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Cogent Physics (2015), 2: 1047559



Received: 25 January 2015
Accepted: 22 April 2015
Published: 29 May 2015

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Reviewing editor:
Anna Lipniacka, University of Bergen, Norway

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Footprint of triplet scalar dark matter in direct, indirect search and invisible Higgs decay

Seyed Yaser Ayazi^{1*} and S. Mahdi Firouzabadi²

Abstract: This article will review Inert Triplet Model (ITM) which provide candidate for dark matter (DM) particles. Then, we study possible decays of Higgs boson to DM candidate and apply current experimental data for invisible Higgs decay to constrain parameter space of ITM. We also consider indirect search for DM and use FermiLAT data to put constraints on parameter space. Ultimately, we compare this limit with constraints provided by LUX experiment for low mass DM and invisible Higgs decay.

Subjects: Astrophysics; Statistical Physics; Theoretical Physics

Keywords: dark matter; direct detection; Higgs decay; indirect search

1. Introduction

There are strong evidences for non-baryonic dark matter (DM) which according to Planck satellite (Ade et al., 2014) constitute more than 0.26 of energy density in the universe. WIMP's as a relic remnants of early universe are the most plausible candidates for DM. Since the standard model (SM) cannot explain DM evidences, there is a strong motivation to extend SM in a way to provide suitable DM candidate. Singlet scalar or fermion fields are preferred as simple candidates for DM. It is shown that allowed regions of parameters space for these models are strictly limited by WMAP data (Bento, Bertolami, & Rosenfeld, 2001; Burgess, Pospelov, & ter Veldhuis, 2001; Davoudiasl, Kitano, Li, & Murayama, 2005; Ettefaghi and Moazzemi, 2013; Kim & Lee, 2007; McDonald, 1994, 2002). One of the simplest models for a scalar DM is Inert Triplet Model (ITM). In this model, a scalar $SU(2)_L$ triplet is odd under Z_2 symmetry so that they cannot decay into the SM particles, and the neutral component of the triplets plays the role of DM.

After a few decades of expectations, the LHC has found a SM-like Higgs particle with a mass of 125 GeV. Since the Higgs boson can participate in DM-nucleon scattering and DM annihilation, current analysis of the LHC data and measurements of its decay rates would set limit on any beyond SM that provides a DM candidate.

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PUBLIC INTEREST STATEMENT

Modern Cosmology is a theory that explains formation of celestial objects and large structures by using the general relativity and laws of physics. "The Dark Matter problem" addresses the issue of a huge missing mass and energy in the context of modern cosmology which is not visible and do not interact with Photons. On the other hand, the standard model of particle cannot provide suitable particle as a candidate for DM. Like many other particle physicists, we offer new extensions of SM and study their capability in explaining DM.

In this paper, we extend SM by a $SU(2)_L$ triplet scalar with hypercharge $Y = 0, 2$. The lightest component of triplet field is neutral and provides suitable candidate for DM (Ayazi & Firouzabadi, 2014). Then, we review allowed parameters space of ITM by PLANCK data and invisible Higgs decay measurement, direct and indirect detection.

This letter is organized as follows: In the next section, we introduce the model. In Section 3, we will review relic density and constraints which arise from experimental observables at LEP and LHC, direct detection and indirect detection. The conclusions are given in Section 4.

2. The model

In ITM, the matter content of SM is extended with a $SU(2)_L$ triplet scalar with $Y = 0$ or $Y = 2$. These additional fields are odd under Z_2 symmetry condition while all the SM fields own even eigenvalues. The Z_2 symmetry is not spontaneously broken since the triplet does not develop a vacuum expectation value. The triplet T for $Y = 0$ has $VEV = 0$ and the SM Higgs doublet H and the triplet T scalars are defined as:

$$T = \begin{pmatrix} \frac{1}{\sqrt{2}}T^0 & -T^+ \\ -T^- & -\frac{1}{\sqrt{2}}T^0 \end{pmatrix}, \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (1)$$

where $v = 246$ GeV. The relevant Lagrangian which is allowed by Z_2 symmetry can be given by:

$$\begin{aligned} \mathcal{L} &= |D_\mu H|^2 + \text{tr}|D_\mu T|^2 - V(H, T) \\ V(H, T) &= m^2 |H|^2 + M^2 \text{tr}[T^2] + \lambda_1 |H|^4 \\ &\quad + \lambda_2 (\text{tr}[T^2])^2 + \lambda_3 |H|^2 \text{tr}[T^2] \end{aligned} \quad (2)$$

