Simplified Models for Resonance plus Missing Transverse Energy Signatures

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Contents

1 Introduction

This document is the manual for a set of simplified models based on the Coannihilation Codex [1], designed to describe resonance plus missing transverse energy signatures at the Large Hadron Collider. The models are constructed by implementing their respective Lagrangians in `FeynRules v2.3.18` [2, 3], while using the `UFO` [4] format to provide an interface with Monte Carlo generators. Specifically, we will focus on the `MadGraph v2.3.3` [5, 6] Monte Carlo generator, which is particularly suited to generate events for BSM models. The models have been tested to work with `Pythia v8.2` [7] and `Delphes v3.3` [8]. The latest versions of all the models presented in this manual can be found in the FeynRules model database [9].

For the calculation of the relic density we provide interfaces with `MicrOMEGAs v4.1.8` [10] through `CalcHEP v3.6.25` [11] output[1] and with `MadDM v2.0` [15] based on the `UFO` [4] output. Both the programs `MicrOMEGAs` and `MadDM` can also calculate DM direct detection rates.

In section 2 we discuss the models from the Coannihilation Codex we have implemented. For each of the simplified models we specify the Lagrangian and the parameters of the new vertex structures introduced on top of the Standard Model. Moreover, whenever possible we provide connections between our simplified model and existing UV-complete models.

In section 3 we validate our models using standard tools provided by the `FeynRules` and `MadGraph` programs. On top of that we reproduce known theoretical properties of these models, like decay widths, scattering cross sections and relic density predictions.

We briefly summarize this manual in section 4. After that, in appendix A we discuss the generation of Monte Carlo data using the `MadGraph` generator for the simplified models we have presented. This discussion focusses on the generation of the new signatures relevant to the LHC experiments. We supplement this with procedures to calculate the relic density in these models, which serves as a guiding principle for LHC searches and parameter space.

2 Simplified Models

We discuss here a set of simplified models which are constructed from the Coannihilation Codex [1]. In all the models the new field content will comprise DM (the dark matter candidate), X (the coannihilation partner) and M (the mediator). We denote a field with its Standard Model quantum numbers and its spin assignment as $(SU(3)_C, SU(2)_L, U(1)_Y)_{\text{spin}}$, where the spin can be S (scalar), F (Dirac fermion), M (Majorana fermion), V (vector).

[1] The `FeynRules` interface to `CalcHEP` [12] does not generate vertices with fields in the sextet represenation of $SU(3)$ for the `CalcHEP` interface. Therefore we provide a separate `CalcHEP` model for sextets constructed using `LanHEP v3.2.0` [13, 14].

For each of the simplified models we specify the parameters we use. For the masses of the new field content we will adopt the notation $m_{\rm DM}$, $m_{\rm X}$ and $m_{\rm M}$. Furthermore, we define two quantities related to coannihilation and these masses, namely

$$\Delta \equiv \frac{m_{\rm X} - m_{\rm DM}}{m_{\rm DM}}\,, \qquad \tau_{\rm DM} \equiv \frac{m_{\rm DM}^2}{m_{\rm M}^2}. \tag{2.1}$$

The fractional mass splitting Δ determines the relative strength of coannihilation and $\tau_{\rm DM}$ allows to write simpler expressions for the widths of the particles.

The mediator, dark matter or the coannihilation partner can be scalar fields, which may lead to complicated potentials including quartic interactions with the Higgs field [16, 17]. In the models we propose, these potentials do not provide interactions relevant to either LHC phenomenology nor to the relic density computation. We therefore ignore them in our `FeynRules` implementation. These potentials could also lead to mass splittings for the components of the $SU(2)$ multiplets when the Higgs field obtains its vacuum expectation value. However, the potential can always be chosen in such a way this splitting is zero. Another source for the mass splitting of the components are electromagnetic radiative corrections, these cause tiny splittings and may allow for additional decays involving charged pions.[2]

