Documentation on the DMsimp_t FeynRules implementation

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This note contains information about the DMsimp_t model implementation in FeynRules, which aims to offer a unique general framework for all simulations relevant for simplified t-channel dark matter models. All files, together with illustrative Mathematica notebooks will be available from http://feynrules.irmp.ucl.ac.be/wiki/DMsimpt.

I. FEYNRULES IMPLEMENTATION AND CONVENTIONS

In order to identify the nature of dark matter and the way it interacts with the Standard Model particles, it is necessary to be able to predict how models that satisfy all cosmological constraints could be tested at colliders. The FeynRules package [1] offers such a possibility, as from a unique FeynRules implementation of any given dark matter model, it is subsequently possible to generate model files suitable for various high-energy physics tools such as MG5_aMC [2], MadDM [3] or MicrOMEGAs [4]. This further allows for the calculation of the dark matter relic density and direct and indirect detection cross sections (to verify the cosmological viability of the model), as well as for the extraction of the exclusion levels of various searches at colliders through the generation of realistic collision events and the recasting of relevant LHC analyses. In the latter case, the MG5_aMC framework allows for handling simulations including next-to-leading order corrections in α_s, so that predictions are accurate enough to derive robust constraints when LHC recasting is at stake, in particular on the context of the MadAnalysis 5 platform [5] whose future version 1.8 will allow for the propagation of the theoretical uncertainties associated with the theoretical predictions for the signal up to the derived exclusion level.

In this work, we adapt the strategy outlined in ref. [6] for s-channel dark matter models to the t-channel case. We detail below a general implementation of these t-channel dark matter models in the FeynRules package, that is general in the sense that it can be employed to study a large class of models simultaneously. We have used the FeynRules implementation to generate a UFO library [7], which can subsequently be imported in programmes like MG5_aMC or MadDM for undertaking various simulations and computations in the framework of many t-channel dark matter models.

We consider a simplified model extending the Standard Model by two extra fields, a dark matter particle and a mediator, potentially lying in a non-trivial representation of $SU(3)_c$ and connecting the dark matter with the Standard Model. We aim to implement the most generic model, allowing the user to pick any possible option for the spin of the new particles. We therefore introduce four new dark matter fields S, $\tilde{\chi}$, χ and V_μ that respectively correspond to a real scalar field, a Majorana spinor, a Dirac spinor and a real vector field and that all lie in the singlet representation of the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. The most general Lagrangian describing all potential t-channel dark matter models can therefore be written, after imposing that electroweak gauge invariance is preserved, as

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} &+ \bigg[\lambda_{\mathbf{Q}}\ \big[(\bar{\tilde{\chi}} + \bar{\chi})Q_L\big]\ \varphi_Q^\dagger + \lambda_{\mathbf{u}}\ \big[(\bar{\tilde{\chi}} + \bar{\chi})u_R\big]\ \varphi_u^\dagger + \lambda_{\mathbf{d}}\ \big[(\bar{\tilde{\chi}} + \bar{\chi})d_R\big]\ \varphi_d^\dagger + \text{h.c.}\bigg] \\ &+ \bigg[\hat{\lambda}_{\mathbf{Q}}\Big([\bar{\psi}_Q Q_L]\ S + [\bar{\psi}_Q \not{V} Q_L]\Big) + \hat{\lambda}_{\mathbf{u}}\Big([\bar{\psi}_u u_R]\ S + [\bar{\psi}_u \not{V} u_R]\Big) + \hat{\lambda}_{\mathbf{d}}\Big([\bar{\psi}_d d_R]\ S + [\bar{\psi}_d \not{V} d_R]\Big) + \text{h.c.}\bigg]\ ,\end{aligned} \tag{1.1}$$

where $\mathcal{L}_{\rm SM}$ is the Standard Model Lagrangian and $\mathcal{L}_{\rm kin}$ contains gauge-invariant kinetic and mass terms for all new fields. In our notation, Q_L stands for the $SU(2)_L$ doublet of left-handed quarks and u_R and d_R are the up-type and down-type $SU(2)_L$ singlets of right-handed quarks respectively. The scalar mediators φ_Q, φ_u and φ_d are chosen to solely interact with the Q_L, u_R and d_R quarks, as for the fermionic mediators ψ_Q, ψ_u and ψ_d (that are thus of a vector-like nature). They therefore lie in the same representation of the Standard Model gauge group as their quark partners. In the above expression, we have moreover understood all flavour indices for clarity. The $\lambda_{\mathbf{L}}$, $\lambda_{\mathbf{u}}$ and $\lambda_{\mathbf{d}}$ coupling strengths are thus 3×3 matrices in flavour space. For simplicity, these matrices are considered real and flavour-diagonal.

