MadGraph 5 Model: EffDM

I. PURPOSE

This is pair of a Madgraph 5 model files which allows one to simulate production of dark matter particles at colliders. It writes interactions between WIMPs and Standard Model quarks or gluons in terms of effective theory, allowing one to capture a wide class of theories of dark matter in which the particles mediating the interactions are somewhat heavier than the energies of interest [1]. In particular, this can allow one to map these interactions from collider observables into the parameter space of searches for direct detection of dark matter. The notation used matches that found in Refs. [2, 3], and is very similar to other studies [4]. The two models are:

- `EffDM_UFO`: A model containing a Dirac WIMP.
- `EffDMS_UFO`: A model containing a complex scalar WIMP.

Both models are generated from Feynrules and use the Madgraph 5 UFO format.

II. PARAMETERS

This model introduces the new particle, `chi`, with antiparticle `chi~` which play the role of dark matter. To consider self-conjugate dark matter one simply must not include operators which vanish in that case (`D5, D6, D9, D10, C3`, and `C4`) and introduce the appropriate phase space factor for identical final state particles by hand. For final states which include exactly two Majorana or real scalar WIMPs, this is a factor of 1/2 which multiplies the Madgraph output cross section to give the correct physical rate.

There are two new parameters included in param_card.dat, `MDM` and `Mstar`:

- `MDM` is the mass of the dark matter particle in GeV, and is used to set the mass of both the Dirac and Complex candidates.
- `Mstar` is the suppression scale of new physics which appears in the higher-dimensional operators giving rise to dark matter interactions with SM

quarks and gluons.

Obviously a little care is needed, because one parameter controls the mass of the dark matter particle, and the second one controls the sizes of **all** of the potential couplings.

All operators listed below have been implemented in the model, and each has its own coupling order which must be specified. Because there now exist more than two types of couplings, all coupling orders must be specified or they will be taken by MadGraph 5 to be unconstrained. This could in particular lead to the behavior where you specify, e.g., `D1=1`, but in neglecting to set other coupling orders to zero actually get all operators simultaneously.

III. EXAMPLE

An example `proc_card_mg5.dat` file for dark matter production is:

```
import model EffDM_UFO --modelname
# Define multiparticle labels
define p = g u c d s b u~c~d~s~b~
define j = g u c d s b u~c~d~s~b~
define l+ = e+ mu+
define l- = e- mu-
define vl = ve vm vt
define vl  = ve  vm  vt
# Specify process(es) to run
generate p p > chi chi~ j QED=0 D1=1 D2=0 D3=0 D4=0
D5=0 D6=0 D7=0 D8=0 D9=0 D10=0 D11=0 D12=0 D13=0 D14=0
# Output processes to MadEvent directory
output -f
```

which will generate the processes relevant for a hadron collider producing a pair of dark matter particles plus a jet for a Dirac WIMPs interacting with quarks through operator `D1`. Note the modifier `--modelname` when the model is imported. This option is needed because the `chi` particle has been assigned the particle identification code of the neutralino.

IV. OPERATOR LIST

The operators are listed below, with their numbering. These labels are also the "coupling types" inside madgraph, so specifying `C1=1` will allow up to one insertion of the first operator listed for scalar WIMPs. Operators involving quarks are summed over all six quarks, $q = u, d, s, c, b, t$, and $G^a_{\mu\nu}$ is the $\mathrm{SU}(3)_C$ field strength tensor, as usual. They are invariant under the $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{EM}$ gauge symmetries. All of them can be made invariant under the full electroweak group by inserting Higgs VEVs appropriately.

The coefficients M_* can be mapped into the plane of direct detection experiments [3]:

$$\sigma_{\mathrm{SI}}^{D1} = 1.60 \times 10^{-37}\ \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{20\ \mathrm{GeV}}{M_*}\right)^6, \tag{1}$$

$$\sigma_{\mathrm{SI}}^{D5,C3} = 1.38 \times 10^{-37}\ \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{300\ \mathrm{GeV}}{M_*}\right)^4, \tag{2}$$

$$\sigma_{\mathrm{SI}}^{D11} = 3.83 \times 10^{-41}\ \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{M_*}\right)^6, \tag{3}$$

$$\sigma_{\mathrm{SI}}^{C1} = 2.56 \times 10^{-36}\ \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{10\ \mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{10\ \mathrm{GeV}}{M_*}\right)^4, \tag{4}$$

$$\sigma_{\mathrm{SI}}^{C5} = 7.40 \times 10^{-39}\ \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{10\ \mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{60\ \mathrm{GeV}}{M_*}\right)^4, \tag{5}$$

$$\sigma_{\mathrm{SD}}^{D8,D9} = 4.70 \times 10^{-39}\ \mathrm{cm}^2 \left(\frac{\mu_\chi}{1\ \mathrm{GeV}}\right)^2 \left(\frac{300\ \mathrm{GeV}}{M_*}\right)^4, \tag{6}$$

where μ_χ is the reduced mass of the WIMP-nucleon system and the labels "SI" and "SD" indicate spin-independent and spin-dependent scattering, respectively. The numerical coefficients in front contain expectation values of partonic matrix elements in the nucleon. This set of operators is to very good approximation iso-spin symmetric, and leads to approximately equal scattering cross sections on protons and neutrons.

