Dark Matter Phenomenology and Higgs Vacuum Stability in A Scotogenic Extension of Inert Higgs Doublet Dark Matter Model

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***Abstract*— In this work we study the dark matter phenomenology and the condition of Higgs vacuum stability of the Inert Higgs Doublet Dark Matter Model with scotogenic extension. Apart from dark matter candidate this model also allows the possibility of radiative neutrino mass in scotogenic framework. We sample over the parameter space consistent with theoretical constraints, as well as dark matter relic abundance and direct detection searches. We use one-loop renormalization group equations to explore the stability of the Higgs vacuum in this model and its effects on the viable regions of this model.**

Keywords—Beyond Standard Model, Dark matter, Vacuum Stability.

I. INTRODUCTION

The Standard Model (SM) of particle physics is an adequate description of the fundamental interactions in nature at the energies probed by the Large Hadron Collider (LHC) [1, 2]. However, there still remains certain issues which are confirmed by experimental observations but he SM is unable to solve with them. One such issue is the presence of mysterious dark matter (DM), which according to the observations from WMAP [3] and cosmic microwave background radiation by Planck [4], constitute about 26.5% of Universe. In addition to DM, there also exists problem with the stability of electroweak vacuum within the SM since the electroweak vacuum becomes unstable at large scale (~10^{10} GeV) [5–8] for top quark mass m_t = 173.2 GeV [13]. At this scale the SM Higgs quartic coupling λ_H becomes negative according to the evolution of renormalization group equations (RGE) which is an indication of possible instability of the Higgs vacuum.

In order to resolve the above mentioned issues, we need to go beyond the SM. In this work, we consider additional scalars which could serve as DM candidate and also stabilize the vacuum simultaneously. We extend the SM with a scotogenic extension of the inert higgs doublet model as proposed by Ma in 2006 [9]. Earlier works on inert doublet model has been carried out in [10-13]. In addition to DM, this framework could also explain the origin of light neutrino masses.

The paper is organized as follows. The model is described in section II with explanation to different model parameters. Section III sheds light on the dark matter phenomenology and vacuum stability. We then discuss the results in section IV and finally conclude in section V.

II. MODEL

In this model in addition to SM Higgs ϕ_1 another SU(2) scalar doublet ϕ_2 is considered. In addition three copies of fermions $N_i, i=1,2,3$, apart from the SM particle content has been considered. We include additional discrete symmetry Z_2 under which all SM-fields are even while field ϕ_2 and N_i are odd. The Yukawa lagrangian for the model is

$$L_N = \overline{N}_i \partial N_i - m_{N_i}/2\, \overline{N}_i^c N_i + y_{i\alpha}\phi_2 \overline{N}_i l_\alpha + h.c \tag{1}$$

The scalar lagrangian is given by

$$V = m_{\phi_1}^2 \phi_1^\dagger \phi_1 + m_{\phi_2}^2 \phi_2^\dagger \phi_2 + \frac{\lambda_1}{2}\left(\phi_1^\dagger \phi_1\right)^2 + \frac{\lambda_2}{2}\left(\phi_2^\dagger \phi_2\right)^2 + \lambda_3\left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4\left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right) + \frac{\lambda_5}{2}\left[\left(\phi_1^\dagger \phi_2\right)^2 + h.c\right] \tag{2}$$

After spontaneous symmetry the SM Higgs ϕ_1 while the inert doublet ϕ_2 is,

$$\phi_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix} \phi_2 = \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}(H_0 + iA_0) \end{pmatrix} \tag{3}$$

The vacuum expectation value (vev) of the neutral component of the doublet ϕ_1 is denoted by v. The h state corresponds to the physical SM Higgs-boson with mass m_h. The inert doublet consists of a neutral CP - even scalar H_0, a pseudo-scalar A_0, and a pair of charged scalars $H^\pm$ with masses m_{H_0}, m_{A_0} and $m_{H^\pm}$ By minimising the potential V in (2) we get the masses of different physical scalars including SM Higgs and inert particles as,

$$m_h^2 = 2\lambda_1 v^2,$$
$$m_{H^\pm}^2 = m_{\phi_2}^2 + \frac{\lambda_3}{2} v^2$$
$$m_{H_0}^2 = m_{\phi_2}^2 + \Lambda_L v^2$$
$$m_{A_0}^2 = m_{\phi_2}^2 + \Lambda'_L v^2 \qquad (4)$$

where,

$$\Lambda_L = \frac{\lambda_3 + \lambda_4 + \lambda_5}{2} \quad \text{and} \quad \Lambda'_L = \frac{\lambda_3 + \lambda_4 - \lambda_5}{2}$$

III. Dark Matter Phenomenology And Higgs Vacuum Stability

In the model one of the scalars between H_0 and A_0 could serve as a DM candidate. In this work we consider CP - even scalar H_0 as the DM candidate. The Z_2 symmetry prevents the decay of the DM candidate to SM particles. As ϕ_2 is inert, no mixing between ϕ_1 and ϕ_2 is possible and the gauge eigenstates are same as the mass eigenstates for the Higgs bosons. The Z_2 -symmetry further prevents any such mixing through the Higgs portal. Hence, the Inert Higgs doublet does not couple to fermions.

In this work we constrain the parameter space of the model, by using the measured value of the DM relic abundance provided by the Planck experiment [2].

$$0.119 < \Omega_{DM} h^2 < 0.121 \qquad (5)$$

We use the MicrOmegas package [14] to compute the correct relic abundance for our DM candidate satisfying PLANCK constraints. Further we apply the limits on DM direct detection cross-section from XEXON1T [15, 16] experiment.

