Physics Letters B 771 (2017) 624–632

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Lepton portal limit of inert Higgs doublet dark matter with radiative neutrino mass

Debasish Borah [a], Soumya Sadhukhan [b,*], Shibananda Sahoo [a]

[a] Department of Physics, Indian Institute of Technology Guwahati, Assam 781039, India
[b] Physical Research Laboratory, Ahmedabad 380009, India

ARTICLE INFO

Article history:
Received 9 April 2017
Received in revised form 17 May 2017
Accepted 2 June 2017
Available online 12 June 2017
Editor: G.F. Giudice

ABSTRACT

We study an extension of the Inert Higgs Doublet Model (IHDM) by three copies of right handed neutrinos and heavy charged leptons such that both the inert Higgs doublet and the heavy fermions are odd under the Z_2 symmetry of the model. The neutrino masses are generated at one loop in the scotogenic fashion. Assuming the neutral scalar of the inert Higgs to be the dark matter candidate, we particularly look into the region of parameter space where dark matter relic abundance is primarily governed by the inert Higgs coupling with the leptons. This corresponds to tiny Higgs portal coupling of dark matter as well as large mass splitting within different components of the inert Higgs doublet suppressing the coannihilations. Such lepton portal couplings can still produce the correct relic abundance even if the Higgs portal couplings are arbitrarily small. Such tiny Higgs portal couplings may be responsible for suppressed dark matter nucleon cross section as well as tiny invisible branching ratio of the standard model Higgs, to be probed at ongoing and future experiments. We also briefly discuss the collider implications of such a scenario.

1. Introduction

The observational evidence suggesting the presence of dark matter (DM) in the Universe are irrefutable, with the latest data from the Planck experiment [1] indicating that approximately 27% of the present Universe is composed of dark matter. The observed abundance of DM is usually represented in terms of density parameter Ω as

$$\Omega_{\mathrm{DM}} h^2 = 0.1187 \pm 0.0017 \quad (1)$$

where $h = (\text{Hubble Parameter})/100$ is a parameter of order unity. In spite of astrophysical and cosmological evidences confirming the presence of DM, the fundamental nature of DM is not yet known. Since none of the particles in the Standard Model (SM) can fulfil the criteria of a DM candidate, several beyond Standard Model (BSM) proposals have been put forward in the last few decades. Among them, the weakly interacting massive particle (WIMP) paradigm is the most popular one. Such WIMP dark matter candidates can interact with the SM particles through weak interactions and hence can be produced at the Large Hadron Collider (LHC) or can scatter off nuclei at dark matter direct detection experiments like the ongoing LUX [2] and PandaX-II experiment [3].

Among different BSM proposals to incorporate dark matter, the inert Higgs doublet model (IHDM) [4–6] is one of the simplest extensions of the SM with an additional scalar field transforming as doublet under $SU(2)$ and having hypercharge $Y = 1$, odd under an imposed Z_2 discrete symmetry. As shown by the earlier works on IHDM, there are typically two mass ranges of DM mass satisfying the correct relic abundance criteria: one below the W boson mass and the other around 550 GeV or above. Among these, the low mass regime is particularly interesting due to stronger direct detection bounds. For example, the latest data from the LUX experiment rules out DM-nucleon spin independent cross section above around 2.2×10^{-46} cm^2 for DM mass of around 50 GeV [2]. In this mass range, as we discuss in details below, the tree level DM-SM interaction through the SM Higgs (h) portal is interesting as it can simultaneously control the relic abundance as well as the DM-nucleon scattering cross section. In this mass range, only a narrow region near the resonance $m_{\mathrm{DM}} \approx m_h/2$ is currently allowed by the LUX data. Though future DM direct detection experiments will be able to probe this region further, it could also be true that the DM-Higgs interaction is indeed too tiny to be observed at experiments. Such a tiny Higgs portal interaction will also be insufficient

* Corresponding author.
E-mail addresses: dborah@iitg.ernet.in (D. Borah), soumyas@prl.res.in (S. Sadhukhan), shibananda@iitg.ernet.in (S. Sahoo).

http://dx.doi.org/10.1016/j.physletb.2017.06.006

to produce the correct relic abundance of DM in this low mass regime. This almost rules out the low mass regime of DM in IHDM $m_{\rm DM} \lessapprox 70$ GeV.

Here we consider a simple extension of IHDM by singlet leptons (both neutral and charged) odd under the Z_2 symmetry such that the inert scalar dark matter can interact with the SM particles through these singlet leptons. This new interaction through lepton portal can revive the low mass regime of inert scalar DM even if future direct detection experiment rules out the Higgs portal interaction completely. The lepton portal interactions can also remain unconstrained from the limits on DM-nucleon interactions. Such a scenario is particularly interesting if LHC finds some signatures corresponding to the low mass regime of inert scalar DM while the direct detection continues to give null results. The dominant lepton portal interactions can explain correct relic abundance, null results at direct detection experiments and also give rise to interesting signatures at colliders. The neutral leptons added to IHDM can also give rise to tiny neutrino masses at one-loop level through scotogenic fashion [12]. We discuss the constraints on the model parameters from neutrino mass, DM constraints and also make some estimates of some interesting collider signatures while comparing them with the pure IHDM.

This article is organised as follows. In section 2, we discuss the IHDM and then consider the lepton portal extension of it in section 3. In section 4, we discuss the dark matter related studies followed by our collider estimates in section 5. We finally conclude in section 6.

