

One-loop corrections for Higgs-portal dark matter

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Abstract. Models endowed with Higgs portals can probe into the hidden sectors of particle physics while providing stable dark matter candidates. Previous tree-level computations in such scenarios have shown that experimental bounds constrain dark matter to a very narrow region in parameter space. Aiming at improving the study of the implications of those constraints, we inspect one-loop corrections to the annihilation cross section for scalar dark matter into observable fermions. We find that these loop contributions might be enough to drastically change those results by deforming in about 10% the allowed parameter space for dark matter particles with masses even below 1 TeV. These findings encourage further investigation.

1. Introduction

Since the early days of cosmology [1], the quest for an understanding of dark matter (DM) and its origin has led to several proposals. These include massive astrophysical compact halo objects (MACHOs) [2], weakly interacting massive particles (WIMPs) [3] and axion-like particles (ALPs) [4]. WIMPs have been considered as optimal DM candidates mainly because of their natural appearance in many models that could explain other longstanding issues of particle physics. Their theoretical appeal has triggered an exhaustive experimental search by, among others, the XENON100 and LUX collaborations, that has resulted in severe constraints on the WIMP parameter space [5, 6]. Verifying that existing models comply with these strict bounds requires now that all their predicted observables, such as the production and decay rates, be computed with maximal precision.

On the other hand, the recent confirmation of the existence of the Higgs particle with a relatively large mass opens up a new set of possibilities. Especially, WIMPs might well couple directly to the Higgs field, establishing a connection known as a *Higgs portal* [7] between the *dark sector* and the Standard Model (SM). If there were such couplings, WIMPs would e.g. decay into visible matter via the exchange of a Higgs boson, affecting direct and indirect detection signals.

Beyond DM, Higgs portals may be relevant to address other intriguing questions, such as the nature of cosmological inflation [8], the instability in the electroweak vacuum [9], and more recently, the 750 GeV diphoton excess reported at the LHC [10]. Despite their great potential, in this work we shall only focus on the features of DM in these models.

The additional particles required in Higgs portals are considered to be *hidden* in the sense that they do not carry SM charges. They are dynamical (real) scalars S , spinors ψ or vectors V_μ , confined to interact with the SM via Lagrangian couplings with the Higgs field H , such as

$$S^2 H^\dagger H, \quad \bar{\psi} \psi H^\dagger H, \quad V_\mu V^\mu H^\dagger H, \quad (1)$$



and affected by their own (in principle, arbitrary) potential energy density. The scalar case clearly requires the inclusion of a \mathbb{Z}_2 symmetry (or another similar mechanism) to avoid tadpole contributions and to ensure DM stability. These different particles are good DM candidates as long as they comply with experimental bounds. In this respect, fermions are disfavored because they do not only yield a non-renormalizable model, but they are already excluded by XENON data when considering only thermal DM [11].

The phenomenological implications of Higgs portals with scalars and vectors as DM have been studied in [11, 12] (and a recent global analysis for the scalar case has been done in [13]), where only tree-level contributions to the decay and production rates have been considered. It was shown in those works that experimental bounds of WMAP [14] and XENON100 [5] allow for a very reduced set of values in the parameter space of the models, so that radiative corrections may become important to falsify them. Although one-loop corrections to DM–nucleon scattering have been already analyzed [15], the corresponding study for DM annihilation processes is still missing. To motivate and to exhibit the importance of completing this task is one of the aims of the present work.

Based on the results obtained in [16], we discuss here the main aspects of Higgs portals and explore the importance of one-loop corrections to the cross sections of the processes associated with DM detection. The structure of this contribution is as follows. In section 2, we give a brief review of the scalar and vector Higgs portals; in section 3 we present the one-loop analysis for the cross section in the context of the scalar portal done with the aid of FeynArts [18] and FormCalc [19] and finally, in section 4 we discuss the obtained results and ongoing work.

2. Scalar and vector Higgs portals

The scalar and vector Higgs portals have been studied previously in [11, 12] and here we will only revise the main features.