Dirac Fermion WIMP operators of interest:

$$\frac{m_q}{M_*^3}\ \overline{\chi}\chi\ \overline{q}q \tag{D1}$$

$$\frac{m_q}{M_*^3}\ \overline{\chi}\gamma^5\chi\ \overline{q}q \tag{D2}$$

$$\frac{m_q}{M_*^3}\ \overline{\chi}\chi\ \overline{q}\gamma^5 q \tag{D3}$$

$$\frac{m_q}{M_*^3}\ \overline{\chi}\gamma^5\chi\ \overline{q}\gamma^5 q \tag{D4}$$

$$\frac{1}{M_*^2}\ \overline{\chi}\gamma^\mu\chi\ \overline{q}\gamma_\mu q \tag{D5}$$

$$\frac{1}{M_*^2}\ \overline{\chi}\gamma^\mu\gamma^5\chi\ \overline{q}\gamma_\mu q \tag{D6}$$

$$\frac{1}{M_*^2}\ \overline{\chi}\gamma^\mu\chi\ \overline{q}\gamma_m u\gamma^5 q \tag{D7}$$

$$\frac{1}{M_*^2}\ \overline{\chi}\gamma^\mu\gamma^5\chi\ \overline{q}\gamma_\mu\gamma^5 q \tag{D8}$$

$$\frac{1}{M_*^2}\ \overline{\chi}\sigma^{\mu\nu}\chi\ \overline{q}\sigma_{\mu\nu} q \tag{D9}$$

$$\frac{1}{M_*^2}\ \epsilon^{\mu\nu\alpha\beta}\overline{\chi}\sigma_{\mu\nu}\chi\ \overline{q}\sigma_{\alpha\beta} q \tag{D10}$$

$$\frac{\alpha_s}{4M_*^3}\ \overline{\chi}\chi\ \left(G^a_{\mu\nu}\right)^2 \tag{D11}$$

$$\frac{\alpha_s}{4M_*^3}\ \overline{\chi}\gamma^5\chi\ \left(G^a_{\mu\nu}\right)^2 \tag{D12}$$

$$\frac{\alpha_s}{4M_*^3}\ \overline{\chi}\chi\ G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \tag{D13}$$

$$\frac{\alpha_s}{4M_*^3}\ \overline{\chi}\gamma^5\chi\ G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \tag{D14}$$

Complex Scalar WIMP operators of interest:

$$\frac{m_q}{M_*^2}\ \chi^\dagger\chi\ \bar{q}q \tag{C1}$$

$$\frac{m_q}{M_*^2}\ \chi^\dagger\chi\ \bar{q}\gamma^5 q \tag{C2}$$

$$\frac{1}{M_*^2}\frac{i}{2}\ \left(\chi^\dagger\partial^\mu\chi - \partial^\mu\chi^\dagger\chi\right)\ \bar{q}\gamma_\mu q \tag{C3}$$

$$\frac{1}{M_*^2}\frac{i}{2}\ \left(\chi^\dagger\partial^\mu\chi - \partial^\mu\chi^\dagger\chi\right)\ \bar{q}\gamma_\mu\gamma^5 q \tag{C4}$$

$$\frac{\alpha_s}{4M_*^2}\ \chi^\dagger\chi\ \left(G^a_{\mu\nu}\right)^2 \tag{C5}$$

$$\frac{\alpha_s}{4M_*^2}\ \chi^\dagger\chi\ G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \tag{C6}$$

[1] M. Beltran, D. Hooper, E. W. Kolb, Z. A. C. Krusberg and T. M. P. Tait, JHEP **1009**, 037 (2010) [arXiv:1002.4137 [hep-ph]].

[2] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait and H. B. P. Yu, Phys. Lett. B **695**, 185 (2011) [arXiv:1005.1286 [hep-ph]].

[3] J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait and H. B. P. Yu, Phys. Rev. D **82**, 116010 (2010) [arXiv:1008.1783 [hep-ph]].

[4] Y. Bai, P. J. Fox and R. Harnik, JHEP **1012**, 048 (2010) [arXiv:1005.3797 [hep-ph]].