Invisible Higgs decay from dark matter freeze-in at stronger coupling

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Abstract

We study the Higgs boson decay into dark matter (DM) in the framework of freeze-in at stronger coupling. Even though the Higgs-DM coupling is significant, up to order one, DM does not thermalize due to the Boltzmann suppression of its production at low reheating temperatures, T_R. We find that this mechanism leads to observable Higgs decay into invisible final states with the branching fraction of 10% and below, while producing the correct DM relic abundance. This applies to the DM masses down to the MeV scale, which requires a careful treatment of the hadronic production modes. As a result, MeV DM with a significant coupling to the Higgs boson remains non-thermal as long as the reheating temperature does not exceed O(100) MeV. Our findings indicate that there are good prospects for observing light non-thermal DM via invisible Higgs decay at the LHC and FCC.

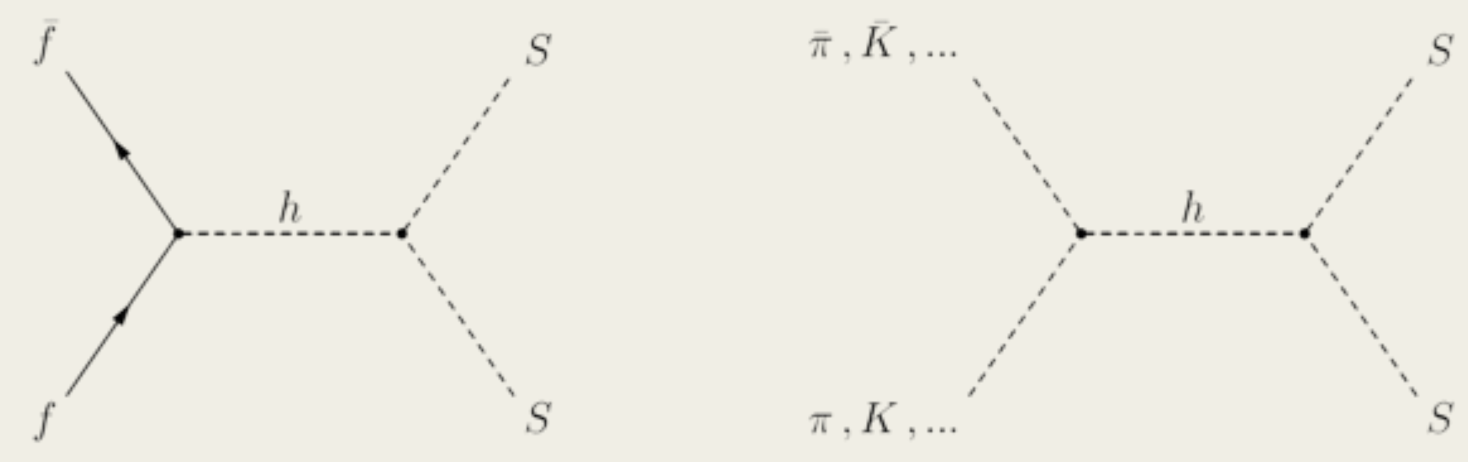
Higgs portal

The goal of this work is to study "invisible" Higgs decay into DM in the framework of freeze-in at stronger coupling. We assume the minimal Higgs portal setup with singlet DM of spin 0, S. The the effective interaction can be written as

$$\mathcal{L}^s_{\rm eff} = \frac{\lambda_{hs} m_f}{2m_h^2}\, \bar{f} f\, SS$$

where f represents the SM fermions.

Production channels



In the framework of freeze-in at stronger coupling, DM is produced via annihilation of the SM thermal bath states at low temperatures as illustrated in the figure above. If temperature T is never higher than the DM mass, the production rate is Boltzmann-suppressed which allows for a significant Higgs coupling to DM.

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References

[1] Lebedev, O., Morais, A., Oliveira, V. \& Pasechnik, R. Invisible Higgs decay from dark matter freeze-in at stronger coupling. Journal Of High Energy Physics. **2025**, 1-25 (2025)