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Field	Spin	Repr.	Self-conj.	FeynRules/UFO name	PDG code
S	0	$(\mathbf{1},\mathbf{1},0)$	yes	Xs	51
$\tilde\chi$	1/2	$(\mathbf{1},\mathbf{1},0)$	yes	Xm	52
χ	1/2	$(\mathbf{1},\mathbf{1},0)$	no	Xd	57
V_μ	1	$(\mathbf{1},\mathbf{1},0)$	yes	Xv	53
$\varphi_Q = \begin{pmatrix}\varphi_Q^{(u)}\\ \varphi_Q^{(d)}\end{pmatrix}$	0	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no	$\texttt{YS3Q} = \begin{pmatrix}\texttt{YS3Qu}\\ \texttt{YS3Qd}\end{pmatrix}$	$\varphi_Q^{(u)}$: 1000002 1000004 1000006 $\varphi_Q^{(d)}$: 1000001 1000003 1000005
φ_u	0	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no	YS3u	2000002 2000004 2000006
φ_d	0	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no	YS3d	2000001 2000003 2000005
$\psi_Q = \begin{pmatrix}\psi_Q^{(u)}\\ \psi_Q^{(d)}\end{pmatrix}$	1/2	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	no	$\texttt{YF3Q} = \begin{pmatrix}\texttt{YF3Qu}\\ \texttt{YF3Qd}\end{pmatrix}$	$\psi_Q^{(u)}$: 5910002 5910004 5910006 $\psi_Q^{(d)}$: 5910001 5910003 5910005
ψ_u	1/2	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	no	YF3u	5920002 5920004 5920006
ψ_d	1/2	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	no	YF3d	5920001 5920003 5920005

TABLE I. *New particles supplementing the Standard Model field content, given together with the representations under $SU(3)_c \times SU(2)_L \times U(1)_Y$, their Majorana nature, their name in the* FeynRules *implementation and the associated Particle Data Group (PDG) identifiers. Three generations of mediators (second part of the table) are included.*

Coupling	Flavour structure	FeynRules (UFO) name	Les Houches block
$(\lambda_Q)_{ij}$	$\lambda_Q^{(i)}\delta_{ij}$	lamS3Q	DMS3Q
$(\lambda_u)_{ij}$	$\lambda_u^{(i)}\delta_{ij}$	lamS3u	DMS3U
$(\lambda_d)_{ij}$	$\lambda_d^{(i)}\delta_{ij}$	lamSdD	DMS3D
$(\hat\lambda_Q)_{ij}$	$\hat\lambda_Q^{(i)}\delta_{ij}$	lamF3Q	DMF3Q
$(\hat\lambda_u)_{ij}$	$\hat\lambda_u^{(i)}\delta_{ij}$	lamF3u	DMF3U
$(\hat\lambda_d)_{ij}$	$\hat\lambda_d^{(i)}\delta_{ij}$	lamF3d	DMF3D

TABLE II. *New couplings dictating the interactions of the new particles with the Standard Model sector. Each coupling is given together with the corresponding flavour structure (taking flavour-conserving by default in the* FeynRules *implementation), the associated* FeynRules *(or UFO) symbol and the Les Houches block of the parameter card.*

The new field content of the simplified model is presented in table I, together with their representation under the gauge and Poincaré groups, their potential Majorana nature, the adopted particle name in the FeynRules (or UFO) implementation and the Particle Data Group identifiers [8]. The name and indicial structure of the different coupling parameters is summarised in table II, win which we also recall that the flavour structure is taken, for each coupling, diagonal. Moreover, we additionally include the name used for the different couplings in the FeynRules implementation and the Les Houches blocks [9] in which the numerical values of the different parameters can be changed by the user, when running tools like MG5_aMC or MadDM.

