Freeze-In in different phases of the N2HDM

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Next to Two Higgs Doublet Model (N2HDM)

Next to Two Higgs Doublet Model [Mühlleitner et al., 2017]

- Extending the scalar sector of the Standard Model with one complex scalar doublet Φ_2 and one real scalar singlet Φ_S
- Imposing two $\mathbb{Z}_2$ symmetries to the Lagrangian

$$\mathbb{Z}_2^1 : \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad \Phi_S \to \Phi_S$$

$$\mathbb{Z}_2^2 : \Phi_1 \to \Phi_1, \quad \Phi_2 \to \Phi_2, \quad \Phi_S \to -\Phi_S$$

- The scalar potential is given by

$$\begin{aligned} V_{\text{N2HDM}} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 \\ & + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger \Phi_2)^2 + h.c\right] + \frac{1}{2} m_s^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} \Phi_1^\dagger \Phi_1 \Phi_S^2 \\ & + \frac{\lambda_8}{2} \Phi_2^\dagger \Phi_2 \Phi_S^2 \end{aligned}$$

Phases of the N2HDM [Engeln et al., 2020]

Table 1: Different phases of the N2HDM

Phase	$\mathbb{Z}_2^1$	$\mathbb{Z}_2^2$	DM Candidate(s)	Suitable for Freeze-In
Broken Phase	broken	broken	0	no
Dark Doublet Phase	unbroken	broken	1	**no**
Dark Singlet Phase	broken	unbroken	1	yes
Full Dark Phase	unbroken	unbroken	2	yes

Scalar Spectrum

Table 2: Scalar particle content of both phases

Phase	visible sector	dark sector
Dark Singlet Phase	H_1, H_2, A, $H^\pm$	H_{DS}
Full Dark Phase	H_{SM}	H_{DD}, A_{D}, $H_{\mathrm{D}}^\pm$, H_{DS}

Freeze-Out vs. Freeze-In

Freeze-Out [Gondolo and Gelmini, 1991]

Assumption: All particles, including the DM particle, are in thermal equilibrium.

Due to the expansion of the universe two phenomena happen:

- As the temperature of the universe is decreasing, the production of heavy particles decreases
  $\Rightarrow$ The annihilation process becomes dominant and the number density of the heavy particles decreases
- The universe is expanding, hence interactions of particles become more unlikely
  $\Rightarrow$ If $\Gamma_{Ann} = H$, the annihilation becomes irrelevant. This point in time is called Freeze-Out point.

Freeze-In [Hall et al., 2010]

Assumption: The DM particle is very weakly coupled to the thermal bath. Therefore it is decoupled from the thermal bath.

- The DM particle is produced through interactions between the thermal bath particles.
- Due to the expansion of the universe the production rate decreases and the number density increases only slowly.

Numerical analysis

Constraints on parameter scans

- A parameter scan is performed with `ScannerS` [Coimbra, Sampaio, and Santos, 2013; Mühlleitner et al., 2020]
- Various experimental and theoretical constraints are applied.
- The dark matter properties are checked with `MicrOMEGAs`[Bélanger et al., 2018].

Relic density calculation

Full Dark phase

In the Full Dark phase one of the two DM candidates undergoes the Freeze-Out process, while the other one undergoes the Freeze-In process.

$$\Rightarrow \quad \Omega_c h^2 = \Omega_{\mathrm{FI}} h^2 + \Omega_{\mathrm{FO}} h^2$$

Dark Singlet phase

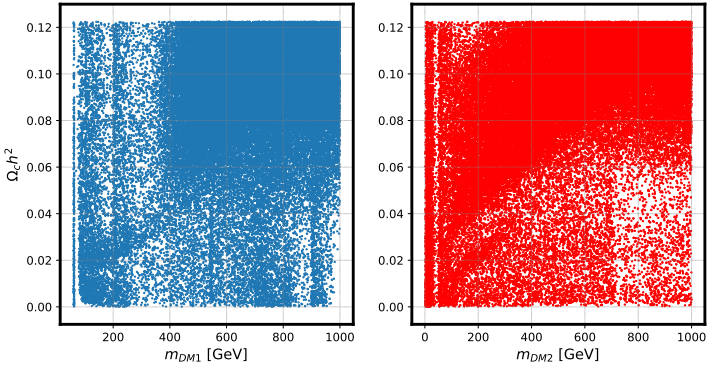
In the Dark Singlet phase only one DM candidate exists, which undergoes the Freeze-In process.

$$\Rightarrow \quad \Omega_c h^2 = \Omega_{\mathrm{FI}} h^2$$

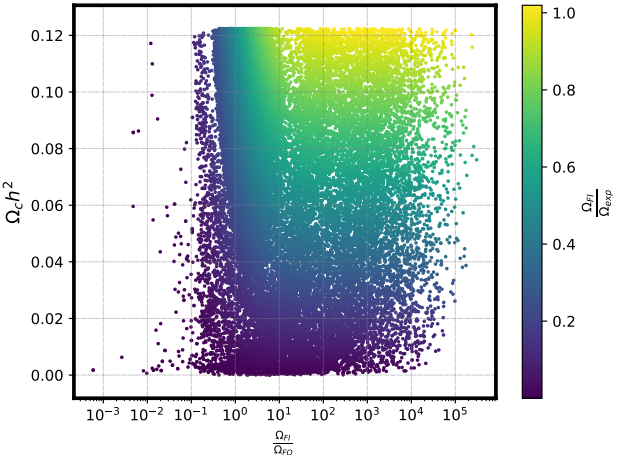
Results

Relic density in the FDP

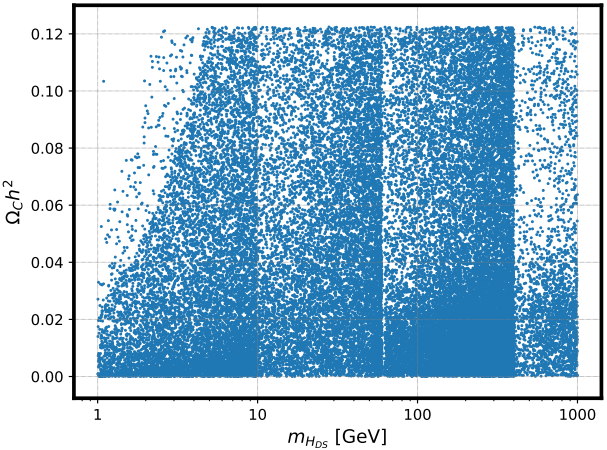
Define $\mathrm{DM}_1 = H_{\mathrm{DD}}/A_{\mathrm{D}}$ as the Freeze-Out particle and $\mathrm{DM}_2 = H_{\mathrm{DS}}$ as the Freeze-In particle



Relic density in the FDP



Relic density in the DSP



Conclusions

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- In two phases, namely the Full Dark phase and the Dark Singlet phase, it is possible to apply the Freeze-In mechanism.
- In both phases it has been shown, that in the scanned parameter regions, it is possible to comply with the observed relic density.
- In the FDP, it is possible to have both production mechanism, Freeze-Out and Freeze-In, for the generation of the observed relic density.