Dark matter from the inert Higgs doublet model

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Abstract. Dark matter is a clear evidence of new physics beyond the Standard Model. In this work, we consider the inert doublet model where dark matter is a member of a new Higgs doublet. In this scenario, dark matter properties can be calculated. We then test model predictions against experimental results such as the LHC Higgs data, the electroweak precision measurements and dedicated dark matter searches. In addition, we subject the model to theoretical constraints: perturbativity, vacuum stability and unitarity. Finally, we identify the viable parameter space of the model.

1. Introduction

Despite the widespread success of the Standard Model (SM), there are many reasons to believe SM is not a whole story. Dark matter (DM) is a prime evidence for physics beyond the Standard Model (BSM). We have indirectly "observed" DM in many astrophysical systems spanning many different length scales. DM is invoked to explain the orbital velocities of stars in galaxies as well as orbital velocities of galaxies within the galaxies cluster. Moreover, DM also facilitate structure formation in the early universe. This last observation indicates that DM must be stable on a cosmological time scale.

Any BSM models containing a stable massive particle can potentially be the model for DM. Typically, these model invoke a discrete symmetry to stabilize the DM particle. In this framework, DM is typically produced from thermal bath while the universe was still hot. The subsequence expansion of the universe, as well as DM annihilation, dilute away the DM density. The resulting DM density at present time is called a thermal relic density. Recent measurements by the Planck and the WMAP satellites put the DM relic density at $\Omega h^2 = 0.1186 \pm 0.0020$ [1].

In this work we focus on the inert doublet model (IDM). This model is attractive because DM is connected to the Higgs boson. This connection allows us to use the LHC Higgs measurements, as well as electroweak precision measurements, to probe the parameter space of the model. Moreover, in this model DM couple to the SM particles via the Higgs boson. Thus, all the DM phenomenologies only depends on the DM-Higgs boson coupling.

The article is organized as follow. Section 2 provides a brief overview of the IDM as well as its phenomenologies. The constraints on model parameter space are discussed in Section 3. The viable parameter space of the IDM is identified in Section 4. We then conclude in Section 5.

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Figure 1. Dark matter self annihilation channels.

2. The Model

We extend the SM by an additional electroweak doublet with hypercharge 1/2, Φ . We also introduce a discrete Z_2 symmetry under which all SM fields are even while Φ is odd. This symmetry ensures that the lightest neutral component of Φ is a good DM candidate. The scalar sector of the model is characterized by the potential

$$V(H,\Phi) = -\mu_1^2 H^{\dagger} H + \mu_2^2 \Phi^{\dagger} \Phi + \frac{\lambda_1}{2} (H^{\dagger} H)^2 + \frac{\lambda_2}{2} (\Phi^{\dagger} \Phi)^2 + \lambda_3 H^{\dagger} H \Phi^{\dagger} \Phi + \lambda_4 H^{\dagger} \Phi \Phi^{\dagger} H + \frac{\lambda_5}{2} \left((\Phi^{\dagger} H)^2 + \text{h.c.} \right).$$

$$(1)$$

where H is the SM Higgs doublet. In unitary gauge, the H and Φ fields can be expanded as

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0\\ v+h \end{pmatrix}, \qquad \Phi = \begin{pmatrix} \phi^+\\ \frac{\chi+iA}{\sqrt{2}} \end{pmatrix}, \qquad (2)$$

where v = 246 GeV is the electroweak vev, h is the 125 GeV Higgs boson, ϕ^+ is a singly charged scalar, χ and A are neutral scalars. The masses of these states are related to the couplings in the potential by

$$m_h^2 = \lambda_1 v^2, \quad m_{\phi^+}^2 = \mu_2^2 + \frac{\lambda_3}{2} v^2, \quad m_{\chi}^2 = m_{\phi^+}^2 + \frac{\lambda_4 + \lambda_5}{2} v^2, \quad m_A^2 = m_{\chi}^2 - \lambda_5 v^2.$$
(3)

Notice λ_2 does not contribute to the scalar spectrum.

In this work, we focus on the case where χ accounts for the entire DM density in the universe. This means that $\lambda_4 + \lambda_5 < 0$ and $\lambda_5 < 0$. We leave the case where A is DM for future study.

2.1. Phenomenology

The couplings of χ relevant for phenomenological studies are

$$\mathcal{L}_{\chi} \supset \frac{m_W^2}{v^2} W^+ W^- \chi^2 + \frac{m_Z^2}{2v^2} Z^2 \chi^2 + \frac{\lambda_3 + \lambda_4 + \lambda_5}{4} \chi^2 (h+v)^2 + \lambda_3 v \phi^+ \phi^- h, \tag{4}$$

where the first two terms arise from gauge interaction and the last two terms come from the scalar potential. Notice the last term is not strictly speaking DM interaction. However, it is relevant for Higgs phenomenology.