The simplest example of these models is the scalar portal. It is achieved by introducing a (real) massive scalar field S subject to a \mathbb{Z}_2 symmetry, under which S is odd and all SM fields are even. The full renormalizable Lagrangian then reads

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}\mu_S^2 S^2 - \frac{\lambda_{hs}}{2} S^2 H^\dagger H - \frac{\lambda_S}{4} S^4, \quad (2)$$

where λ_{hs} , μ_S and λ_S are the portal and the two self-interaction real parameters. After electroweak symmetry breaking (EWSB), the Higgs–portal potential becomes

$$V(h, S) = \frac{1}{2}m_S^2 S^2 + \frac{\lambda_{hs}v}{2} S^2 h + \frac{\lambda_{hs}}{4} S^2 h^2 + \frac{\lambda_S}{4} S^4, \quad (3)$$

where $m_S^2 = \mu_S^2 + \lambda_{hs}v^2/2$ is the physical mass of S , $v \approx 246 \text{ GeV}$ denotes the electroweak vacuum expectation value (VEV) of the Higgs field H , such that $H(x) \rightarrow (v + h(x))/\sqrt{2}$ (and S has vanishing VEV) in the vacuum, with the small Higgs field perturbation h .

Similarly, for the vector Higgs portal we introduce a vector field V_μ , probably stemming from a U(1) gauge symmetry, whose Higgs–portal potential is given by

$$\mathcal{L} \supset \frac{1}{2}\mu_V^2 V_\mu V^\mu + \frac{\lambda_{hv}}{2} V_\mu V^\mu H^\dagger H + \frac{\lambda_V}{4} (V_\mu V^\mu)^2. \quad (4)$$

Since the mass term $V_\mu V^\mu$ is not gauge invariant if V_μ arises from a gauge symmetry,¹ some gauge–restoring mechanism, such as the Stueckelberg mechanism,² must be invoked. After EWSB, the physical mass of the vector is given by $m_V^2 = \mu_V^2 + \lambda_{hv}v^2/2$.

¹ V_μ may have a different origin. E.g. it could be a composite field, whose effective potential is eq. (4).

² For a review on the Stueckelberg mechanism, see [20]

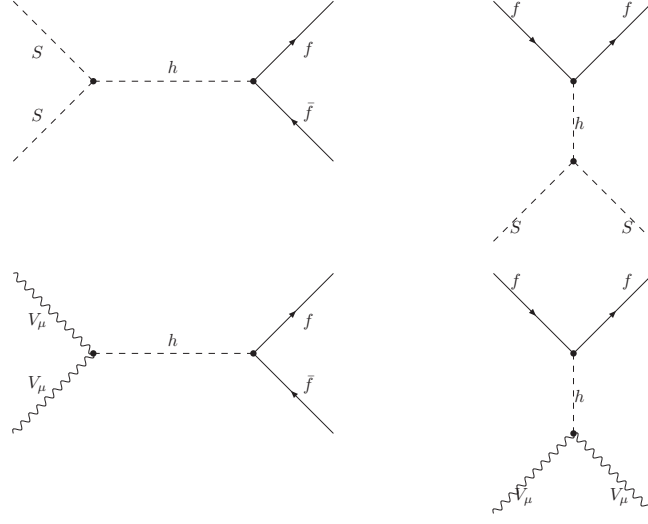


Figure 1: The left-hand-side diagrams depict DM annihilation into SM fermions, while those on the right, DM–fermion scattering for the scalar and vector cases.

Not only does EWSB generate the physical masses m_S and m_V of the DM particles, but, as eq. (3) evidences, it also “produces” the cubic interactions $h S^2$ and $h V_\mu V^\mu$. These interaction terms allow for the possibility of the *invisible* decay of the Higgs particle into DM. LHC bounds [21] on the associated decay width $\Gamma(h \rightarrow SS)$ do not constrain DM with masses over few hundred GeV [13]; hence, this decay shall not be investigated in this work.

