Suplemento de la Revista Mexicana de Física **4** 021127 (2023) 1–8

Update on the parameter space for the dark matter with extended scalar sector

A. Hernández Cruz, J. H. Montes de Oca Yemha, and R. Gaitán Lozano

Departamento de Física, Facultad de Estudios Superiores Cuautitlán,
Universidad Nacional Autónoma de México.

Received 16 May 2023; accepted 27 September 2023

We discuss extensions to the Standard Model that increase only the scalar sector with a singlet and doublet fields. We consider the current values and limits for the Dark Matter (DM) observable in order to constraint the model parameters. We also take into account the latest data related to the physics of the Higgs. We find an update allowed regions for the masses of the DM particle for each extended model in this work.

Keywords: Dark matter; beyond standard model.

DOI: https://doi.org/10.31349/SuplRevMexFis.4.021127

1. Introduction

One of the current challenges in physics is to answer the question, what is the Dark Matter (DM) from the point of view of particle physics? The observations related to DM are obtained through rotation velocity for Galaxies and Cluster, Cosmic Microwave Background and Gravitational Lensing [1]. The Planck collaboration reports the most recent and precise value for the abundance of non-baryonic matter, $\Omega_{DM}h^2 = 0.120 \pm 0.001$ [2].

For the Standard Model (SM), which establishes the particle physics of ordinary matter in the universe, it does not contain a candidate for DM. One of the most promising candidates for the DM particle is a Weakly Interacting Massive Particle (WIMP). WIMPs, such as Scalar fields, can be included in the SM to play the role of DM candidates [1].

The search for DM is based on three different detection depending on the process involved. Indirect detection consists of the annihilation of DM to produce ordinary matter, while if there is a collision between DM with ordinary matter it is known as direct detection. The third possible detection is to collide ordinary matter to produce DM, collider detection.

We focus on the DM relic density and nucleon-DM scattering cross section, that is, indirect and direct detection respectively. The DM relic density, denoted as Ω_{DM}, can be computed using the concept of freeze-out in the context of Big Bang cosmology. Freeze-out refers to the moment in the early universe when the interactions between DM particles and other particles in the universe became inefficient, leading to a freeze in the DM abundance.

The Spin Independent (SI) scattering cross section for DM is a direct detection process in which DM interacts with ordinary matter, in the case of experiments the ordinary matter is the nuclei of the atoms in the detectors. Currently, collaborations that carry out this type of experiments only report a limit for the SI scattering cross section [3].

We implement High Energy Physics (HEP) computing packages in order to numerically obtain the Ω_{DM} and SI scattering cross section. `LanHep` package is used to write a code with the information of the SM extension [4]. Then, `LanHep` package can produce output files with such information. These files will be useful to load into specialized packages to numerically calculate physics quantities such as decay widths or scattering cross sections. In particular, we study Ω_{DM} and SI scattering cross section, then `micrOMEGAs` package is one of the most versatile package to numerically obtain DM relic density and scattering cross sections [5].

2. DM in extended scalar sectors

Of all the field content of the SM, there is only one scalar field which is doublet under $SU(2)_L$ group. One reason why there is only one doublet is for simplicity, however, there are no theoretical or even experimental reasons to assume the existence of more scalar fields that extend the standard model. The simplest proposals have been of interest for years, with the model with two doublets being one of the most studied [6–8]. This section presents two extensions to the scalar sector, one including a singlet field [9] and another including a doublet field [10–12].

2.1. Singlet scalar field

We follow closely the work developed by McDonald to present the scalar sector that adds a singlet scalar field [9,13]. In this model, the scalar sector of the SM is extended by including a complex scalar field S that it is singlet under SU(2) group. The Lagrangian that extends the SM scalar sector with the singlet scalar field is written as follows:

$$\begin{aligned}\mathcal{L}_S &= \left(\partial_\mu S\right)^* \partial^\mu S - \mu_S S^* S \\ &+ \lambda_S \left(S^\dagger S\right)\left(\Phi^\dagger \Phi\right) - \eta \left(S^\dagger S\right)^2, \end{aligned} \tag{1}$$

where μ_S, λ_S and η are free parameters, while the Φ is the SM doublet field. The expression for the S mass is a relationship between μ_S and λ_S, which is given by $m_S = \mu_S + (1/2)\lambda_S v^2$, where v is the Vacuum Expectation Value, $v = 246$ GeV. It is more convenient to rewrite $\mathcal{L}_S$ in terms of m_S rather than μ_S, as is usually done. To guarantee the stability of the S field, which is considered the candidate for DM, a Z_2 discrete symmetry is introduced, such that the S is transformed as its negative (referred to as odd) and the rest of the SM field is transformed as trivial (referred to as even). If the L_S is invariant under Z_2 symmetry, then the particle associated to S field is stable. It is important to note that L_S is also gauge invariant and renormalizable.