By relying on a joint use of the FeynRules [1], NLOCT [10] and FeynArts [11] packages, we automatically generate a UFO model [7] that can be used by MG5_aMC for both LO and NLO computations. The model is shipped with a few restrictions that allow the user to focus on specific t-channel simplified models. They are summarised in table III where for each restriction card, we specify the active new physics states (all other states being decoupled and non-interacting), namely a specific class or subclass of mediators and a given dark matter state. In order to reduce the number of free parameters, the masses of all (active) mediators are taken equal. A given restriction named XYZ can then be loaded in MG5_aMC as usual, *i.e.* by typing, within the command line interface,

```
import model DMSimp_t-XYZ --modelname
```

In the following, we describe all 12 restrictions shipped with the model. In the first three cases, all potential twwelve mediators are considered, their mass and interaction strengths being taken flavour-conserving and universal. In the next three cases, medatiors solely coupling to the right-handed up quark are included, whilst in the last three cases, we consider a full generation of four nediators.

Restriction name	Mediators	Dark matter	Free parameters
`S3M_uni` / `S3D_uni`	$\varphi \equiv \varphi_{Q_f} + \varphi_{u_f} + \varphi_{d_f}$	$\tilde\chi$ / χ	M_φ, M_χ, λ_φ
`S3M_3rd` / `S3D_3rd`	$\varphi \equiv \varphi_{Q_3} + \varphi_{u_3} + \varphi_{d_3}$	$\tilde\chi$ / χ	M_φ, M_χ, λ_φ
`S3M_uR` / `S3D_uR`	φ_{u_3}	$\tilde\chi$ / χ	M_φ, M_χ, λ_φ
`F3S_uni`	$\psi \equiv \psi_{Q_f} + \psi_{u_f} + \psi_{d_f}$	S	M_S, M_ψ, $\hat\lambda_\psi$
`F3S_3rd`	$\psi \equiv \psi_{Q_3} + \psi_{u_3} + \psi_{d_3}$	S	M_S, M_ψ, $\hat\lambda_\psi$
`F3S_uR`	ψ_{u_1}	S	M_S, M_ψ, $\hat\lambda_\psi$
`F3V_uni`	$\psi \equiv \psi_{Q_f} + \psi_{u_f} + \psi_{d_f}$	V_μ	M_V, M_ψ, $\hat\lambda_\psi$
`F3V_3rd`	$\psi \equiv \psi_{Q_3} + \psi_{u_3} + \psi_{d_3}$	V_μ	M_V, M_ψ, $\hat\lambda_\psi$
`F3V_uR`	ψ_{u_1}	V_μ	M_V, M_ψ, $\hat\lambda_\psi$

TABLE III. *List of all restrictions included in the* `DMsimp_t` *UFO model. In each case, the simplified model contains a single class or subclass of mass-degenerate mediators (where f stands for a flavour index), a specific dark matter candidate and universal and flavour-conserving dark matter interactions. In the* `S3M` *series of models, the dark matter particle is the Majorana fermion $\tilde\chi$ whilst in the* `S3D` *series of models, it consists in the Dirac fermion χ.*

I.1. The `S3M`/`S3D` class of models

In `S3M`-type and `S3D`-type models, the dark matter is taken to respectively be the Majorana and Dirac state $\tilde\chi$ and χ of mass $M_{\tilde\chi}$ and M_χ. All mediators are moreover taken degenerate with mass M_φ, although such an assumption is not built in in the parameter card, so that all masses can be independently modified. Moreover, all new physics interactions are taken universal and flavour-conserving, the coupling being commonly denoted by λ_φ. The Lagrangian of eq. (1.1) is therefore simplified, in the Majorana case, to

