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Dark Matter and Higgs Sector ¹

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Abstract.

The inert doublet model is an extension of the Standard Model of Elementary Particles that is defined by the only addition of a second Higgs doublet without couplings to quarks or leptons. This minimal framework has been studied for many reasons. In particular, it has been suggested that the new degrees of freedom contained in this doublet can account for the Dark Matter of the Universe.

1. Introduction

In spite of many and continuous efforts, the ultraviolet (UV) completion of the gravitational interaction is still an open question. In these conditions, it is difficult to make general statements about very early cosmology (although, in general, different types of new scalar fields are commonly predicted [1, 2]). However, these details are not needed to compute the relic density of many Dark Matter (DM) candidates [3, 4, 5, 6]. Although there are other possibilities [7], DM is usually assumed to be in the form of stable Weakly-interacting massive particles (WIMPs) that naturally freeze-out with the right thermal abundance. One of the most interesting features of WIMPs, is that they emerge in well-motivated particle physics scenarios as in R-parity conserving supersymmetry (SUSY) models [8, 9], universal extra dimensions (UED) [10, 11], or brane-worlds [12, 13]. Another interesting property of WIMPs, it is that they can be tested with high energy experiments as the new generation of colliders [14]. All these interesting features are also shared by the DM provided inside the Inert Higgs Doublet Model.

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2. Inert Higgs Doublet Model (IHDM)

The two-Higgs-doublet model (2HDM) is one of the simplest extensions of the Higgs mechanism of the electroweak symmetry breaking beyond the standard model (SM) [15, 16, 17, 18, 19]. In this model, an additional Higgs doublet field is introduced in the Higgs sector of the SM with the same quantum numbers. We use the notation

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a + i\chi_a \end{pmatrix}, \quad (1)$$

where $a = 1, 2$ for the Higgs doublets before the spontaneous symmetry breaking (SSB); that is, in the electroweak basis. Here ϕ_a^+ , ϕ_a and χ_a represent Higgs fields. After SSB, these Higgs fields interact with the matter fields and also self-interact via an appropriate Higgs potential. This model presents new physics such as Flavor Changing Neutral Currents (FCNC) and new types of CP violation [15, 16, 17, 18, 19]. Nevertheless, we are interested in a DM candidate; so this candidate must be a neutral scalar field which weakly interacts with other particles.

In the literature, the classification of the 2HDM is done considering the Higgs-fermion couplings given by the Yukawa terms in the Lagrangian [20]. For the IHDM just one Higgs doublet interacts with the fermions in the Yukawa terms as follows

$$\mathcal{L}_Y = Y_{ij}^{(u)} \bar{q}_{Li} \tilde{\Phi}_1 u_{Rj} + Y_{ij}^{(d)} \bar{q}_{Li} \Phi_1 d_{Rj} + h.c. + \text{leptons}, \quad (2)$$

where $\tilde{\Phi}_1 = i\sigma_2 \Phi_1^*$, $Y_{ij}^{(u,d)}$ are the Yukawa couplings for $i, j = 1, 2, 3$; u_{Ri} , d_{Ri} are the right singlets quarks and q_{Li} are left doublets under the electroweak symmetry group [20].

Now, for the potential we shall assume an additional Z_2 discrete symmetry² in order to avoid the mixing term $\Phi_1^\dagger \Phi_2$, which could introduce CP violation in the potential. Then, the potential under this last condition is

$$\begin{aligned} \mathcal{V} = & \mu_1^2 \Phi_1^\dagger \Phi_1 + \mu_2^2 \Phi_2^\dagger \Phi_2 + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\ & + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2], \end{aligned} \quad (3)$$

where $\mu_{1,2}^2$, $\lambda_{1,2,3,4}$ are real parameters, while λ_5 could be complex. The Φ_1 obtains a vacuum expectation value (VEV): $v/\sqrt{2} = 174$ GeV, as in the SM, while Φ_2 does not obtain a VEV [21, 22, 23]. Since this Z_2 symmetry is unbroken, the inert particles will be stable [26]. After SSB and by changing to the physical basis, the Yukawa terms (2) have the form [20]:

$$\begin{aligned} \mathcal{L}_{Hf\bar{f}} = & -\frac{g}{2M_W \sin \beta} \bar{d} M_d d (H^0 \sin \alpha + h^0 \cos \alpha) - \frac{ig \cot \beta}{2M_W} \bar{d} M_d \gamma_5 d A^0 \\ & -\frac{g}{2M_W \sin \beta} \bar{u} M_u u (H^0 \sin \alpha + h^0 \cos \alpha) + \frac{ig \cot \beta}{2M_W} \bar{u} M_u \gamma_5 u A^0 \\ & + \frac{g \cot \beta}{2\sqrt{2}M_W} (H^+ \bar{u} [M_u V_{CKM} (1 - \gamma_5) - V_{CKM} M_d (1 - \gamma_5)] d + h.c. \end{aligned} \quad (4)$$

where α and β angles are the mixing angles for the Higgs bosons, V_{CKM} is the CKM matrix and H^0 , h^0 are neutral CP even scalar Higgs bosons while A^0 is a neutral CP odd pseudo scalar Higgs boson.