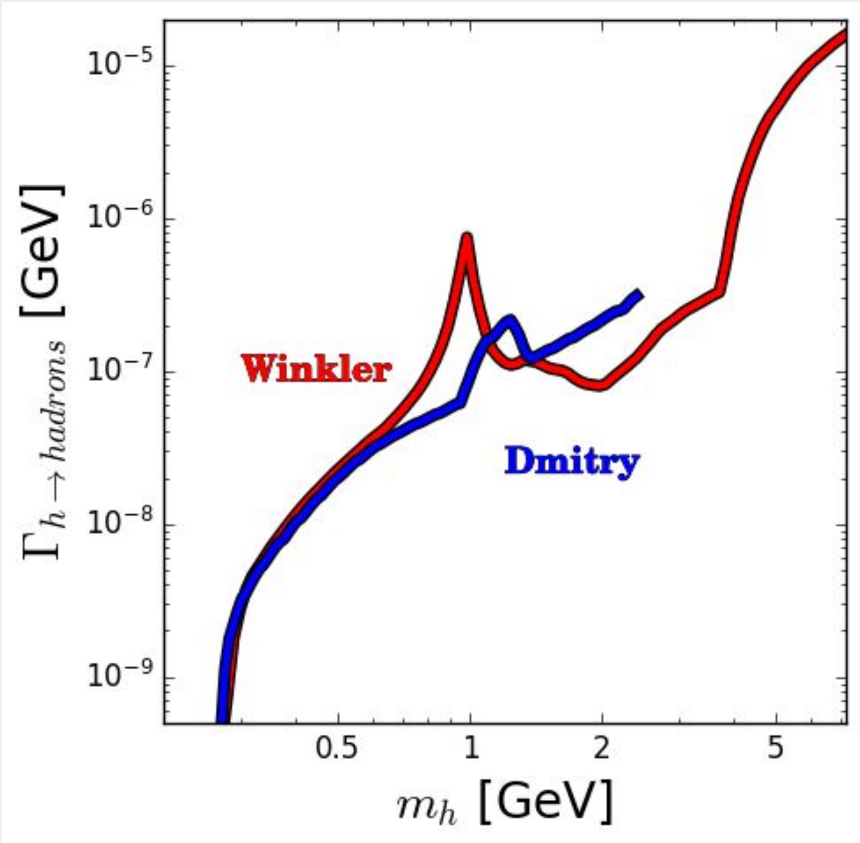
General case and hadronic contributions

For the *pure freeze-in* scenario we have the Boltzmann equation for number density quantity

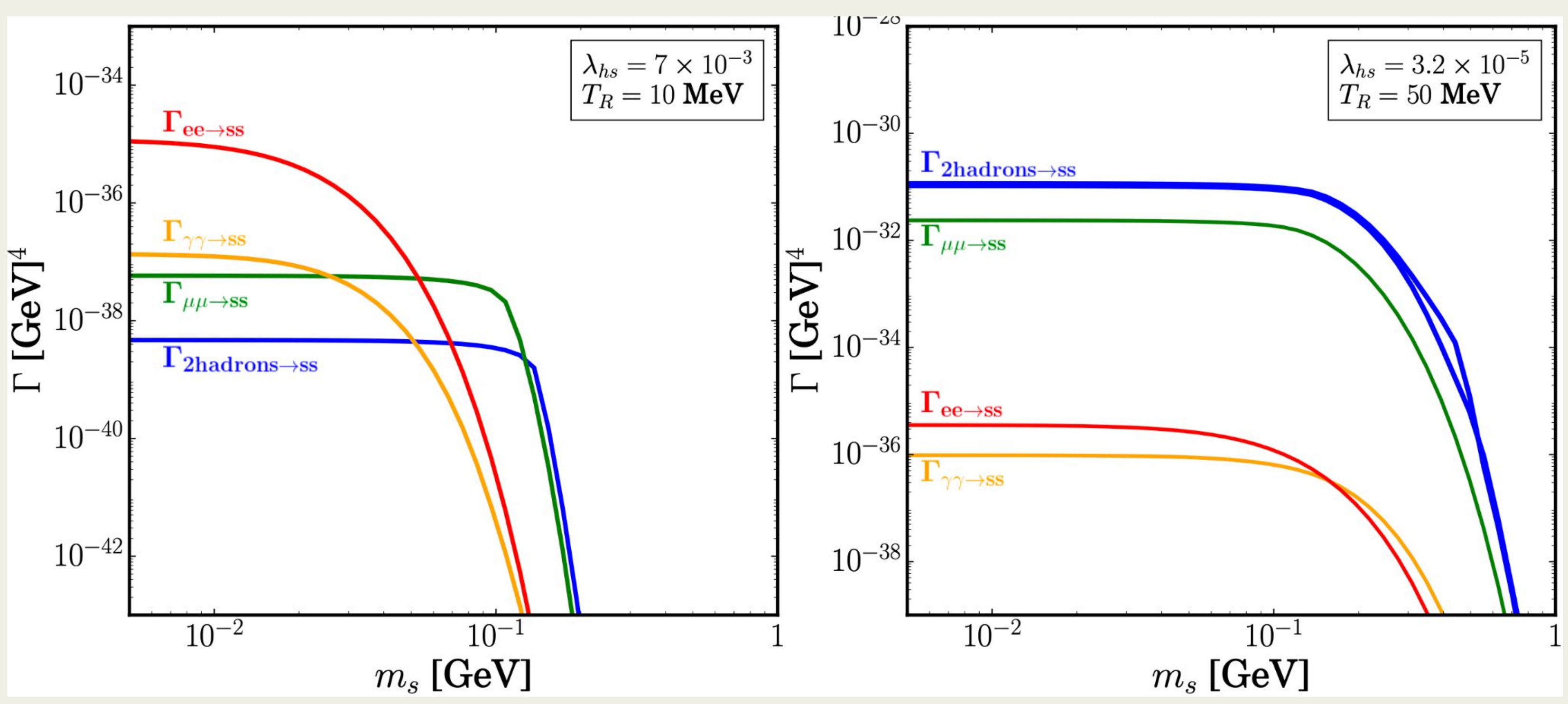
$$\dot{n} + 3Hn = 2\,\Gamma(\bar{f} f \to SS)$$

where $\mathbf{\Gamma}$(f f → S S) is the rate of interaction, and 2 signifies production of 2 DM particles in each reaction.