2.2. Doublet scalar field

Let us consider a scalar sector that is extended by including a second scalar doublet field with hypercharge 1, denoted as Φ_2 meanwhile the first doublet is written as Φ_1. Unlike the scalar sector with a singlet scalar field, the scalar sector with two doublets presents not only a more complete potential but also in the Yukawa sector both doublets can participate. Within the simple modification of introducing a field into an appropriate representation for the $SU(2)_L$ group provides a more complete model from the perspective of physics. For instance, a new source of CP violation may arise in the scalar sector [14, 15]. In the literature, extended scalar sector models that incorporate an additional doublet scalar field are commonly referred to as Two Higgs doublet Models (2HDMs) [7]. The different types of models with two doublets are classified based on the way the doublets are introduced into the Yukawa couplings. As in the singlet scalar model, Z_2 symmetry is introduced to control the couplings of the scalar fields. Only now Z_2 symmetry is introduced to suppress flavor neutral changing currents. Moreover, this suppression combined with a vacuum expectation value equal to zero for the second doublet will provide a consistent model for DM. In the specific case under last assumption, the second doublet is considered as the source of the DM candidate, this model is known as the Inert Doublet Model (IDM) [10–12].

The IDM requires a Z_2 discrete symmetry to achieve stability of the DM candidate, such that $\Phi_2 \rightarrow -\Phi_2$ while all SM fields and Φ_1 are transformed as even. The scalar potential invariant under Z_2 discrete symmetry is given by

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

After the spontaneous breaking of the electroweak symmetry, the model yields two neutral scalars $(h,\, H)$, a neutral pseudoscalar (A), and a charged scalar $(H^\pm)$, each possessing the following masses:

$$m_h^2 = \lambda_1 v^2, \tag{3}$$

$$m_H^2 = \mu_2^2 + \frac{(\lambda_3+\lambda_4+\lambda_5)v^2}{2}, \tag{4}$$

$$m_A^2 = \mu_2^2 + \frac{(\lambda_3+\lambda_4-\lambda_5)v^2}{2}, \tag{5}$$

$$m_{H^\pm}^2 = \mu_2^2 + \frac{\lambda_3 v^2}{2}. \tag{6}$$

The neutral scalar H is considered as the candidate for DM. The model presents free parameters, which are the $\mu_{1,2}$ and $\lambda_{1,\ldots,5}$. It is more convenient to select the free parameter set as $m_h, m_H, m_A, m_{H^\pm}, \lambda_2, \lambda_L$, where $\lambda_L = \lambda_3+\lambda_4+\lambda_5$ is the couplings for the interaction between h and H.

3. Dark matter detection

The search for DM is based on three types depending on the process involved. Indirect detection consists of the annihilation of DM to produce ordinary matter, while if there is a collision between DM with ordinary matter it is known as direct detection. The third possible detection is to collide ordinary matter to produce DM, collider detection.

We focus on the DM relic density and nucleon-DM scattering cross section, that is, indirect and direct detection respectively. The DM relic density, denoted as Ω_{DM}, can be computed using the concept of freeze-out in the context of Big Bang cosmology. Freeze-out refers to the moment in the early universe when the interactions between DM particles and other particles in the universe became inefficient, leading to a freeze in the DM abundance. The relic density can be calculated by considering the annihilation and expansion processes of DM particles.

The Spin Independent (SI) scattering cross section for DM is a direct detection process in which DM interacts with an ordinary matter, in the case of experiments it is with nuclei the atoms of the detectors. Currently, collaborations that carry out this type of experiments only report a limit for the SI scattering cross section [3].

To calculate both the Ω_{DM} and SI scattering cross section numerically, we implement specialized computing packages to accomplish this task. The `LanHep` package is used to write a code with the information of the SM extension [4]. `LanHep` package can produce output files with such information. These files will be useful to load into specialized packages to numerically calculate physics quantities such as decay widths or scattering cross sections. In particular, we study Ω_{DM} and SI scattering cross section associated, then the microMegas package is one of the most versatile package to numerically obtain DM quantities [5].

4. Numerical results

We obtain the Ω_{DM} and SI scattering cross section for both the models, 2.1. and 2.2. sections. The results are obtained by performing a routine in the `MicrOMEGAs` package [5] based on the models generated by the `LanHEP` package [4].

For the S as DM, the relic density and the SI scattering cross section are shown in Figs. 1 and 2, respectively.