In the case $Y = 0$, ITM has three new parameters compared to the SM. We require that Higgs potential is bounded from below, which leads to following conditions on the parameters of the potential:

$$\lambda_1, \lambda_2 \geq 0, \quad (\lambda_1 \lambda_2)^{1/2} - \frac{1}{2} |\lambda_3| > 0 \quad (3)$$

The conditions for local minimum are satisfied if and only if $m^2 < 0$, $v^2 = -m^2/2\lambda_1$ and $2M^2 + \lambda_3 v^2 > 0$. The masses of triplet scalars can be written:

$$m_{T^0} = m_{T^\pm} = \sqrt{M^2 + \frac{1}{2} \lambda_3 v^2} \quad (4)$$

Note that at tree level, masses of neutral and charged components are the same, but at loop level the T^\pm are slightly heavier than T^0 (Cirelli, Fornengo, & Strumia, 2006). The scalar and gauge interactions of ITM have been extracted in terms of real fields in Araki, Geng, and Nagao (2011). In case $Y = 0$, the Z_2 symmetry ensures that T^0 cannot decay to SM fermions and can be considered as cold DM candidate. Nevertheless, the Z boson can decay to T^\pm . The decay rate of $Z \rightarrow T^\mp T^\pm$ is given by:

$$\Gamma(Z \rightarrow T^\mp T^\pm) = \frac{g^2 c_W^2 m_Z}{\pi} \left(1 - \frac{4m_{T^\pm}^2}{m_Z^2} \right)^{3/2} \quad (5)$$

where g is the weak coupling and $c_W = \cos \theta_W$. The Z boson decay width was measured by LEP experiment ($\Gamma_Z = 2.4952 \pm 0.0023$ GeV). This measurement is consistent with SM prediction. This means the Z boson decay width will strictly constrain ITM parameters space. Therefore, we assume that $m_{T^0}, m_{T^\pm} > 45.5$ GeV.

In case $Y = 2$, the $SU(2)_L$ triplet can be parameterized with five new parameters. The ITM with $Y = 2$ is already excluded by the limits from direct detection experiments. There won't be any use to study the case in this regard (Araki et al., 2011).

3. Observables and numerical results

In this section, we will review the relic density conditions for ITM and constraints arising from experimental observables at LHC, direct and indirect detection. In our analysis, we noticed that experimental observables are only sensitive to λ_3 and m_{DM} . We should mention λ_2 as self interaction parameter causes negligible effect on relic density.

3.1. Relic density

The relic density of DM is well measured by WMAP and Planck experiments and the current value is (Ade et al., 2014):

$$\Omega_{DM} h^2 = 0.1199 \pm 0.0027 \tag{6}$$

where $h = 0.67 \pm 0.012$ is the scaled current Hubble parameter in units of 100 km/s.Mpc. In the following, we will use this value as upper bound on the contribution of ITM in production of DM. Before the onset of freeze out, the universe is hot and dense. As the universe expand, the temperature fall down. Ultimately T^0 particles will become so rare that they will not be able to find each other fast enough to maintain the equilibrium abundance. So the equilibrium ends and the freeze out starts. Inert particles, T^0 , can contribute in the relic density of DM through freeze-out mechanism. Solving Boltzman equation will determine the freeze-out abundance. We have used *LanHep* (Semenov, 2009) to generate model files which *Micromega* 3.2 (Bélanger, Boudjema, Pukhov, & Semenov, 2014) employs to calculate relic density. The relic density as a function of interaction rate changes for the different values in parameter space. Figures 1 and 2 indicate how inert particles contribute in DM density for the different values of mass and coupling. In large mass regimes and low couplings, inert particle can constitute whole the DM which is very plausible. As it is seen in Figures 1 and 2, in context of ITM, in mass regimes lower than 7 TeV, relic density conditions are satisfied. We emphasise that for $m_{DM} \leq 2$ TeV, ITM cannot contribute effectively in the relic density and it demands multi-components DM to explain whole density.

Figure 1. Relic density as a function of DM mass for all the valid values of λ_3 . The shaded cyan panel indicates regions in which T^0 particles contribute more than 10 per cent of dark matter density.