Additionally, as depicted in Fig. 1, the hSS vertex allows for DM annihilation into SM fermions as well as DM–fermion scattering. The thermally-averaged cross section of the first process, $\langle\sigma_{DM}v_{rel}\rangle$ (with DM referring either to S or V_μ), relates to Planck’s measurement of DM relic abundance [22], $\Omega_{CDM}h^2 = 0.1198 \pm 0.0015$, roughly by

$$\Omega_{CDM}h^2 \sim 3 \cdot 10^{-27} \text{cm}^3 \text{s}^{-1} / \langle\sigma_{DM}v_{rel}\rangle, \quad (5)$$

where v_{rel} denotes the DM relative velocity or Møller velocity. On the other hand, DM–fermion scattering is important for direct DM detection, because the spin-independent DM–nucleon scattering cross section σ_{SI} can be computed from it under certain assumptions, allowing for a comparison with LUX and XENON100 data.

For scalar and vector Higgs portals, the newest version of micrOMEGAs [23] performs the numerical computation of σ_{SI} up to one-loop level and compares it with the LUX and XENON100 bounds. Therefore, only the computation of radiative corrections to $\langle\sigma_{DM}v_{rel}\rangle$ may be relevant if those contributions are sizable, as we shall show that they turn out to be.

At tree-level, the thermally-averaged annihilation cross sections are given by

$$\langle\sigma_S v_{rel}\rangle = \frac{\lambda_{hs}^2 m_f^2 (1 - m_f^2/m_S^2)^{3/2}}{16\pi (4m_S^2 - m_h^2)^2}, \quad (6)$$

$$\langle\sigma_V v_{rel}\rangle = \frac{\lambda_{hv}^2 m_f^2 (1 - m_f^2/m_V^2)^{3/2}}{48\pi (4m_V^2 - m_h^2)^2}, \quad (7)$$

for the scalar and vector case, respectively. In these eqs., m_f is the mass of the fermions in the final state. Note that the cross section eq. (6) (eq. (7)) depends solely on λ_{hs} (λ_{hv}) and m_S (m_V). It then follows that Planck’s data bound on Ω_{CDM} leads to constraints on these parameters.

3. One-loop corrections in the scalar portal

Sizable one-loop contributions to DM cross sections in Higgs portals may become important as they may close further the narrow region of allowed parameters, thereby finding the model already falsified by data.

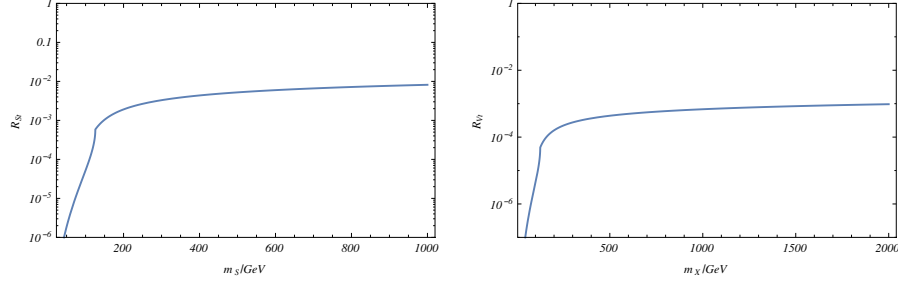


Figure 2: Approximate comparison between the amplitudes at one-loop and at tree-level for the process $SS \rightarrow t\bar{t}$ (left) and $V_\mu V^\mu \rightarrow t\bar{t}$ (right).

In a previous analysis [16], we studied the WIMP mass evolution of the ratio between the simplest one-loop amplitude correction and the tree-level amplitude for DM annihilation into t quarks,

$$R_{DMt} \equiv \frac{|\mathcal{M}_{\text{only 1-loop}}(DM DM \rightarrow t\bar{t})|^2}{|\mathcal{M}_{\text{tree}}(DM DM \rightarrow t\bar{t})|^2}, \quad (8)$$

where, as before, DM stands for either S or V_μ WIMP candidates. This ratio lets us estimate how subdominant one-loop corrections are. As it is evident from Fig. 2 (left), in the scalar case this ratio shows that, for DM masses around 1 TeV and larger, the simplest one-loop contribution analyzed can be as large as $\sim 1\%$ of the tree-level amplitude. This preliminary result encourages further study, since other one-loop contributions may enlarge this already sizable correction. In the vectorial case, this approach reveals (see Fig. 2 (right)) that one-loop contributions may not be so relevant. Thus, we can safely focus on the corrections to the scalar Higgs portal.

