# LHC-friendly minimal freeze-in models

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Abstract: In this brief note we describe the FeynRules implementation of the three simple freeze-in models with a charged vector-like fermion. If you use these models, please cite [1, 2].

## Contents



# 1 Model description

In [1, 2] we proposed three simple models of freeze-in dark matter with an interesting phenomenology at the LHC. In all three models the Standard Model of particle physics is augmented by a scalar dark matter candidate $s$ that is neutral under the Standard Model gauge group, along with a vector-like fermion $F$ transforming as $(\mathbf{1}, \mathbf{1}, -\mathbf{1})$ ("heavy lepton"), $(\mathbf{3}, \mathbf{1}, -\mathbf{2/3})$ ("heavy up-type quark") or $(\mathbf{3}, \mathbf{1}, \mathbf{1/3})$ ("heavy down-type quark") under $SU(3)_c \times SU(2)_L \times U(1)_Y$ for the three models respectively. Both the dark matter candidate and the vector-like fermion are taken to be odd under a discrete $\mathcal{Z}_2$ symmetry, under which all Standard Model particles are even. The dark matter candidate is coupled to the Standard Model through Yukawa-type terms involving the left-handed component of the vector-like fermion and the Standard Model right-handed fermions. The Lagrangian reads

$$\begin{aligned} \mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right) \\ + \bar{F}\left(i \not{D}\right) F - m_F \bar{F} F - \sum_f y_s^f \left( s \bar{F} \left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right), \end{aligned} \tag{1.1}$$

where $f = \{e, \mu, \tau\}$, $\{u, c, t\}$ or $\{d, s, b\}$, depending on the $SU(3)_c \times U(1)_Y$ transformation properties of $F$.

# 2 Implementation of the models in `FeynRules`

Let us now describe the implementation of our models in `FeynRules`.

- The three models have been implemented separately. If the user wishes a single model involving all three kinds of vector-like fermions, our models can serve as a basis for further development.

- In all three cases, the dark matter candidate is denoted by `~s0` and the vector-like fermion as `~he` and `~HE` for the particle and its antiparticle respectively.

- The three models are each described by a set of seven free parameters. We choose these parameters to be

$$m_s, m_F, \lambda_{sh}, \lambda_s, \{y_s^f\} \ . \tag{2.1}$$

The first four, respectively called `ms0`, `mHE`, `lams0h` and `lams0` in the model files, are common to the three models, and correspond to the dark matter mass, the vector-like fermion mass, the dark matter-Higgs quartic coupling and the dark matter quartic self-coupling respectively. Note that the dark scalar mass is related to the $\mu_s$ parameter entering Eq.(1.1) through

$$\mu_s^2 = m_s^2 + \lambda_{sh} v^2 \ . \tag{2.2}$$

The Yukawa-type couplings (three for each model) $y_s^f$ are called `yHEeR`, `yHEmuR`, `yHEtaR` in the lepton case, `yHEuR`, `yHEcR`, `yHEtR` in the up-type quark case and `yHEdR`, `yHEsR`, `yHEbR` in the down-type quark case, for the first, second and third generation fermions respectively in each case.

- All three models are available both in Feynman and Unitary gauge. By default, the existing `UFO` and `CalcHEP` model files that can be found in the `FeynRules` webpage have been exported in Feynman gauge (recommended for use with `micrOMEGAs 5.0`). This can be changed by setting

  `FeynmanGauge = True` or `False`

  in the files `LesHouchesModelFreezeIn-leptons/up/down.fr` respectively and exporting anew to `UFO` and `CalcHEP` model file formats by running the corresponding `Mathematica` scripts. Don't forget to change the `FeynRules` path according to your system.

- Upon running these scripts, the Standard Model Lagrangian is also loaded through the file `SM_noH.fr`, which is a tweaked version of the Standard Model model file that can be found on the `FeynRules` Model Database. The tweaking consists in that the Higgs doublet and the Standard Model scalar potential are declared in the New Physics `.fr` files.

Feel free to use these model files and, if you do so, please don't forget to cite [1, 2]. Have fun!

## References


[1] G. Brooijmans et al., *Les Houches 2017: Physics at TeV Colliders New Physics Working Group Report*, in *10th Les Houches Workshop on Physics at TeV Colliders (PhysTeV 2017) Les Houches, France, June 5-23, 2017*, 2018. arXiv:1803.10379.

[2] G. Bélanger et al., *LHC-friendly minimal freeze-in models*, arXiv:1811.05478.