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

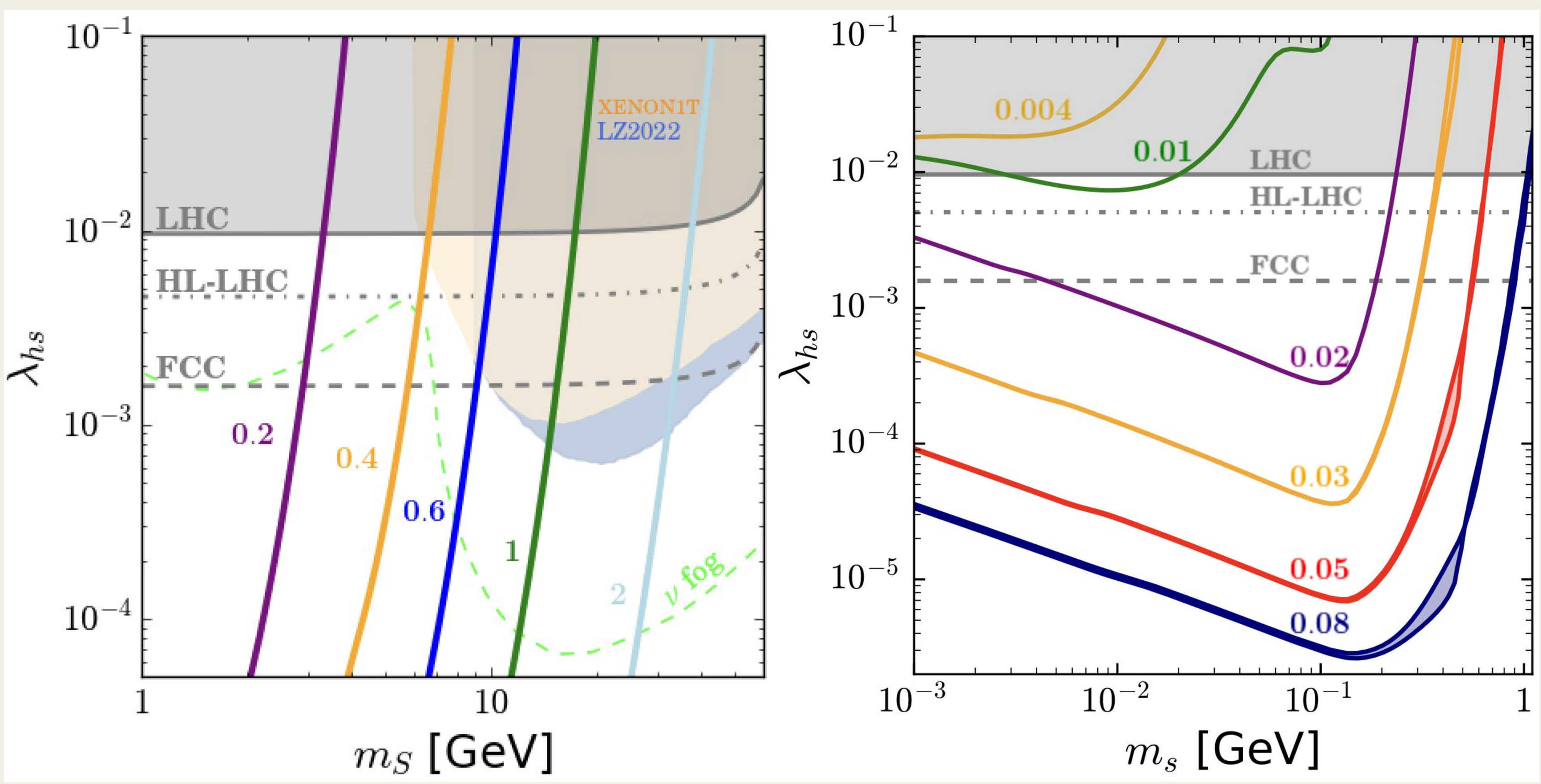


Decay width of h → hadrons for variable Higgs mass m_h.



Individual reaction rates. The broadening of the blue curve in the right panel represents hadronic uncertainties.

Results



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 is represented by the green dashed line.