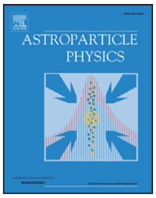
Astroparticle Physics 71 (2015) 31–35

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys



The finite shelf life of minimal Higgs portal dark matter

Frederick S. Sage[a], Rainer Dick[a,*]

[a] Department of Physics and Engineering Physics, University of Saskatchewan, 116 Science Place, Saskatoon, SK, Canada S7N 5E2

ARTICLE INFO

Article history:
Received 13 November 2014
Revised 13 May 2015
Accepted 18 May 2015
Available online 27 May 2015

Keywords:
Minimal dark matter models
Direct dark matter search
Nuclear recoils
Higgs nucleon coupling
Higgs portal

ABSTRACT

We point out that even a very conservative estimate for the uncertainty of the effective Higgs-nucleon coupling yields nuclear recoil cross sections for perturbative Higgs portal dark matter models which will be probed by DEAP-3600 and XENON1T within two years of observations.

1. Introduction

The bullet-type clusters have conclusively demonstrated the existence of dark matter halos which leave the decelerated baryonic gas components of galaxy clusters behind during collisions [1,2]. Furthermore, recent observations also indicate collisional separation of X-ray gas and dark matter halos in smaller systems [3]. The resulting estimates on upper limits of the specific internal dark matter interaction cross sections vary from 1.25 cm^2/g [4] to 10 cm^2/g [3], but the general evidence is clearly that dark matter particles in these systems are very weakly interacting with baryons or other dark matter particles.

Bullet-type clusters constitute only one example of the increasing number of astronomical proofs for the existence of dark matter, and yet all attempts to observe signatures of dark matter in cosmic rays or in particle physics labs remain inconclusive at best. Many of the dark matter models which were motivated by developments in particle physics increase the number of helicity states in particle physics by more than a factor of two, thus naturally providing for large parameter spaces which limit the predictive power of these theories. On the other hand, it has been realized already a long time ago that Higgs exchange provides for a natural interaction mechanism between dark matter particles and baryonic matter, thus also motivating bottom-up attempts to solutions of the dark matter problem which add only a small number of electroweak singlets to account for dark matter [5–8]. The revival of this porposal by Patt and Wilczek [9] has triggered a flurry of activity on minimal dark matter models in recent years, in particular on indirect detection of minimal dark matter [10–13] and on constraints from Big Bang nucleosynthesis and from vacuum stability [12,14]. Occam's razor naturally motivates investigations of dark matter models with small hidden sectors, but another attractive feature from a scientific perspective is their predictive power. Adding only two or three new parameters to the Standard Model leads to highly constrained theories without much wiggle room to avoid experimental bounds. This is a very rewarding feature if we want to reap maximum benefits from current and upcoming dark matter search experiments. We will limit attention in the present paper to the highly constrained minimal Higgs portal models and point out that within the mass range between 200 GeV and 2 TeV, they will fit into the anticipated sensitivity ranges of DEAP-3600 and XENON1T.

For the purposes of this paper, we define a minimal dark matter model as a model which extends the Standard Model by only one new particle species within the energy range that can be tested by the LHC, and we invoke the usual assumption of thermal dark matter creation in the early universe. This already rules out minimal fermionic Higgs portal models which would add a Lagrangian of the kind

$$\begin{aligned}\mathcal{L}_\chi &= \overline{\chi}\left(\mathrm{i}\gamma^\mu\partial_\mu - m_\chi^{(0)}\right)\chi - \frac{1}{\mu}\overline{\chi}\chi H^+\cdot H\\ &= \overline{\chi}\left(\mathrm{i}\gamma^\mu\partial_\mu - m_\chi\right)\chi - \frac{v_h}{\mu}\overline{\chi}\chi h - \frac{1}{2\mu}\overline{\chi}\chi h^2 \qquad (1)\end{aligned}$$

to the Standard Model. The second line is the Lagrangian in unitary gauge

$$H = \frac{v_h + h}{\sqrt{2}}\begin{pmatrix}0\\1\end{pmatrix},$$

and μ has dimension of mass. The requirement of thermal dark matter creation relates the mass of dark matter particles to their coupling