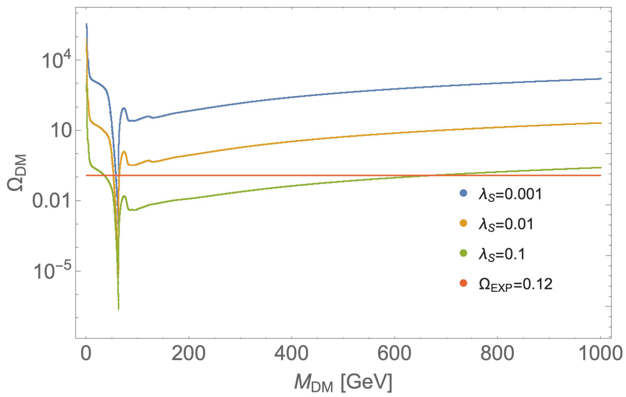

FIGURE 1. Relic density as function of DM mass for singlet scalar sector. The horizontal red line is the reported value 0.12 ± 0.001 [3].

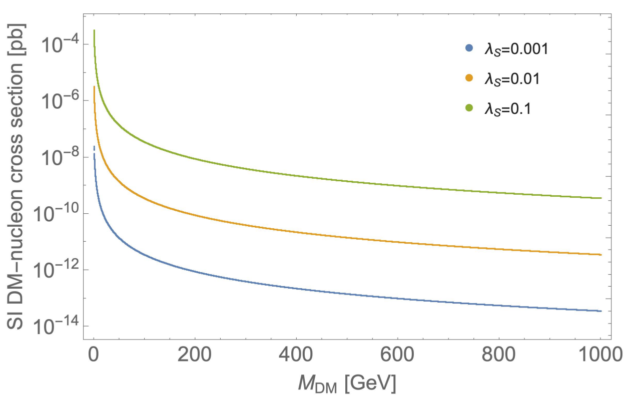

FIGURE 2. SI independent scattering cross section as function of DM mass for singlet scalar sector.

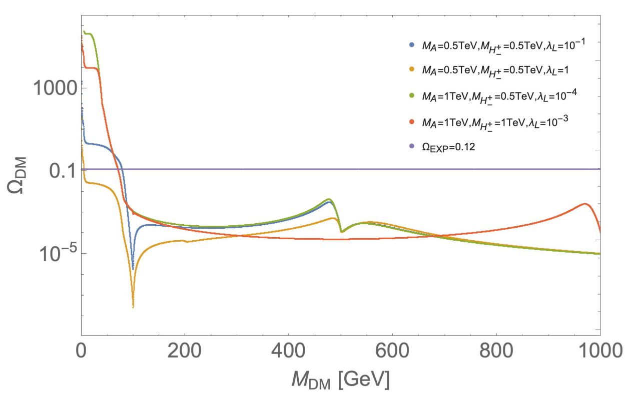

FIGURE 3. Relic density as function of DM mass for IDM. Horizontal red line is the reported value 0.12 ± 0.001 [3].

In the case of the IDM, the number of free parameters is greater than the Singlet model. However, Ω_{DM} and SI independent scattering cross section are independent on the values for λ_2 [10]. The behavior for the Ω_{DM} as function of the DM mass is shown in Fig. 3, while the Fig. 4 shows the SI independent scattering cross section. To explore the behavior of Ω_{DM} and SI scattering cross section, representative values for the m_A, $m_{H^\pm}$ and λ_L coupling are considered. These representative values are based on Refs. [10, 16].

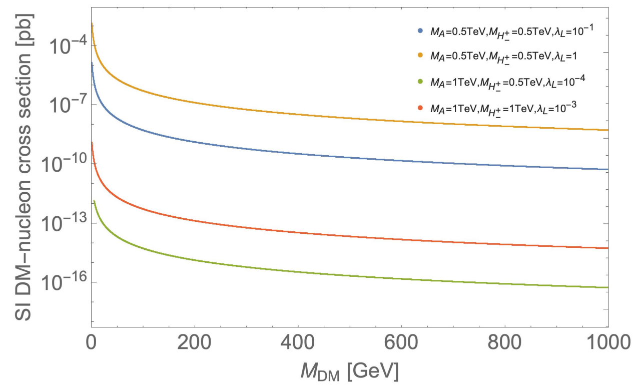

FIGURE 4. SI independent scattering cross section as function of DM mass for IDM.

5. Conclusions

A brief review of models with an additional Singlet or Doublet fields in SM scalar sector is presented. We study these extensions in order to incorporate scalar fields to play the role of DM.

In this work, the most current measured values for the mass of the Higgs boson and Ω_{DM} are considered, while in the case of direct observation there are only limits for SI scattering cross section [3]. For the Singlet scalar as DM, we obtain that the allowed mass decreases as the quartic coupling increases, for instance $m_{DM} \approx 40$ GeV for $\lambda_S = 0.1$ meanwhile $m_{DM} \approx 60$ GeV for $\lambda_S = 0.001$, see Fig. 1. In the case of IDM the Fig. 3 shows allowed masses from a few GeV to 100 GeV for the Ω reported by Planck collaboration [3].