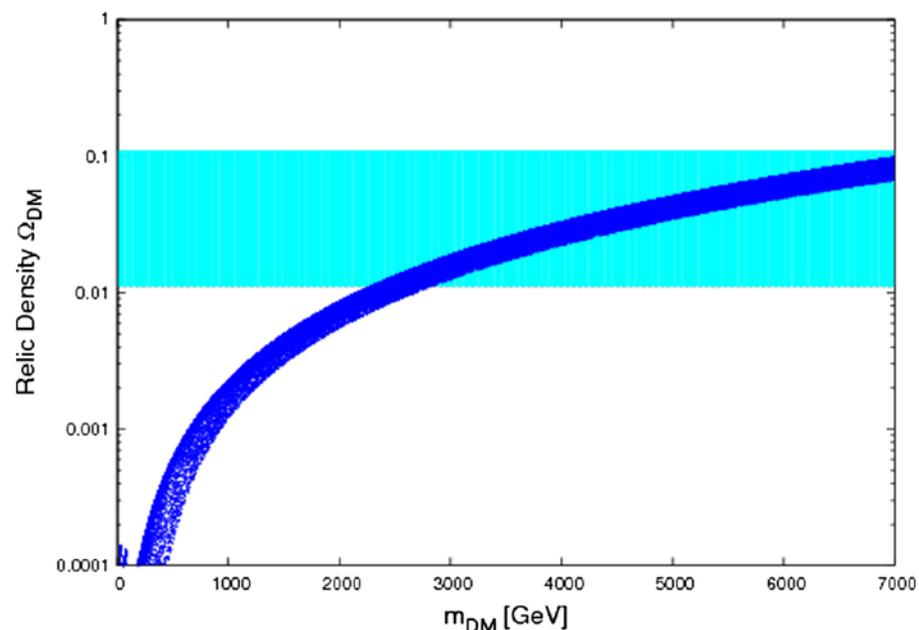
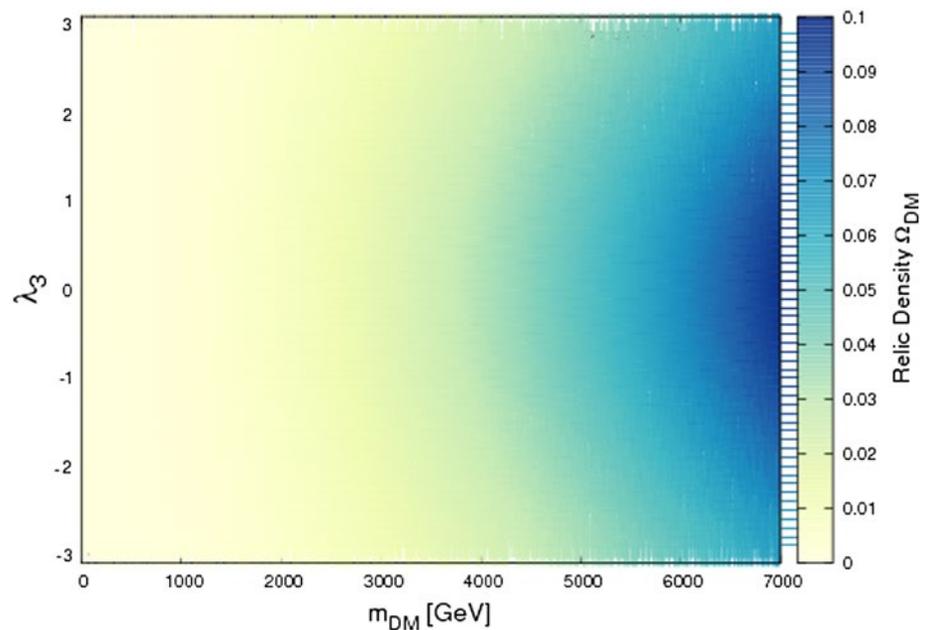


Figure 2. The relic density plot in λ_3 and DM mass plane. The shaded blue region leads to more participation in relic density.