In order that the the potential (2) is bounded from below, the quartic couplings must satisfy the stability conditions [17].

$$\lambda_1, \lambda_2 > 0,$$
$$2\lambda_1 \lambda_2 + \lambda_3 > 0,$$
$$2\lambda_1 \lambda_2 + \lambda_3 + \lambda_4 - 2(\lambda_5) > 0 \qquad (6)$$

As already mentioned in section I, in SM the Higgs quartic coupling λ_H becomes negative at a scale around 10^{10} GeV 5–8], due to top quark Yukawa coupling $y_t \sim O(1)$. The addition of new scalars can stabilize the vacuum [18–22] by providing a positive contribution to the beta function of λ_H. For doing the analysis we use one-loop renormalization group equations by implementing the model in SARAH 4.14.3 [23] and the beta functions for various gauge, quartic and Yukawa couplings in the model are evaluated up to one-loop level.

IV. Results And Discussions

We have considered a scotogenic extension of SM with inert doublet model, such that the lightest of CP even scalar of the inert doublet i.e H_0 with mass m_{DM} is considered as the DM candidate. We compute the relic abundance of DM in our

model, and in Fig.1 we have shown a plot of variation of relic density with dark matter mass. The black line represent the observed relic density as given in (5). In Fig. 2 we observe the possibility of generating correct spin-independent cross section σ_{SI} varying with DM mass, which is consistent with the experimental bounds from XENON1T experiment [15, 16]. In Fig. 2 the red points represent the experimental points from XENON1T experiment for spin-independent cross section. The blue points below the red curve satisfies the constraint of correct relic density. The parameters used are $m_h = 125$ GeV, $\lambda_2 = 0.01$ .Thus the model predicts DM mass above 800 GeV that could give correct relic density.

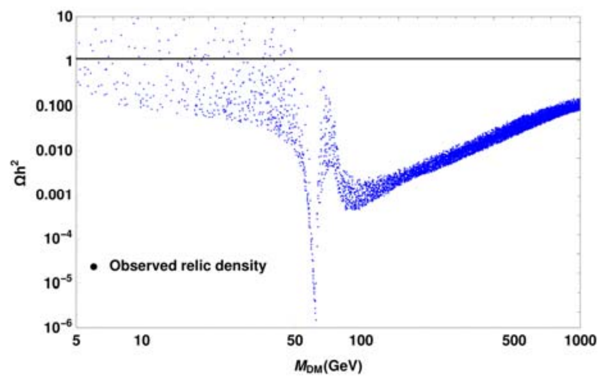

Fig. 1. *Plot of variation of relic density* Ωh^2 *with DM mass* m_{DM}

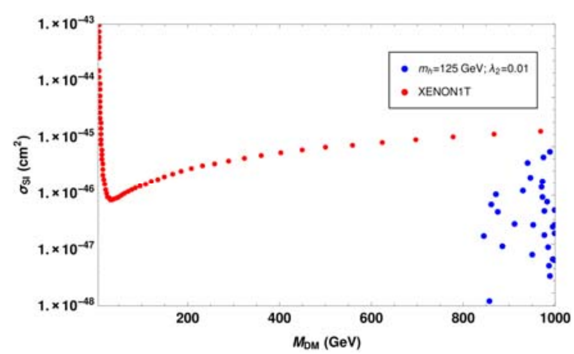

Fig. 2. *Plot of variation of Spin-independent cross section* σ_{SI} *with DM mass* m_{DM}

We also studied the role of the new scalars in the stability of the electroweak vacuum by performing an RG analysis for the Higgs quartic coupling. Fig. 3 shows the one loop running of the Higgs quartic coupling λ_H as a function of the energy scale μ. The blue curve represents the contribution from SM and the red line represents the contribution for the scotogenic extension of inert doublet model. It is found that with respect to the SM case, the additional scalars enhance the vacuum stability scale to ~ 10^8 GeV and makes $\lambda_H > 0$ near the Planck scale.

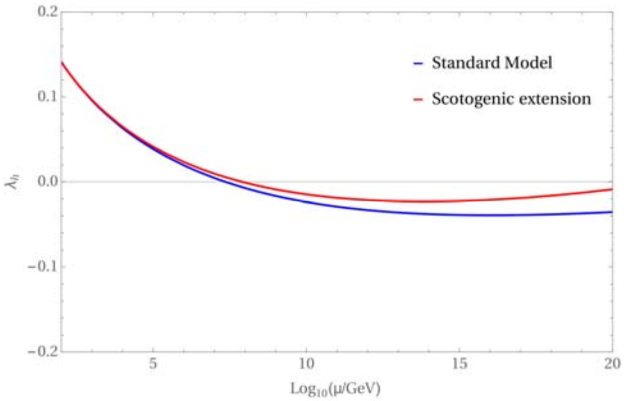

Fig. 3. *One loop running of the Higgs quartic coupling* λ_H *as a function of the energy scale* μ.

V. CONCLUSIONS

To conclude, we studied the possibility of enhancement of stability of vacuum due to scotogenic extension of SM with inert doublet fields, which also can explain correct DM relic density. It is seen that DM mass above 800 GeV very well satisfy the constraints from relic abundance and that of spin-independent cross-section measurement experiment like XENON1T. Thus the model predicts DM candidates in this mass range which could be probed in higher sensitivity experiments like XENON1T in future. In addition the scalar fields of model serves the purpose of stabilizing the higgs vacuum.

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