This is a short document to describe the use of the the `MadGraph5` model files for scalar and pseudoscalar mediators, coupling to fermionic dark matter and to Standard Model quarks and leptons. The coupling to SM particles is proportional to Yukawa couplings. The model files are attached, in two tarballs `DMscalar.tar.gz` and `DMpseudoscalar.tar.gz`. These models have been constructed in `FeynRules2.1`. Both models can be loaded into `MadGraph5` (I've been using version 2.1.1, but other versions should be fine) in the standard way: Place the untarred folders into the `model` subdirectory in `MadGraph5`, then after launching `MadGraph`, type:

`import model <modelname> --modelname`

The addition of `--modelname` is necessary, since the model file has been constructed to overwrite the supersymmetric dark matter neutralino PDG code with a new dark matter particle. The advantage of this is that all event analysis code that treats neutralinos correctly do not have to be modified to accept the event files from these models.

Both the scalar and pseudoscalar models contain only two new particles beyond the Standard Model. Both models use the same names and PDG code numbers for simplicity. There is the dark matter `chi` and `chi~` (particle and antiparticle) (with code 1000022) and the mediator `phim` (code 1000000). The mediator phim is either a scalar or pseudoscalar, depending on which model file you loaded. In the `param_card.dat`, the mass of the dark matter and mediator are set in the `dmmass` block, along with the width of the mediator. I will address the choice of the mediator width below.

COUPLINGS

The particle `phim` has the following interactions: three-point couplings `phim - chi - chi~`, `phim - f - f~`, `phim - A - A`, `phim - g - g`, and four-point interactions `phim - g - g - g` and `phim - A - A - A`. Here `f` are all the massive SM fermions (*i.e.* everything but neutrinos), `A` is the photon, and `g` is the gluon. The coupling between dark matter and the mediator is set in the `param_card.dat` as `gDM` in block `dmmass`. The coupling between the mediator and all the fermions is `gSM` in block `dmmass`. The couplings to the vector bosons are set by a loop-induced coupling (as with Higgs production), with the numerical coupling set in the `param_card.dat` with `Gphi` and `Fphi` for couplings to gluons and photons respectively. Unfortunately, though these two couplings are determined by the `phim` mass and `gSM`, we could not automate the calculation for these loop couplings, so they must be reset by hand as the masses and couplings are varied.

The loop coupling to gluons for the scalar and pseudoscalar models are:

$$\begin{aligned} G_{\rm scalar} &= \frac{\alpha_S}{8\pi}\frac{y_t}{v}\tau\left[1+(1-\tau)f(\tau)\right]\times g_{\rm SM} && (1)\\ G_{\rm pseudoscalar} &= \frac{\alpha_S}{4\pi}\frac{y_t}{v}\tau f(\tau)\times g_{\rm SM}, && (2)\end{aligned}$$

where $\tau = 4m_t^2/m_\phi^2$, $g_{\rm SM}$ is the coupling `gSM`, y_t is the top yukawa coupling, $v = 246$ GeV is the Higgs vev, and

$$f(\tau) = \begin{cases} \arcsin^2\tau^{-1/2} & \tau \geq 1 \\ -\frac{1}{4}\left(\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right)^2 & \tau < 1. \end{cases} \quad (3)$$

The photon coupling is similar:

$$\begin{aligned} F_{\rm scalar} &= \frac{\alpha}{8\pi}\frac{y_t}{v}\left(3Q_t^2\right)\tau\left[1+(1-\tau)f(\tau)\right]\times g_{\rm SM} && (4)\\ F_{\rm pseudoscalar} &= \frac{\alpha}{4\pi}\frac{y_t}{v}\left(3Q_t^2\right)\tau f(\tau)\times g_{\rm SM}, && (5)\end{aligned}$$

where $Q_t = 2/3$ is the top charge. The coupling in the `param_card.dat` is defined with the $g_{\rm SM}$ factored out, so the actual interaction calculated in `MadGraph` will be `Gphi`×`gSM`.

So, when choosing a set of masses, if you want to have couplings to gluons and photons, recalculate `Gphi` and `Fphi` using the above equations (with $g_{\rm SM} \to 1$), and replace the values in the `param_card.dat`. For some range of masses, the couplings will have imaginary components, you can just take the magnitude. This would cause problems if you had diagrams that interfere with each other, but you shouldn't be generating monojet events with these model files anyway.

If you are using these model files to generate heavy quarks in association with dark matter, it would be better to set `Gphi = 0` in the `param_card.dat`. It is important to remember that the coupling to gluons can not be used to generate accurate distributions of dark matter events in the monojet channel using `MadGraph`. With heavy flavor production, most of your cross section will come from production of ϕ off of b or t, but for accuracy, you should shut off the gluon channel completely. For details, refer to our paper 1410.6497, specifically Figure 3. We are currently working to make available an implementation for these models produced via monojets using `Sherpa`. Until then, the gluon couplings in these models can be used in `MadGraph` to generate approximations for internal testing, if so desired. The couplings to heavy quarks do not have this issue, so these models can be safely used in those channels.