3.2. Direct detection

In the case of $Y = 0$, DM candidate can interact with nucleon by exchanging Higgs boson. The DM–nucleon scattering cross section is given by (Giedt, Thomas, & Young, 2009):

$$\sigma_{SI} = \frac{\lambda_3^2 f_N^2}{4\pi m_h^4} \frac{m_N^4}{(m_N + m_{T^0})^2} \quad (7)$$

where the coupling constant f_N is given by nuclear matrix elements (He, Li, Li, Tandean, & Tsai, 2009) and $m_N = 0.939$ GeV is nucleon mass. The most strict bound on the DM–nucleon cross section obtained from LUX (Akerib et al., 2014) experiment. The minimum upper limit on the spin independent cross section for WIMP mass of 33 GeV is:

$$\sigma_{SI} \leq 7.6 \times 10^{-46} \text{ cm}^2 \quad (8)$$

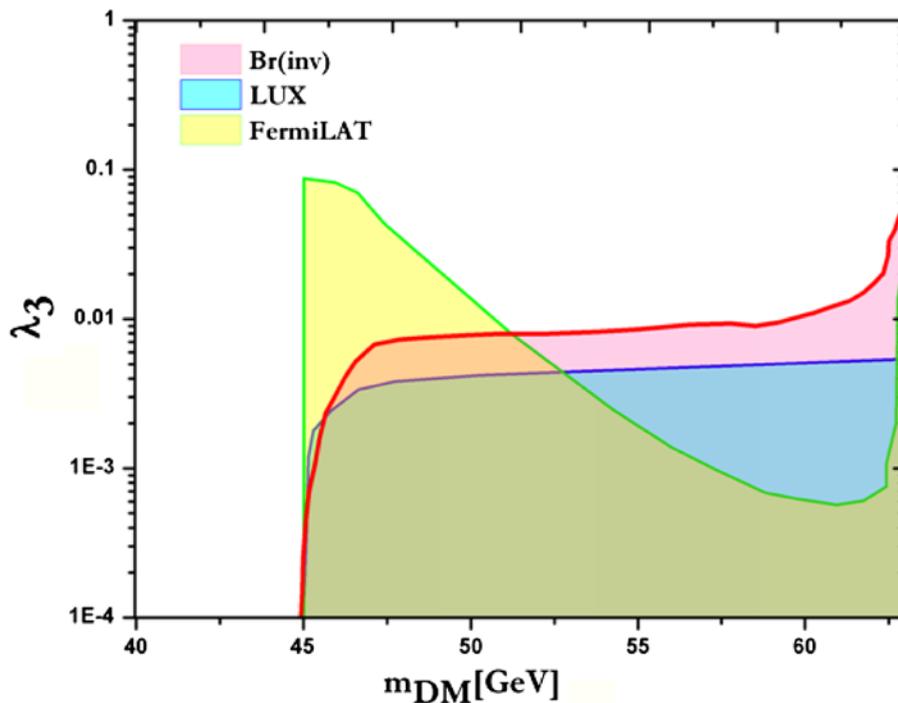
We have applied this limit as most conservative constraint for whole mass spectrum. As it was mentioned in $Y = 2$ case, due to gauge coupling of Z to DM candidate, the DM–nucleon cross section is 10^{-38} cm^2 and much larger than upper limit by LUX experiment. This excludes all the regions of parameter.

Figure 3 shows allowed region in DM mass and λ_3 couplings plane which does not violate 90% C.L experimental upper bounds of LUX for $m_Z/2 < m_{T^0} < m_h/2$. In this figure, we compare these bounds with other constraints which arise from other observables.

3.3. Invisible Higgs decays

A SM-like Higgs boson was discovered at the LHC in 2012. Some extensions of the SM allow a Higgs particle to decay into new stable particle which is not observed by ATLAS and CMS detectors yet. For example, the Higgs boson can decay into pair of DM particles. The branching ratio of the Higgs particle to invisible particle can be used directly to constrain parameter space of new physics. Nevertheless, invisible Higgs boson decay is not sensitive to DM coupling when $m_{T^0} > m_h/2$. In ITM, if triplet scalar mass is lighter than half SM Higgs boson mass, then it can contribute to the invisible decay mode of Higgs boson. The total invisible Higgs boson branching ratio is given by:

Figure 3. Shaded areas depict ranges of parameter space in mass of DM and λ_3 coupling plane which are consistent with experimental measurements of $Br(h \rightarrow Invisible)$, upper limit on σ_{SI}^{DM-N} (indirect detection) and σ_{SI}^{DM-P} (direct detection).