2. Inert Higgs Doublet Model

The inert Higgs Doublet Model (IHDM) [4–6] is an extension of the Standard Model (SM) by an additional Higgs doublet Φ_2 and a discrete Z_2 symmetry under which all SM fields are even while $\Phi_2 \to -\Phi_2$. This Z_2 symmetry not only prevents the coupling of SM fermions to Φ_2 at renormalisable level but also forbids those terms in the scalar potential which are linear or trilinear in Φ_2. Therefore, the second Higgs doublet Φ_2 can interact with the SM particles only through its couplings to the SM Higgs doublet and the electroweak gauge bosons. The Z_2 symmetry also prevents the lightest component of Φ_2 from decaying, making it stable on cosmological scale. If one of the neutral components of Φ_2 happen to be the lightest Z_2 odd particle, then it can be a potential dark matter candidate. The scalar potential of the model involving the SM Higgs doublet Φ_1 and the inert doublet Φ_2 can be written as

$$\begin{aligned} V(\Phi_1,\Phi_2) &= \mu_1^2|\Phi_1|^2+\mu_2^2|\Phi_2|^2 \\ &+\frac{\lambda_1}{2}|\Phi_1|^4+\frac{\lambda_2}{2}|\Phi_2|^4+\lambda_3|\Phi_1|^2|\Phi_2|^2 \\ &+\lambda_4|\Phi_1^\dagger\Phi_2|^2+\{\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2+\text{h.c.}\}, \end{aligned} \tag{2}$$

To ensure that none of the neutral components of the inert Higgs doublet acquire a non-zero vacuum expectation value (vev), $\mu_2^2 > 0$ is assumed. This also prevents the Z_2 symmetry from being spontaneously broken. The electroweak symmetry breaking (EWSB) occurs due to the non-zero vev acquired by the neutral component of Φ_1. After the EWSB these two scalar doublets can be written in the following form in the unitary gauge.

$$\Phi_1 = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} H^+ \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix} \tag{3}$$

The masses of the physical scalars at tree level can be written as

$$\begin{aligned} m_h^2 &= \lambda_1 v^2, \\ m_{H^+}^2 &= \mu_2^2+\frac{1}{2}\lambda_3 v^2, \\ m_H^2 &= \mu_2^2+\frac{1}{2}(\lambda_3+\lambda_4+\lambda_5)v^2 = m_{H^\pm}^2+\frac{1}{2}(\lambda_4+\lambda_5)v^2, \\ m_A^2 &= \mu_2^2+\frac{1}{2}(\lambda_3+\lambda_4-\lambda_5)v^2 = m_{H^\pm}^2+\frac{1}{2}(\lambda_4-\lambda_5)v^2. \end{aligned} \tag{4}$$

Here m_h is the SM like Higgs boson mass, m_H, m_A are the masses of the CP even and CP odd scalars from the inert doublet. Without loss of generality, we consider $\lambda_5 < 0, \lambda_4+\lambda_5 < 0$ so that the CP even scalar is the lightest Z_2 odd particle and hence a stable dark matter candidate.

The new scalar fields discussed above can be constrained from the LEP I precision measurement of the Z boson decay width. In order to forbid the decay channel $Z \to HA$, one arrives at the constraint $m_H + m_A > m_Z$. In addition to this, the LEP II constraints roughly rule out the triangular region [7]

$$m_H < 80 \text{ GeV}, \quad m_A < 100 \text{ GeV}, \quad m_A - m_H > 8 \text{ GeV}$$

The LEP collider experiment data restrict the charged scalar mass to $m_{H^+} > 70$–90 GeV [8]. The Run 1 ATLAS dilepton limit is discussed in the context of IHDM in Ref. [9] taking into consideration of specific masses of charged Higgs. Another important restriction on m_{H^+} comes from the electroweak precision data (EWPD). Since the contribution of the additional doublet Φ_2 to electroweak S parameter is always small [4], we only consider the contribution to the electroweak T parameter here. The relevant contribution is given by [4]

$$\Delta T = \frac{1}{16\pi^2\alpha v^2}[F(m_{H^+},m_A)+F(m_{H^+},m_H)-F(m_A,m_H)] \tag{5}$$

where

$$F(m_1,m_2) = \frac{m_1^2+m_2^2}{2}-\frac{m_1^2m_2^2}{m_1^2-m_2^2}\ln\frac{m_1^2}{m_2^2} \tag{6}$$

The EWPD constraint on ΔT is given as [10]

$$-0.1 < \Delta T + T_h < 0.2 \tag{7}$$

where $T_h \approx -\frac{3}{8\pi\cos^2\theta_W}\ln\frac{m_h}{m_Z}$ is the SM Higgs contribution to the T parameter [11].

3. Lepton portal extensions of IHDM

As discussed in the introduction, considering lepton portal extensions of IHDM is very well motivated, specially from the origin of neutrino mass, dark matter direct detections and other flavour physics observables in the lepton sector. The inert Higgs doublet of the IHDM can couple to the SM leptons, if the model is suitably extended either by Z_2 odd neutral Majorana fermions or by charged vector like leptons, none of which introduce any chiral anomalies. The addition of three copies of neutral heavy singlet fermions N_i, odd under the Z_2 symmetry leads to the upgradation of the IHDM to the scotogenic model [12]. Apart from providing another dark matter candidate in terms of the lightest N_i, the model also can explain tiny neutrino masses at one loop level. In the set up we study here, all of these singlet neutral fermions are assumed to be heavier than the neutral component of the inert Higgs doublet and hence our dark matter analysis is confined to the scalar dark matter only. The relevant interaction terms of these singlet fermions can be written as

$$\mathcal{L} \supset M_N NN + \left((Y_N)_{ij}\,\bar{L}_i\tilde{\Phi}_2 N_j + \text{h.c.}\right). \tag{8}$$