We see from the interactions in equation (4), that DM can annihilate directly into a pair of W, Z or h if they are kinematically open. DM can also annihilate to a pair of SM particles through the Higgs boson, see figure 1. These annihilation channels are important for determining the DM relic density as well as the possible gamma ray signals from regions of dense DM population such as dwarf galaxy or the galactic center.

The interaction between a single Higgs boson and a pair of DM, proportional to $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$, gives rise to DM nucleon elastic scattering. In the case where $2m_{\chi} \leq m_h$, the same coupling also lead to decay of the Higgs boson into a pair of DM. Since DM do not like to interact with anything, this decay mode is usually referred to as an invisible decay channel of the Higgs boson.

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3. Constraints

The quartic couplings, λ_i , in equation (1) cannot be arbitrary. First, we impose perturbativity constraint $|\lambda_i| \leq 4\pi$ so that we can rely on tree-level computation. Also, the scalar potential must be bounded from below to ensure a stable vacuum. This impose non trivial conditions on the couplings [2]

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$
 (5)

Moreover, these couplings are further constrained by unitarity of the 2-2 scattering amplitudes. Unitarity implies the following constraints on the couplings [3]

$$|\lambda_3 + 2\lambda_4 \pm 3\lambda_5| \le 8\pi, \quad 3(\lambda_1 + \lambda_2) + \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2} \le 16\pi.$$
 (6)

In addition to the constraints imposed by theoretical considerations above, the existence of new scalar bosons impacts low energy precisions measurements. These measurements are parametrized by the electroweak oblique parameter S and T. The most updated measurements of these parameters are $S = 0.06 \pm 0.11$ and $T = 0.10 \pm 0.07$ with a correlation coefficient of 0.92 [4]. For the IDM, the expressions for the S and T parameters can be deduced from the general result given in Ref. [5].

Collider experiments also impose constraints on the model. The coupling between the Higgs boson and a pair of charged scalars contributes to the diphoton decay of the Higgs. This decay mode is traditionally characterized by the ratio $R_{\gamma\gamma} = Br(h \to \gamma\gamma)/Br^{SM}(h \to \gamma\gamma)$. The ratio $R_{\gamma\gamma}$ has been measured by the ATLAS and CMS experiment at the LHC [6, 7, 8]. A naive combination of their measurements gives $R_{\gamma\gamma} = 1.17 \pm 0.09$. Moreover, for light enough DM mass, $2m_{\chi} \leq m_h$, the Higgs boson can decay invisibly. The invisible branching ratio of the Higgs boson is constrained to be less than 0.37 at 95% confidence level by the ATLAS collaboration [9]¹.

Lastly, the coupling λ_{345} is constrained by the bound on DM nucleon scattering cross-section. The most recent bounds are provided by the LUX [11] and the XENON1T [12] experiments.

4. Viable parameter space

We perform a full model parameter scan to determine the viable parameter space consistent with the above constraints. We use micrOMEGAS public code [13] to compute DM relic density and DM-nucleon scattering cross-section.

In our parameter scan we take m_{χ} , m_A , m_{ϕ^+} , λ_2 and λ_{345} as free parameters. We consider parameters in the range

5 GeV
$$\leq m_{\chi} < m_A, m_{\phi^+} \leq 1000$$
 GeV, $0 < \lambda_2 < 4\pi$, and $|\lambda_{345}| \leq 0.5.$ (7)

Notice we only scan λ_{345} over a small range. This is in anticipation that χ must produces the correct DM relic density. The preliminary result of our parameter scan is shown in figure 2.

5. Discussion and Final Remarks

One can see that for light DM, $m_{\chi} \leq m_h/2$, the model is tightly constrained by the invisible decay width of the Higgs boson and the DM nucleon scattering cross-section. The intermediate DM mass range, 60 GeV $\leq m_{\chi} \leq 500$ GeV, DM can efficiently annihilate into a pair of gauge bosons via gauge interactions. As a result, this parameter range give too low relic density. For heavier DM, $m_{\chi} \gtrsim 500$ GeV, DM become massive enough that gauge interactions alone are not

¹ CMS also measure the invisible branching ratio of the Higgs boson, $Br_{inv} \leq 0.19$ at 95% confidence level [10]. However, in this work we only use the ATLAS bound which represents a more conservative constraint.

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Figure 2. Viable parameter space for the inert doublet model. The shaded regions are excluded by the Higgs invisible decay width. The dotted (dashed) lines are the XENON1T (LUX) bounds on DM-nucleon scattering cross-section. The positive (negative) λ_{345} above (below) each line is ruled out by the corresponding experiment.

enough to annihilate away DM relic density. Thus, we get the bulk of the viable parameter space in this region. At the same time, direct detection experiments are sensitive enough to start probing this region. This region will be constrained further with the next generation of direct detection experiments such as the LZ and XENONnT.

As a possible future work, we plan to study the signal from DM annihilation. In this model, heavy DM annihilate mostly into W, Z, h and t. These particles subsequently decay to photons. These signal could be probed by gamma ray telescopes such as MAGIC, VERITAS and CTA.

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