---

[*] Corresponding author. Tel.: +1 3069666443.
E-mail address: rainer.dick@usask.ca (R. Dick).

http://dx.doi.org/10.1016/j.astropartphys.2015.05.001

strengths to Standard Model particles, and the analysis for (1) reveals e.g. that μ should be around 900 GeV for $m_\chi = 200$ GeV, with μ decreasing for increasing m_χ. Fermionic dark matter models are therefore not strictly minimal in the sense that they would require at least one additional particle species in the TeV range, see e.g. [15–17] for "next-to-minimal" Higgs portal models. Indeed, these models relieve several of the constraints which exist for minimal dark matter models with only one new particle species at the TeV sacle. However, in the present investigation we wish to focus on models which are constrained by the requirement of only one new particle at the TeV scale. The constraints on fermionic models leave scalar electroweak singlets or vector electroweak singlets as the only possible options with only one new particle species within the LHC search range. This would add Lagrangians

$$\mathcal{L}_S = -\frac{1}{2}\partial S\cdot\partial S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4}S^4 - \frac{\eta_S v_h}{2}S^2 h - \frac{\eta_S}{4}S^2 h^2 \tag{2}$$

or

$$\begin{aligned}\mathcal{L}_V = &-\frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\lambda_V}{4}(V_\mu V^\mu)^2 - \frac{\eta_V v_h}{2}V_\mu V^\mu h\\ &- \frac{\eta_V}{4}V_\mu V^\mu h^2,\end{aligned} \tag{3}$$

$$V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu, \tag{4}$$

respectively, to the Standard Model Lagrangian. The dark matter mass term generically has tree-level and dynamical contributions, but purely dynamical mass generation from conformally invariant models is also of interest, see e.g. [18,19] for scalar models. An updated analysis of the general scalar minimal Higgs portal dark matter model was recently presented by Cline and collaborators for a particular value of the effective Higgs-nucleon coupling [20]. We implement a very conservative estimate of the uncertainties of nucleon strangeness and light quark content, thus including a band of possible Higgs-nucleon couplings in our analysis and we also discuss the vector model.

Analysis of the correlation between dark matter mass and couplings from thermal creation requires the corresponding dark matter annihilation cross sections. For completeness we recall the leading order contributions for scalar singlet annihilations into Higgs, fermions, and gauge bosons,

$$\sigma_{SS\to hh} = \eta_S^2\frac{\sqrt{k^2+m_S^2-m_h^2}}{32\pi k(k^2+m_S^2)}\frac{(2k^2+2m_S^2+m_h^2)^2}{(4k^2+4m_S^2-m_h^2)^2+m_h^2\Gamma_h^2}, \tag{5}$$

$$\sigma_{SS\to f\bar{f}} = N_c\eta_S^2\frac{(k^2+m_S^2-m_f^2)^{3/2}}{8\pi k(k^2+m_S^2)}\frac{m_f^2}{(4k^2+4m_S^2-m_h^2)^2+m_h^2\Gamma_h^2}, \tag{6}$$

with $N_c = 1$ for leptons and $N_c = 3$ for quarks, and

$$\begin{aligned}\sigma_{SS\to ZZ,W^+W^-} = &\frac{2m_{W,Z}^4+(m_{W,Z}^2-2k^2-2m_S^2)^2}{(4k^2+4m_S^2-m_h^2)^2+m_h^2\Gamma_h^2}\\ &\times\frac{\eta_S^2\sqrt{k^2+m_S^2-m_{W,Z}^2}}{16\pi k(k^2+m_S^2)(1+\delta_z)},\end{aligned} \tag{7}$$

where $\delta_z = 1$ for annihilation into Z bosons and $\delta_z = 0$ for annihilation into W^+W^-.