WIDTH

The width of the mediator is set as a free parameter. When the dark matter production proceeds on-shell, that is $2m_\chi < m_\phi$, the width Γ_ϕ will be important to determine the total cross section into the dark matter channel. That is, the total cross section of dark matter pair production will be proportional to the production of the mediator $\texttt{gSM}^2$ times the branching ratio into dark matter $\propto \texttt{gDM}^2/\Gamma_\phi$. Therefore, the most accurate thing to do to scale the overall cross section appropriately is to select a width consistent with your choice of couplings. The width of scalars in terms of the scalar mass, couplings, and fermion masses:

$$\Gamma_{\rm scalar} = \frac{g_{\rm DM}^2}{8\pi}\left(1-\frac{4m_\chi^2}{m_\phi^2}\right)^{3/2} + \sum_f N_C \frac{g_{\rm SM}^2 y_f^2}{8\pi}\left(1-\frac{4m_f^2}{m_\phi^2}\right)^{3/2} \tag{6}$$

where the sum is over all fermions that the mediator can decay into, N_C is the number of colors of the fermion, and y_f is the SM fermion yukawa m_f/v. The width for the pseudoscalar is

$$\Gamma_{\rm pseudoscalar} = \frac{g_{\rm DM}^2}{8\pi}\left(1-\frac{4m_\chi^2}{m_\phi^2}\right)^{1/2} + \sum_f N_C \frac{g_{\rm SM}^2 y_f^2}{8\pi}\left(1-\frac{4m_f^2}{m_\phi^2}\right)^{1/2}. \tag{7}$$

In practice, for on-shell mediators, for a choice of masses m_ϕ and m_χ a benchmark width Γ_B can be chosen, and the resulting cross section into dark matter rescaled as the couplings are varied by the factor

$$g_{\rm SM}^2 \frac{\frac{g_{\rm DM}^2}{8\pi}\left(1-\frac{4m_\chi^2}{m_\phi^2}\right)^{3/2}}{\Gamma_B} \tag{8}$$

for scalars and

$$g_{\rm SM}^2 \frac{\frac{g_{\rm DM}^2}{8\pi}\left(1-\frac{4m_\chi^2}{m_\phi^2}\right)^{1/2}}{\Gamma_B} \tag{9}$$

for pseudoscalars. As we demonstrated in 1410.6497, for choices of the width that are consistent with perturbative couplings, there is no significant change in the detector acceptance as the width is varied, so rescaling the cross section in this way is acceptable.

For off-shell production of dark matter $2m_\chi > m_\phi$, the overall production cross section scales straightforwardly as $g_{\rm SM}^2 g_{\rm DM}^2$, and the width is not a relevant parameter (again, barring extremely large widths inconsistent with perturbative couplings).

SUGGESTIONS FOR PARAMETER SPACE

Ideally, one would like to see a plot of the upper limit on the couplings $g_{\rm DM}$ and $g_{\rm SM}$ as a function of dark matter and mediator masses m_χ and m_ϕ. I am thinking of something akin to Figure 1 of 1308.2679. That paper concerns t-channel mediators (squarks essentially). In that case, the $m_\chi > m_{\rm mediator}$ regime is not theoretically interesting (as the neutral particle is no longer the lightest), and there is only a single coupling to deal with. The width is also not important in this sort of simplified model.

I would therefore suggest a set of simplifying assumptions be made, with the goal of producing a 2D limit plot. Since we have two couplings to deal with, make the assumption $g_{\rm SM} = g_{\rm DM}$, and calculate the width accordingly. Then, for each choice of masses, the experimental limits can be shown on the universal coupling $g \equiv g_{\rm SM} = g_{\rm DM}$. Theorists can then do the necessary work of rescaling the limits using the Eqs. (8) and (9), if they are so inclined. As

I realize that placing exclusion curves is a desirable thing, showing the mass region where you rule out $g = 1$ would be the obvious choice, but I at least would find the heat-map exclusion plot more helpful.

As noted, there are important differences between the production of dark matter when the mediator is on- or off-shell. On-shell, with the universal coupling assumption made above, you will see a discontinuity when $m_\phi > 2m_t$, as the branching ratio to dark matter drops once the top channel opens. The decay to dark matter will still dominate (unless you remove the universality assumption and set $g_{\rm SM} \gg g_{\rm DM}$). Off-shell, this won't matter, as the cross section for the production of dark matter is insensitive to the mediator branching ratios.

The relevant range of masses is something I'm not 100% sure about at this point. I would suggest scanning over masses of dark matter and mediators up to the point where the limit on the coupling set by experiments are non-perturbative. I would expect this to be in the few hundred GeV range for the mediator, for light or massless dark matter. The mass range shown in Figure 7 of the ATLAS heavy flavor plus missing energy paper 1410.4031 would be a good estimate, but this model might not be accessible with Run-I data up to as high of a mediator mass. My theoretical prejudice is towards lower (100-200 GeV) masses of mediators.

I would also suggest, if possible, to separate out limits set by the production of the mediator in association with b quarks and those in association with tops. If I read the ATLAS paper 1410.4031 correctly, the limits for this model in the b-channel (SR2 in particular) are actually largely being driven by $pp \to t\bar{t} + \phi$ events, with hadronic or semi-leptonic decays of the tops. While allowing couplings to both b and t is the simplest version of the scalar and pseudoscalar models (and what is implemented in the attached files), it might be useful to know what limit is being placed on the mediator-b coupling separately from the mediator-t coupling. To separate this in MadGraph, one would generate `p p > t t~chi chi~` (matched with jets) for the top events and `p p > b chi chi~`, `p p > b~chi chi~`, `p p > b b~chi chi~` (again matched with jets) for the bottom. Separating limits in this way would be useful for models with connections to extended higgs sectors, as one might have a $\tan\beta$-type enhancement to the bottom coupling over the top.