$$\mathcal{L}_{\texttt{S3M\_uni}} = \mathcal{L}_{\rm SM} \frac{i}{2}\bar{\tilde\chi}\partial\!\!\!/\tilde\chi - \frac{M_{\tilde\chi}}{2}\bar{\tilde\chi}\tilde\chi + \sum_{F=Q,u,d}\sum_{f=1}^{3}\Big[D_\mu\varphi^\dagger_{F_f}D^\mu\varphi_{F_f} - M^2_\varphi\varphi^\dagger_{F_f}\varphi_{F_f} + \Big(\lambda_\varphi[\bar\chi F_f]\ \varphi^\dagger_{F_f} + \text{h.c.}\Big)\Big]\ , \tag{1.2}$$

where $Q_f \equiv Q^f_L$, $u_f \equiv u^f_R$ and $d_f \equiv d^f_R$, f being a generation index. The model is thus defined by three parameters,

$$\Big\{M_{\tilde\chi},\ M_\varphi,\ \lambda_\varphi\Big\}\ . \tag{1.3}$$

In the `S3M_uni` restriction, the simplified model includes all twelve mediators, whilst in the `S3M_3rd` and `S3M_uR` models, the setup is further simplified and dark matter only couples to the third generation and to the up-right quark, respectively. The simplified models correspondingly include four and one mediators, the associated Lagrangians reading, in the Majorana case,

$$\mathcal{L}_{\texttt{S3M\_3rd}} = \mathcal{L}_{\rm SM} + \frac{i}{2}\bar{\tilde\chi}\partial\!\!\!/\tilde\chi - \frac{M_{\tilde\chi}}{2}\bar{\tilde\chi}\tilde\chi + \sum_{F=Q,u,d}\Big[D_\mu\varphi^\dagger_{F_3}D^\mu\varphi_{F_3} - M^2_\varphi\varphi^\dagger_{F_3}\varphi_{F_3} + \Big(\lambda_\varphi[\bar\chi F_3]\ \varphi^\dagger_{F_3} + \text{h.c.}\Big)\Big]\ , \tag{1.4}$$

and

$$\mathcal{L}_{\texttt{S3M\_uR}} = \mathcal{L}_{\rm SM} \frac{i}{2}\bar{\tilde\chi}\partial\!\!\!/\tilde\chi - \frac{M_{\tilde\chi}}{2}\bar{\tilde\chi}\tilde\chi + D_\mu\varphi^\dagger_{u_1}D^\mu\varphi_{u_1} - M^2_\varphi\varphi^\dagger_{u_1}\varphi_{u_1} + \Big(\lambda_\varphi[\bar\chi u^1_R]\ \varphi^\dagger_{u_1} + \text{h.c.}\Big)\ . \tag{1.5}$$

In the `S3D` class of models, the Majorana fermionic dark matter state $\tilde\chi$ is replaced by its Dirac fermionic counterpart χ. The three simplified models and their associated Lagrangians are unchanged (up to the normalisation of the kinetic and mass terms).

I.2. The `F3S` class of models

In `F3S`-type models, the dark matter is the scalar state S of mass M_S, all mediators are taken degenerate with mass M_ψ (which must be enforced at the `param_card.dat` file level, and all new physics interactions are taken universal and flavour-conserving, the couplings being commonly denoted by $\hat\lambda_\psi$. The Lagrangian of eq. (1.1) is therefore simplified to

$$\mathcal{L}_{\texttt{F3S\_uni}} = \mathcal{L}_{\rm SM} + \frac12 \partial_\mu S \partial^\mu S - \frac{M_S^2}{2} S^2 + \sum_{F=Q,u,d} \sum_{f=1}^3 \bigg[i\bar\psi_{F_f} \not{D} \psi_{F_f} - M_\psi \bar\psi_{F_f} \psi_{F_f} + \Big(\hat\lambda_\psi [\bar\psi_{F_f} F_f]\ S + \text{h.c.}\Big)\bigg] \ , \qquad (1.6)$$

where $Q_f \equiv Q_L^f$, $u_f \equiv u_R^f$ and $d_f \equiv d_R^f$, f being a generation index. The model is again defined by three parameters,