$$Br(h \rightarrow Invisible) = \frac{\Gamma(h \rightarrow Inv)_{SM} + \Gamma(h \rightarrow 2T^0)}{\Gamma(h)_{ITM}} \quad (9)$$

where $\Gamma(h)_{SM} = 4.15 \text{ MeV}$ (Dittmaier et al., 2011) is total width of Higgs boson in SM and $\Gamma(h)_{ITM}$ is total decay width of Higgs boson in ITM:

$$\Gamma(h)_{ITM} = \Gamma(h)_{SM} + \sum_{\chi=T^0, T^\pm, \gamma} \Gamma(h \rightarrow 2\chi) \quad (10)$$

The partial width for $h \rightarrow 2T^0$ and $h \rightarrow T^\pm T^\pm$ is given by:

$$\begin{aligned} \Gamma(h \rightarrow 2T^0) &= \frac{\lambda_3^2 v_0^2}{4\pi m_h} \sqrt{1 - \frac{4m_{T^0}^2}{m_h^2}} \\ \Gamma(h \rightarrow T^\pm T^\pm) &= \frac{\lambda_3^2 v_0^2}{\pi m_h} \sqrt{1 - \frac{4m_{T^\pm}^2}{m_h^2}} \end{aligned} \quad (11)$$

and $h \rightarrow 2\gamma$ was given in Ayazi and Firouzabadi (2014). The SM branching ratio for the decay of Higgs to invisible particles is 1.2×10^{-3} which is produced by $h \rightarrow ZZ^* \rightarrow 4\nu$ (Brein, Djouadi, & Harlander, 2004; Denner, Heinemeyer, Puljak, Rebuszi, & Spira, 2011; Dittmaier et al., 2012; Heinemeyer et al., 2013). A search for evidence of invisible decay mode of a Higgs boson has done by ATLAS collaboration and an upper limit of 75% with 95% C.L is set on branching ratio of Higgs boson invisible mode (Aad et al., 2014). Since invisible Higgs decay is forbidden kinematically for $m_D > m_{h/2}$, we present our results for $Br(h \rightarrow Invisible)$ and other observables only for $m_z/2 < m_{T^0} < m_{h/2}$. In Figure 3, we suppose $m_z/2 < m_{T^0} < m_{h/2}$ and depict allowed region in mass of DM and λ_3 coupling plane which is consistent with experimental upper limit on $Br(h \rightarrow Invisible)$ (with 95% C.L). It is remarkable that valid area of $Br(h \rightarrow Invisible)$ and direct detection experiments is very similar.

3.4. Annihilation of DM into monochromatic gamma-ray

DM particles annihilation or decay can produce monochromatic photon and contribute to the diffuse gamma-ray background. In ITM, T^\pm can contribute to annihilation of DM candidate into monochromatic photons $2T^0 \rightarrow 2\gamma$. The amplitude of possible annihilation of DM candidate in ITM into 2γ has been calculated in Ayazi and Firouzabadi (2014).