The latest reported limit for SI scattering cross section is given by Xenon 1T [3]. For the Singlet as DM, the viable scenario occurs at $\lambda_S = 0.001$, while scenarios with larger λ_S values require the mass to be above the value accepted by Ω_{DM}. In the case of IDM, the viable scenario is obtained when $m_A = 1$ TeV, $m_{H^\pm} = 1$ TeV and $\lambda_L = 0.001$. A study that simultaneously considers the Singlet and Doublet fields can be reviewed in [16].

Finally, it is important to mention that one of the objectives of this work has been to train one of the authors to use public generic High Energy Physics packages as part of his undergraduate formation.

Acknowledgements

This work was supported by projects Programa de Apoyo a Proyectos de Investigacion e Innovación Tecnológica (PAPIIT) with registration codes IN105322 and IN102122 in Dirección General de Asuntos de Personal Académico de Universidad Nacional Autónoma de México (DGAPA-UNAM), and Cátedra de Investigación with registration code CI2208 in FES-Cuautitlán UNAM and Sistema Nacional de Investigadores (SNI) of the Consejo Nacional de Ciencia y Tecnología (CONACYT) in Mexico.

1. G. Bertone, Particle dark matter: observations, models and searches (Cambridge University Press, 2010). https://doi.org/10.1017/CBO9780511770739.
2. N. Aghanim *et al.*, Planck 2018 results-VI. Cosmological parameters, *A. & A.* **641** (2020) A6. https://doi.org/10.1051/0004-6361/201833910.
3. R. L. Workman *et al*., Particle data group, *Prog. Theor. Exp. Phys.* (2022)
4. A. Semenov, LanHEP-a package for automatic generation of Feynman rules from the Lagrangian, *Computer physics communications* **115** (1998) 124, https://doi.org/10.1016/S0010-4655(98)00143-X.
5. G. Bélanger *et al*., micrOMEGAs5. 0: Freeze-in, *Computer Physics Communications* **231** (2018) 173. https://doi.org/10.1016/j.cpc.2018.04.027.
6. J. Gunion, The Higgs hunter's guide 1st ed. (CRC Press, 1990), https://doi.org/10.1201/9780429496448.
7. G. C. Branco *et al*., Theory and phenomenology of two-Higgsdoublet models, *Physics reports* **516** (2012) 1. https://doi.org/10.1016/j.physrep.2012.02.002.
8. J. Lorenzo Díaz-Cruz, The Higgs profile in the standard model and beyond, *Rev. Mex. Fis*. **65** (2019) 419, https://doi.org/10.31349/RevMexFis.65.419.
9. J. McDonald, Gauge singlet scalars as cold dark matter, *Physical Review D* **50** (1994) 3637, https://doi.org/10.1103/PhysRevD.50.3637.
10. E. M. Dolle and S. Su, Inert dark matter, *Physical Review D* **80** (2009) 055012, https://doi.org/10.1103/PhysRevD.80.055012.
11. L. L. Honorez *et al*., The inert doublet model: an archetype for dark matter, *Journal of cosmology and Astroparticle Physics* **2007** (2007) 028. https://dx.doi.org/10.1088/1475-7516/2007/02/028.
12. L. Lopez Honorez and C. E. Yaguna, The inert doublet model of dark matter revisited, *Journal of High Energy Physics* **2010** (2010) 1. https://doi.org/10.1007/JHEP09(2010)046.
13. J. McDonald, Thermally generated gauge singlet scalars as self-interacting dark matter, *Physical review letters* **88** (2002) 091304. https://doi.org/10.1103/PhysRevLett.88.091304.
14. R. Martinez, *et al*., SM Higgs boson and $t \to cZ$ decays in the 2HDM type III with CP violation, *Phys. Rev. D* **98** (2018) 035031, https://doi.org/10.1103/PhysRevD.98.035031. https://doi.org/10.1103/PhysRevD.98.035031.
15. G. C. Branco, L. Lavoura, and J. P. Silva, CP violation, 103 (Oxford University Press, 1999). .
16. M. Arroyo-Ureña *et al.*, Dark matter in inert doublet model with one scalar singlet and U(1)X gauge symmetry, *The European Physical Journal C* **80** (2020) 788. https://doi.org/10.1140/epjc/s10052-020-8316-9.
17. W.-L. Guo and Y.-L. Wu, The real singlet scalar dark matter model, *Journal of High Energy Physics* **2010** (2010) 1. https://doi.org/10.1007/JHEP10(2010)083.
18. J. McDonald, Thermally generated gauge singlet scalars as selfinteracting dark matter, *Phys. Rev. Lett*. **88** (2002) 091304, https://doi.org/10.1103/PhysRevLett.88.091304.