$$\Big\{ M_S ,\ M_\psi ,\ \hat\lambda_\psi \Big\} \ . \qquad (1.7)$$

In the `F3S_uni` restriction, the simplified model includes all twelve mediators, whilst in the `F3S_3rd` and `F3S_uR` models, the setup is further simplified and dark matter only couples to the third generation and to the up-right quark, respectively. The simplified models correspondingly include four and one mediators, the associated Lagrangians reading

$$\mathcal{L}_{\texttt{F3S\_3rd}} = \mathcal{L}_{\rm SM} + \frac12 \partial_\mu S \partial^\mu S - \frac{M_S^2}{2} S^2 + \sum_{F=Q,u,d} \bigg[i\bar\psi_{F_3} \not{D} \psi_{F_3} - M_\psi \bar\psi_{F_3} \psi_{F_3} + \Big(\hat\lambda_\psi [\bar\psi_{F_3} F_3]\ S + \text{h.c.}\Big)\bigg] \ , \qquad (1.8)$$

and

$$\mathcal{L}_{\texttt{F3S\_uR}} = \mathcal{L}_{\rm SM} + \frac12 \partial_\mu S \partial^\mu S - \frac{M_S^2}{2} S^2 + i\bar\psi_{u_1} \not{D} \psi_{u_1} - M_\psi \bar\psi_{u_1} \psi_{u_1} + \Big(\hat\lambda_\psi [\bar\psi_{u_1} u_R^1]\ S + \text{h.c.}\Big) \ . \qquad (1.9)$$

I.3. The `F3V` class of models

In `F3V`-type models, the dark matter is the vector state V_μ of mass M_V, all mediators are taken degenerate with mass M_ψ (which must be enforced on run-time at the level of the `parameter_card.dat` file) and all new physics interactions are taken universal and flavour-conserving, the couplings being commonly denoted by $\hat\lambda_\psi$. The Lagrangian of eq. (1.1) is therefore simplified to

$$\mathcal{L}_{\texttt{F3V\_uni}} = \mathcal{L}_{\rm SM} - \frac14 V_{\mu\nu} V^{\mu\nu} + \frac{M_V^2}{2} V_\mu V^\mu + \sum_{F=Q,u,d} \sum_{f=1}^3 \bigg[i\bar\psi_{F_f} \not{D} \psi_{F_f} - M_\psi \bar\psi_{F_f} \psi_{F_f} + \Big(\hat\lambda_\psi [\bar\psi_{F_f} \not{V} F_f] + \text{h.c.}\Big)\bigg] \ , \qquad (1.10)$$

where $Q_f \equiv Q_L^f$, $u_f \equiv u_R^f$ and $d_f \equiv d_R^f$, f being a generation index. The model is again defined by three parameters,

$$\Big\{ M_V ,\ M_\psi ,\ \hat\lambda_\psi \Big\} \ . \qquad (1.11)$$

In the `F3V_uni` restriction, the simplified model includes all twelve mediators, whilst in the `F3V_3rd` and `F3V_uR` models, the setup is further simplified and dark matter only couples to the third generation and to the up-right quark, respectively. The simplified models correspondingly include four and one mediators, the associated Lagrangians reading

$$\mathcal{L}_{\texttt{F3V\_3rd}} = \mathcal{L}_{\rm SM} - \frac14 V_{\mu\nu} V^{\mu\nu} + \frac{M_V^2}{2} V_\mu V^\mu + \sum_{F=Q,u,d} \bigg[i\bar\psi_{F_3} \not{D} \psi_{F_3} - M_\psi \bar\psi_{F_3} \psi_{F_3} + \Big(\hat\lambda_\psi [\bar\psi_{F_3} \not{V} F_3] + \text{h.c.}\Big)\bigg] \ , \qquad (1.12)$$

and

$$\mathcal{L}_{\texttt{F3S\_uR}} = \mathcal{L}_{\rm SM} - \frac14 V_{\mu\nu} V^{\mu\nu} + \frac{M_V^2}{2} V_\mu V^\mu + i\bar\psi_{u_1} \not{D} \psi_{u_1} - M_\psi \bar\psi_{u_1} \psi_{u_1} + \Big(\hat\lambda_\psi [\bar\psi_{u_1} \not{V} u_R^1] + \text{h.c.}\Big) \ . \qquad (1.13)$$

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