PROCEEDINGS OF SCIENCE

Probing freeze-in via invisible Higgs decay

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In this work, we explore Higgs boson decays into dark matter (DM) within the context of the freeze-in mechanism under stronger coupling scenarios. Our analysis focuses on scalar DM candidates interacting through the Higgs portal, where the coupling strength can be significant without establishing thermal equilibrium, owing to a suppressed reheating temperature. We find that for DM masses as low as the MeV scale, the observed relic density can be reproduced while remaining consistent with existing collider and cosmological constraints. Notably, the framework predicts invisible Higgs decays at the level of a few percent, providing exciting prospects for experimental verification at the HL-LHC and FCC.

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1. Introduction

The Higgs boson [1] serves as a key probe for exploring physics beyond the Standard Model (SM). Deviations in its couplings with SM particles can indicate new states, additional interactions, or exotic decay channels [2]. In this work, we investigate the Higgs decay into light DM, which manifests as an "invisible" decay mode.

In Weakly Interacting Massive Particle (WIMP) models, DM achieves thermal equilibrium with the SM plasma, and its relic density is determined by the freeze-out mechanism. For Higgs portal models [3, 4], this requires significant coupling to the Higgs field. However, LHC data constrain the branching ratio of invisible Higgs decays to below 10%, effectively excluding light thermal DM in this framework [5].

Non-thermal DM production through the freeze-in mechanism [6] offers an alternative, relying on extremely weak DM-SM couplings to avoid equilibrium. While this scenario typically evades collider constraints, the recently proposed "freeze-in at stronger coupling" [7] introduces a novel approach: if the reheating temperature T_R is lower than the DM mass $m_{\rm DM}$, production and thermalization are suppressed even at larger couplings. This allows for observable Higgs decays into DM and enhances prospects for direct DM detection [8, 9].

2. Set-up

We assume the interactions between the SM Higgs SU(2)$_{\rm W}$-doublet $\mathcal{H}$ and DM are given by

$$\mathcal{L}_{hs} = \frac{\lambda_{hs}}{2}\, \mathcal{H}^\dagger \mathcal{H} S S \,, \tag{1}$$

where S is a real scalar with mass m_s. This state is assumed to be stable and thus constitute DM.

The Boltzmann equation for the DM number density n for the the *pure freeze-in* scenario takes the form

$$\dot{n} + 3Hn = 2\,\Gamma(\bar{f}f \to SS) \,, \tag{2}$$

where H is the Hubble rate, and $\Gamma(\bar{f}f \to SS)$ is the DM production rate per unit volume. Here, the factor of two signifies production of two DM quanta in each reaction.

2.1 Hadronic contributions

The DM production is primarily driven by processes involving elementary fermions in the initial state. However, at temperatures below the critical QCD temperature, $T_c \sim 150\,\text{MeV}$, quarks are confined into hadrons, and the reactions instead involve hadrons and leptons. Consequently, our approach must be adapted to account for this transition.

The production rate $\Gamma(\text{SM} \to SS)$ can be rewritten as the DM annihilation rate. Indeed, consider the reaction $1 + 2 \to 3 + 4$. Energy conservation implies that

$$e^{-E_1/T} e^{-E_2/T} = e^{-E_3/T} e^{-E_4/T} \,. \tag{3}$$

Thus, our first step is to factorize $|\mathcal{M}(SS \to \text{SM})|^2$ using the fact that DM annihilation always proceeds via the Higgs mediator. We have

$$|\mathcal{M}_{SS\to\text{SM}}|^2 = |\mathcal{M}_{SS\to h}|^2 \, \frac{1}{(\text{s} - m_h^2)^2} \, |\mathcal{M}_{h\to\text{SM}}|^2 \,, \tag{4}$$

where the usual spin state summation/averaging is implied, and m_h is the Higgs mass. The same relation applies to fermionic DM. Putting these ingredients together, we find

$$\Gamma^{\rm th}_{SS\to\rm SM} = \int \left(\prod_i \frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} f(p_i)\right) |\mathcal{M}_{SS\to h}|^2 \frac{1}{(s-m_h^2)^2} \times (2m_h\Gamma_h)\Big|_{m_h=\sqrt{s}} , \tag{5}$$