We have extended that previous analysis in two ways. First, we completed the computation of the one-loop cross section σ_S for annihilation into t 's, including all possible contributions. Secondly, we further studied the complete cross section at one-loop level for the annihilation of

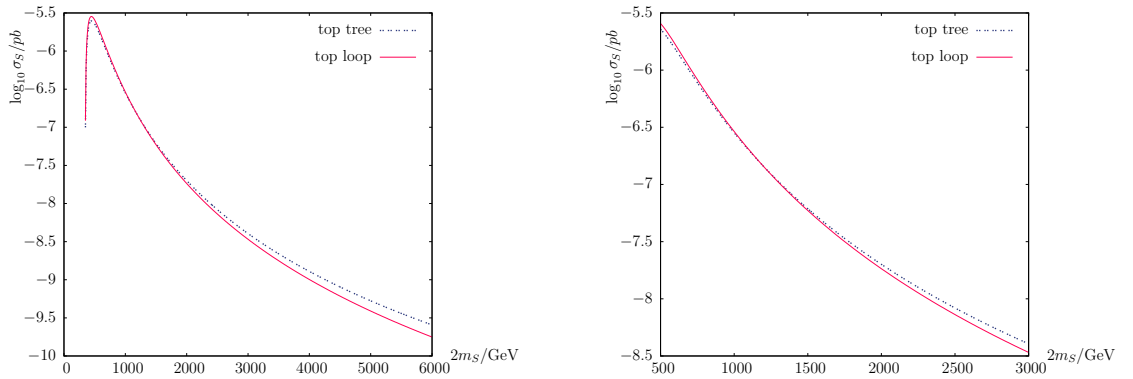


Figure 3: Annihilation cross section of scalar DM into t quarks for $\lambda_{hs} = 10^{-3}$ and m_S between 0.25 and 3 TeV and a zoomed-in interval. We compare the tree-level (blue/dashed line) contribution vs. the full up-to-one-loop cross sections (red/solid line). For $m_S \gtrsim 600$ GeV, the one-loop contribution becomes negative and can be (for $m_S \sim 3$ TeV) as large as 30% of the tree-level cross section.

scalar DM into t , b and c quarks and μ and τ leptons. The Feynman rules were generated with LanHEP [17]; the computation of amplitudes, one loop integrals and the cross sections have been performed by using the public numerical and analytical tools FeynArts [18], LoopTools and FormCalc [19].

Our results are displayed in Figs. 3 and 4. Fig. 3 shows the comparison of the tree-level $\sigma_{S,\text{tree}}$ and full up-to-one-loop $\sigma_{S,1\text{-loop}}$ cross sections for scalar DM annihilation into t quarks and $\lambda_{hs} = 10^{-3}$. We note that for $2m_S \gtrsim 1.2$ TeV, this contribution is negative and significantly larger than 1%, becoming as large as 20% for scalar Higgs-portal WIMPs with $m_S \sim 2$ TeV. A similar comparison has been done for DM annihilation into light quarks and heavy leptons (Fig. 4), to confirm our expectation that top contributions are dominant. For different values of λ_{hs} , we find similar results.