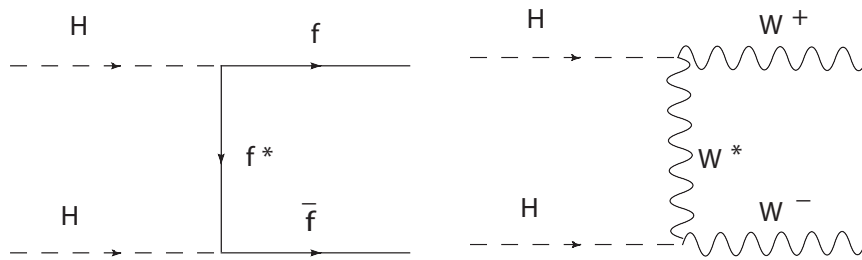


Figure 1. Feynman diagrams for the considered processes. H represents the scalar or pseudoscalar neutral Higgs bosons. On left, the products of the annihilation are fermion and antifermion pairs. On the right, the products are W charged bosons.

3. Neutral Higgs as Dark Matter candidate

The physical fields for the Higgs sector are given by two charged scalar Higgs bosons (H^\pm), two neutral CP even scalar Higgs bosons (H^0 and h^0) and one neutral CP odd pseudo scalar Higgs boson (A^0) [20]. Due to its characteristics of being inert and stable, the lightest neutral scalar Higgs boson or the pseudoscalar Higgs boson of the IHDM have been proposed as DM candidates [24, 25, 26, 27, 23, 28]. Only the scalar part h^0 has been considered for numerical results performed using the programs MICROMEAS and CALCHEP; the pseudo-scalar part A^0 is only mentioned to behave in a similar way [23, 26, 27, 28].

In order to explore the possibilities and differences of the pseudo-scalar part, our aim is to calculate the relic abundance for both, h^0 and A^0 , using an analytical method [5, 6]. The relic density computation requires the neutral Higgs bosons (of the IHDM) annihilations in standard model pairs. We shall consider the relevant processes for the case: scalar and pseudoscalar annihilations. In this approximation the relevant processes are $HH \rightarrow f\bar{f}$ and $HH \rightarrow W^+W^-$, where H could be h^0 or A^0 and f stands for fermion (we just take the top quark). For example, in the limit $E_{CM} > M_{top}$, the amplitude square for the scalar case is given by:

$$|\mathcal{M}_{\text{scalar}}|^2 = \left(\frac{gM_t \sin \alpha}{2M_W \sin \beta} \right)^4 \frac{(6E_{CM}^2 M_t^2 - 8M_t^4)}{(E_{CM}^2 - M_t^2)^2} + \frac{(gM_W \sin(\beta - \alpha))^4}{(E_{CM}^2 - M_W^2)^2} \left(2 + \left(\frac{\frac{1}{2}E_{CM}^2 - M_W^2}{M_W^2} \right)^2 \right) \quad (5)$$

and for the pseudoscalar:

$$|\mathcal{M}_{\text{pseudoscalar}}|^2 = \left(\frac{gM_t \cot \beta}{2M_W} \right)^4 \frac{(2E_{CM}^2 M_t^2 - 8M_t^4)}{(E_{CM}^2 - M_t^2)^2}, \quad (6)$$

where E_{CM} , M_t and M_W are the energy in the center of mass frame, the top quark mass and W boson mass, respectively. The behavior of the amplitude for scalar case is shown in Figure 2. We have taken some characteristic values for the free parameters α and β based on [29].

4. Summary

In this work we have obtained the amplitude for the neutral Higgs bosons annihilation under a tree level approximation. The expressions for scalar and pseudoscalar cases have a pole when

² One doublet changes its sign under this Z_2 symmetry.

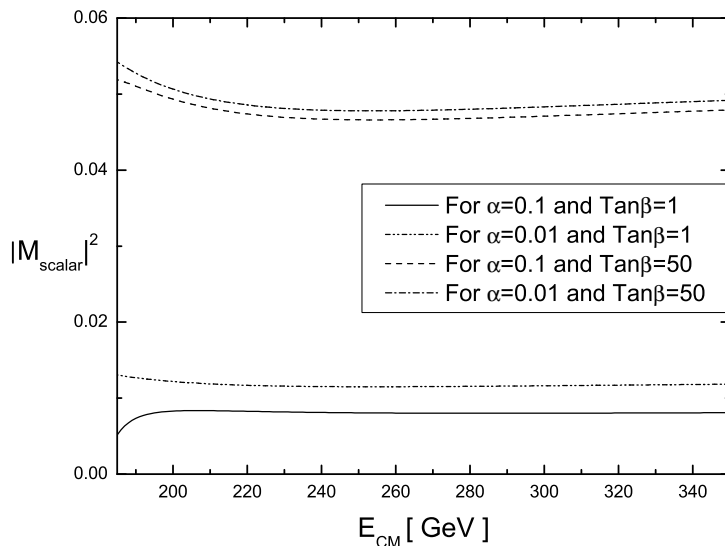


Figure 2. The graphic shows the numerical value for $|\mathcal{M}_{\text{scalar}}|^2$ as function of the energy in the center of mass frame. We are considering that $E_{CM} > M_{top}$.

the E_{CM} is equal to the top quark mass. The mixing angles are stable for the amplitude. For the pseudoscalar case we did not consider the second diagram contribution in order to maintain CP symmetry in this part. However, it is necessary to consider it to obtain a more precise value for the amplitude. Currently, we are working in a more complete expression for amplitudes in order to compute the discussed relic abundances.

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