where the superscript “th” implies that DM in the initial states is treated as *thermal*. The Γ_h represents the Higgs decay width, this quantity is known in the SM for all Higgs masses, with variable accuracy. In our numerical analysis, we use two recent estimations by Winkler [10] and Gorbunov *et al.* [11]. Here, the SM Higgs mass in the last factor is *variable* and given by the center-of-mass energy of the annihilating DM state, in analogy with the result of [17]. We therefore conclude that at energies below the physical Higgs mass,

$$\boxed{\Gamma_{\rm SM\to SS} = \Gamma^{\rm th}_{SS\to\rm SM} = \frac{T}{2^5\pi^4 m_h^4}\int_{4m_s^2}^{\infty} ds\, \sqrt{s(s-4m_s^2)}\, K_1\left(\sqrt{s}/T\right)\, \Gamma_h\left(m_h=\sqrt{s}\right)\, |\mathcal{M}_{SS\to h}|^2} \tag{6}$$

3. Results and Conclusion

Our main results are shown in Fig. 1, which displays the allowed parameter space for λ_{hs} and m_s. The colored curves correspond to the correct relic density for different reheating temperatures T_R. For DM masses above the muon threshold, λ_{hs} grows exponentially with m_s. Despite the suppressed muon abundance at $T_R < m_\mu$, the reaction $\bar{\mu}\mu \to SS$ remains more efficient than the electron counterpart, thanks to the larger Yukawa coupling. This effect diminishes for $T_R < 10$ MeV. The grey shaded region is excluded by LHC constraints on invisible Higgs decays ($\text{BR}_{\rm inv} \lesssim 10\%$ [14]), while dashed and dash-dotted lines indicate the sensitivities of the HL-LHC ($\text{BR}_{\rm inv} = 3\%$ [15]) and FCC ($\text{BR}_{\rm inv} = 0.3\%$ [16]). The figure shows that $T_R \gtrsim 10$ MeV is consistent with current constraints for a range of DM masses, and the corresponding parameter space can be explored

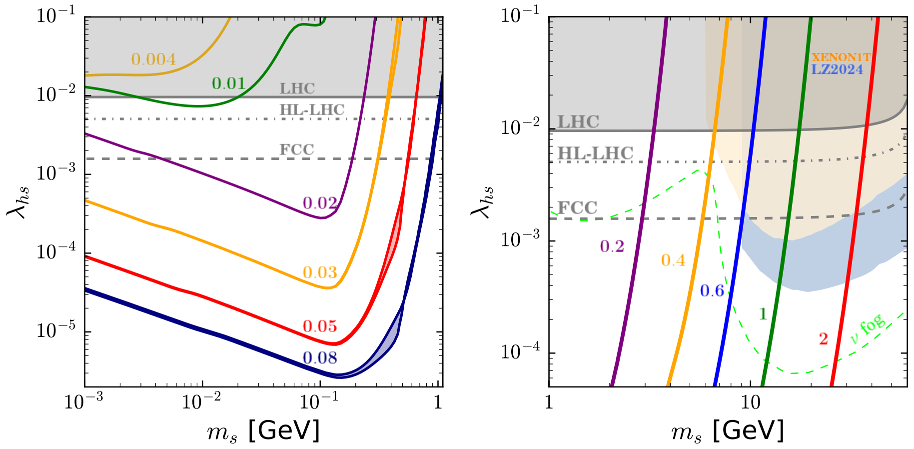

Figure 1: Parameter space for scalar DM freeze-in. Along the colored curves marked by T_R in GeV, the correct relic density is reproduced. The shaded areas are excluded by the LHC and direct DM detection bounds. Sensitivities of the HL-LHC and FCC are shown by the grey dashed lines, while the neutrino “fog” for direct DM detection [12] is represented by the green dashed line.

by future experiments. The DM direct detection (DD) experiments [18, 19] impose an additional constraint on the model. The strictest constraint by the recent LZ2024 result [18].

Hadronic uncertainties have limited impact on these results. At $T_R \gtrsim 50\,\mathrm{MeV}$ (but below T_c), pion contributions slightly broaden the relic density curves. However, these differences occur in regions unlikely to be probed at colliders, minimally affecting our predictions.

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