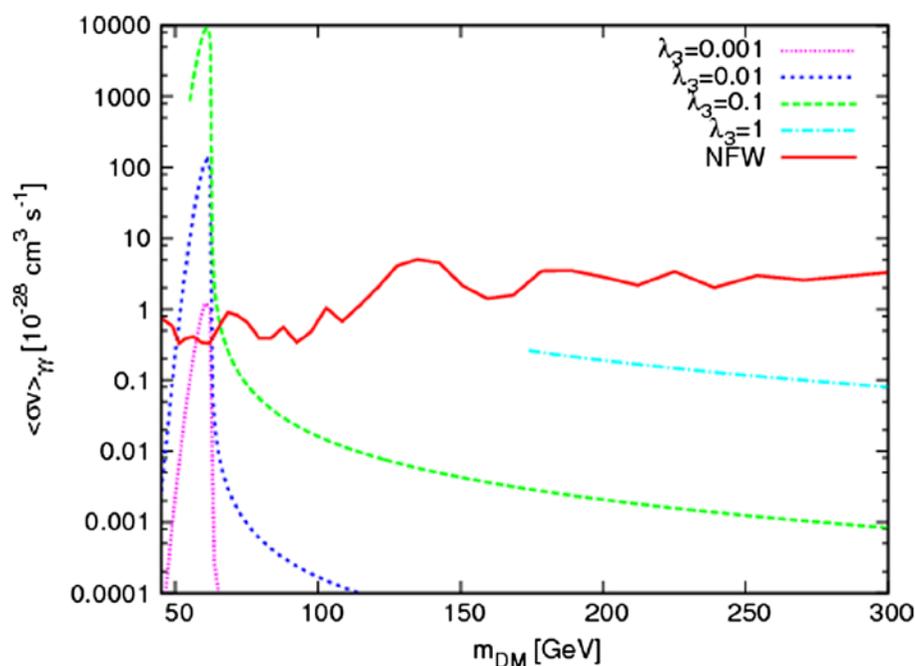
Flux upper limits for diffuse gamma-ray background and gamma-ray spectral lines from 7 to 300 GeV obtained from 3.7 years data have been presented by FermiLAT collaboration in Ackermann et al. (2013). In this section, we obtain thermal average cross section of annihilation and apply these data to set constrain on ITM parameter space. In Figure 4, we display the thermal average cross section for annihilation of DM to $\gamma\gamma$ as a function of the DM mass for several values of λ_3 . For process $2T^0 \rightarrow \gamma\gamma$, we assume $E_\gamma = m_{DM}$. The solid red lines depicts the upper limits on annihilation cross section for NFW density profile in the Milky Way which have borrowed from Ackermann et al. (2013). In this figure, for $m_{DM} > 63$ GeV, total annihilation cross section is much lower than FermiLAT upper limit. This means FermiLAT data cannot constrain ITM parameters space in this region. The current upper limits of LUX and FermiLAT are based on the event rate counting. The number of related events is correlated with number density and cross section. ITM in low-mass regime makes small portion of DM density and this will loose the reported upper bounds on the cross section. In our analysis, we apply the most conservative bound to avoid consequential statistical uncertainty.

For low DM mass ($m_{DM} < 63$ GeV near to the pole of Higgs propagator at $m_{DM} = m_h/2$), the annihilation cross section increases and will be larger than upper limit. To study this phenomena, we consider the minimum upper limit on $\sigma_{FermiLAT} = 0.33 \times 10^{-28}$ for NFW profile (Navarro, Frenk, & White, 1996) in Figure 3 and depict allowed regions on DM mass and λ_3 coupling plane which are consistent with this limit. We compared all results for direct search, invisible Higgs decay and indirect search in this figure. It is remarkable that indirect search constraint is stronger than direct detection limit in region $52 < m_{DM} < 63$.

4. Concluding remarks

In this letter, we have presented an extension of SM which includes a $SU(2)_L$ triplet scalar with hypercharge $Y = 0, 2$. This model provide suitable candidate for DM, because the lightest component

Figure 4. The thermal average annihilation cross section of T^\pm (DM) to $\gamma\gamma$ as a function of the DM mass for several values of λ_3 . The solid red lines shows the upper limits on annihilation cross section which have borrowed from Ackermann et al. (2013).



of triplet field is neutral and for the $m_{DM} < 7\text{TeV}$, conditions of relic abundance are satisfied. We focus on parameter space which is allowed by PLANCK data and study collider phenomenology of inert triplet scalar DM at the LHC.

We have shown that the effect of ITM on invisible Higgs decay for low mass DM ($m_{DM} < 63\text{ GeV}$) can be as large as constraints from LUX direct detection experiment (see Figure 4).

We consider the annihilation cross section of DM candidate into 2γ . The minimum upper limit on annihilation cross section from FermiLAT has been employed to constraint parameters space of ITM. We also compared our results with constraints from direct detection and showed for $52 < m_{DM} < 63\text{ GeV}$, FermiLAT constraint is stronger than direct detection constraint for low mass DM.

We must conclude that collider physics and DM experiments strictly confine the model parameter space only in low-mass regime which cannot participate in relic density efficiently. However, the heavy mass regime will remain as the possibility for the DM in universe.

Acknowledgements

We would like to thank the organizer of “From Higgs to Dark Matter” conference held at Geilo, Norway (14–17 December 2014) where this paper was presented.

Funding

This work was supported by the Institute for Research in Fundamental Sciences (IPM).

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Citation information

Cite this article as: Footprint of triplet scalar dark matter in direct, indirect search and invisible Higgs decay, Seyed Yaser Ayazi & S. Mahdi Firouzabadi, *Cogent Physics* (2015), 2: 1047559.

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Note

1. This article is associated with the From Higgs to Dark Matter 2014 meeting in Geilo, Norway.

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