rangle \sim y^4/m_N^2 \sim y^2/v_\Phi^2. \tag{17}$$

Therefore, in order to keep $\langle\sigma v\rangle$ fixed to its value provided by the DM relic abundance, y increases when v_Φ increases. The CW mechanism then requires that g_X is increased to have a positive scalon mass. Notice the key role played by the DM constraint; keeping m_ϕ fixed and increasing m_X leads to an increase of g_X. This is in contrast to the model without DM where one naively expects $m_\phi \sim g_X m_X$. In other words, in the regime of large v_Φ the Majorana fermion N starts to play an important role in the CW mechanism.

For the minimal value $v_\Phi \sim 700$ GeV, the DM constraint requires a relatively large Yukawa coupling. The CW mechanism pulls g_X in the same direction, which is the origin of g_X being of order one. The perturbative restrictions provide upper bounds on masses in the hidden sector. We find the mass of the DM to be in the range from 500 GeV up to a few TeV.

4. Conclusion

Postulating a hidden $U(1)_X$ sector consisting of a doubly X-charged scalar and a singly charged Majorana fermion we have examined an SI extension of the SM with Majorana fermion as a DM candidate. Using the GW approach we have calculated masses of the new particles. The Majorana fermion saturates the DM relic abundance via the $NN \to \phi\phi$ annihilation.

We predict the DM particle mass to be in the range from 500 GeV to a few TeV. While the lower bound is obtained by the LHC limit on $\sin\theta$, the upper bound is a conservative estimate set by moderate values of the dark gauge and Yukawa couplings. The DM constraint plays an essential role here as it requires an appreciable Yukawa coupling. In this sense similar results are obtained by [15,16] where DM constraint enforces a gauge coupling of order one.

A general statement may be drawn for an SI extension of SM with a new gauge group; the couplings in the hidden sector can be taken to be small provided the *vev* of the hidden scalar is large enough. However, identifying possible stable states of the hidden sector with DM particles, the scale set by CW mechanism requires moderate couplings in the hidden sector.

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