The cross sections for annihilation of the dark vector bosons are

$$\begin{aligned}\sigma_{VV\to hh} = &\frac{\eta_V^2\sqrt{k^2+m_V^2-m_h^2}}{288\pi k(k^2+m_V^2)}\left(\frac{2k^2+2m_V^2+m_h^2}{4k^2+4m_V^2-m_h^2}\right)^2\\ &\times\frac{(2k^2+m_V^2)^2+2m_V^4}{m_V^4},\end{aligned} \tag{8}$$

$$\sigma_{VV\to f\bar{f}} = N_c\frac{\eta_V^2 m_f^2(k^2+m_V^2-m_f^2)^{3/2}}{72\pi m_V^4 k(k^2+m_V^2)}\frac{(2k^2+m_V^2)^2+2m_V^4}{(4k^2+4m_V^2-m_h^2)^2+m_h^2\Gamma_h^2}, \tag{9}$$

and

$$\begin{aligned}\sigma_{VV\to ZZ,W^+W^-} = &\frac{\eta_V^2\sqrt{k^2+m_V^2-m_{W,Z}^2}}{144\pi(1+\delta_z)k(k^2+m_V^2)}\\ &\times\frac{(2k^2+2m_V^2-m_{W,Z}^2)^2+2m_{W,Z}^4}{(4k^2+4m_V^2-m_h^2)^2+m_h^2\Gamma_h^2}\\ &\times\frac{(2k^2+m_V^2)^2+2m_V^4}{m_V^4}.\end{aligned} \tag{10}$$

Eqs. (5)–(10) are the annihilation cross sections in the center of mass frame, i.e. k is the magnitude of the momenta $\pm\vec{k}$ of the colliding dark matter particles. Calculation in the center of mass frame is sufficient since we only need the velocity weighted annihilation cross sections $v\sigma$ in the non-relativistic limit, which is frame independent. Eqs. (5)–(10) yield the velocity weighted annihilation cross sections through multiplication with $v = 2k/\sqrt{k^2+m_S^2}$ or $v = 2k/\sqrt{k^2+m_V^2}$, respectively. The velocity weighted annihilation cross section $v\sigma_{VV\to f\bar{f}}$ in the case of light leptons and for $k \to 0$ has already been reported in [21].

We will focus on dark matter masses in the classical WIMP mass range above 200 GeV, although light dark matter masses are also under intense srutiny both due to the discussion of the proposed signals from DAMA [22], CoGeNT [23], CRESST-II [24], or CDMS [25], and due to the improved low mass search capacity of SuperCDMS [26]. Low mass windows, in spite of their appeal in other models, can be excluded for the minimal Higgs portal dark matter models ([2,3]). We will explain this in the following two paragraphs. Readers who are primarily interested in our results can safely skip the remainder of this section and continue with Section 2.

Low mass Higgs portal models with $m_D < m_h/2$ are highly constrained through the contribution of the dark matter particles to the Higgs decay width. The leading order contributions from Higgs decay to scalar or vector electroweak singlets are

$$\Gamma_{h\to SS} = \frac{\eta_S^2 v_h^2}{32\pi m_h^2}\sqrt{m_h^2-4m_S^2} \tag{11}$$

and

$$\Gamma_{h\to VV} = \frac{\eta_V^2 v_h^2}{64\pi m_h^2}\sqrt{m_h^2-4m_V^2}\,\frac{(m_h^2-2m_V^2)^2+8m_V^4}{m_V^4}, \tag{12}$$

respectively.

The Standard Model decay width of a 125 GeV Higgs is dominated by decay into light particles and therefore by small Higgs coupling constants. This yields a narrow Standard Model decay width of only about 6.3 MeV in order m^2/v_h^2, which is the proper order to compare with ([11,12]). Therefore the contributions (11–12) would dominate the Higgs decay width if the Higgs portal dark matter mass satisfies $m_D < m_h/2$. This would contradict recent bounds on the invisible Higgs decay width from colliders [27–30], unless the couplings are too small for thermal dark matter creation or the dark matter mass would be artificially tuned to be very close to $m_h/2$. The upper limits from the ATLAS and CMS collaborations on the invisible Higgs decay branching fraction are 75% and 58%, respectively [27,28]. This cannot be accommodated in the light minimal vector models due to the factor m_V^{-4} in the invisible decay constant from summation over helicity states. The coupling constants e.g. for the proposed CRESST-II mass value of 25.3 GeV [24] would be restricted to $\eta_V \lesssim 4\times10^{-3}$ from the ATLAS bound or $\eta_V \lesssim 3\times10^{-3}$ from the CMS bound, and these small couplings could not reproduce the required nucleon recoil cross sections to explain the proposed CRESST-II signal [24,31]. For the scalar model, the Higgs invisible decay limits imply weaker