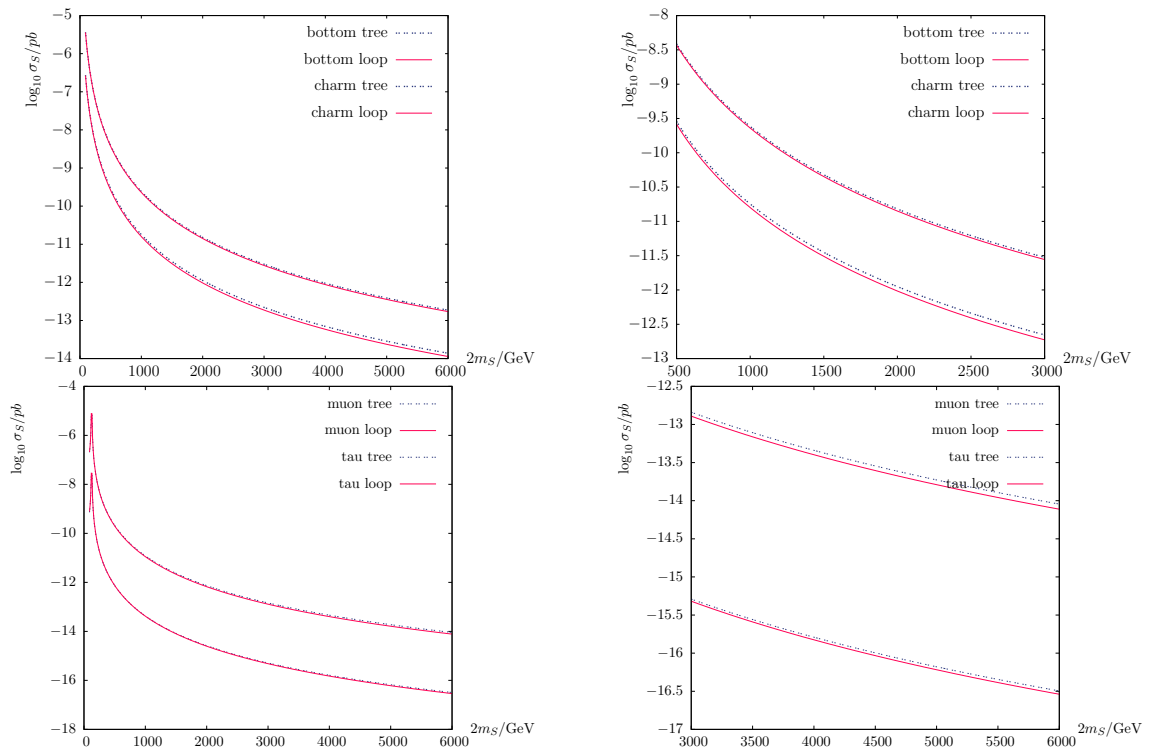


Figure 4: Annihilation cross section of scalar DM for $\lambda_{hs} = 10^{-3}$ and m_S between 45 GeV and 3 TeV (left panels) and a zoomed-in interval (right panels). The upper panels depict the tree-level (blue/dashed line) and the full up-to-one-loop (red/solid line) contributions with b and c quarks in the final states, whereas the lower panels display the same contributions with μ and τ leptons in the final states.

4. Punchline and outlook

We have computed the one-loop corrections to the annihilation cross section of Higgs-portal DM into SM fermions. Our preliminary results stress the need to carefully determine the influence of radiative corrections in the computation of the cross sections in models with Higgs portals. We notice that, particularly for the scalar Higgs portal and certain parameter values, the one-loop contributions can be negative and as large as 13% (21%) of the tree level cross section for admissible DM with masses of about 1 TeV (2 TeV).

The resulting thermally averaged cross sections $\langle \sigma_S v_{rel} \rangle$ are functions of the two parameters of the Higgs portal, m_S and λ_{hs} , such that for each value of m_S an interval of λ_{hs} is still allowed by Planck's data, according to eq. (5). Since the computed cross section σ_S is reduced

by a sizable amount for heavy WIMPs, so is $\langle\sigma_{SI}v_{rel}\rangle$. Thus, the predicted relic abundance increases, stressing the tension between Higgs portals and measurements by WMAP, LUX and XENON100, when the one-loop corrections to the DM–nucleon scattering amplitude σ_{SI} are additionally included. The detailed report of this analysis shall be presented elsewhere [24].

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