2.1 Leptoquark

The leptoquark model is based on ST11 in the codex, for which the following new fields

$$\mathrm{DM} \equiv (1,1,0)_{\rm M} \qquad \mathrm{X} \equiv (3,2,\tfrac{7}{3})_{\rm F} \qquad \mathrm{M} \equiv (3,2,\tfrac{7}{3})_{\rm S} \tag{2.2}$$

are introduced. With this new field content the Lagrangian on top of the Standard Model reads

$$\begin{aligned}
\mathcal{L}_{\rm DM} &= \frac{i}{2}\overline{\rm DM}\,\partial\!\!\!/\,{\rm DM} - \frac{m_{\rm DM}}{2}\overline{\rm DM}\,{\rm DM} \\
\mathcal{L}_{\rm X} &= i\overline{\rm X}\,D\!\!\!\!/\,{\rm X} - m_{\rm X}\overline{\rm X}\,{\rm X} \\
\mathcal{L}_{\rm M} &= (D_\mu {\rm M})^\dagger\,(D^\mu {\rm M}) - m_{\rm M}^2 {\rm M}^\dagger\,{\rm M} \\
\mathcal{L}_{\rm vis} &= -y_{Q\ell}\,\overline{Q_L}{\rm M}\,\ell_R - y_{Lu}\overline{L_L}{\rm M}^c u_R + {\rm h.c.} \\
\mathcal{L}_{\rm dark} &= -y_D\overline{\rm X}\,{\rm DM}\,{\rm M} + {\rm h.c.}\,.
\end{aligned} \tag{2.3}$$

Besides kinetic terms we have interactions between the mediator and leptons and quarks, where the generation indices of the couplings ($y_{Q\ell}^{ij}$ and y_{Lu}^{ij}) have been suppressed. Furthermore we have interactions between M, X and DM, the coupling strength of which is given by y_D. NLO corrections for pair production of leptoquarks are presented in [18, 19].

[2] These splittings can be introduced by hand as the masses of the components can be set individually in the parameter card.

Given this Lagrangian we can calculate the decay widths of the new unstable particles X and M, these are (with neglected lepton masses)

$$\begin{aligned}
\Gamma\left(\mathrm{M}^{(1)} \to u_i\,\bar{\ell}_i\right) &= \frac{y_{Q\ell}^2 + y_{Lu}^2}{16\pi} m_{\mathrm{M}}\,(1-\tau_u)^2 \\
\Gamma\left(\mathrm{M}^{(2)} \to d_i\,\bar{\ell}_i\right) &= \frac{y_{Q\ell}^2}{16\pi} m_{\mathrm{M}}\,(1-\tau_d)^2 \\
\Gamma\left(\mathrm{M}^{(2)} \to u_i\,\bar{\nu}_i\right) &= \frac{y_{Lu}^2}{16\pi} m_{\mathrm{M}}\,(1-\tau_u)^2 \\
\Gamma\left(\mathrm{M}^{(n)} \to \mathrm{DM}\,\mathrm{X}^{(n)}\right) &= \frac{y_D^2}{8\pi} m_{\mathrm{M}}\left(1-\Delta^2\tau_{\mathrm{DM}}\right)^{\frac{1}{2}}\left(1-(2+\Delta)^2\tau_{\mathrm{DM}}\right)^{\frac{3}{2}}.
\end{aligned} \tag{2.4}$$

2.2 Diquark (Triplet)

The triplet diquark model is based on ST6 in the codex, we have

$$\mathrm{DM} \equiv (1,1,0)_{\mathrm{M}} \qquad \mathrm{X} \equiv (3,1,-\tfrac{2}{3})_{\mathrm{F}} \qquad \mathrm{M} \equiv (3,1,-\tfrac{2}{3})_{\mathrm{S}}. \tag{2.5}$$

The Lagrangian reads

$$\begin{aligned}
\mathcal{L}_{\mathrm{DM}} &= \frac{i}{2}\overline{\mathrm{DM}}\not{\partial}\mathrm{DM} - \frac{m_{\mathrm{DM}}}{2}\overline{\mathrm{DM}}\,\mathrm{DM} \\
\mathcal{L}_{\mathrm{X}} &= i\overline{\mathrm{X}}\not{D}\mathrm{X} - m_{\mathrm{X}}\overline{\mathrm{X}}\,\mathrm{X} \\
\mathcal{L}_{\mathrm{M}} &= (D_\mu \mathrm{M})^\dagger (D^\mu \mathrm{M}) - m_{\mathrm{M}}^2 \mathrm{M}^\dagger\,\mathrm{M} \\
\mathcal{L}_{\mathrm{vis}} &= \epsilon_{ijk}\mathrm{M}_i^\dagger\,\bar{d}_j\left(y_{ud}^L P_L + y_{ud}^R P_R\right)(u^c)_k + \text{h.c.} \\
\mathcal{L}_{\mathrm{dark}} &= -y_D \overline{\mathrm{X}}\,\mathrm{DM}\,\mathrm{M} + \text{h.c.}.
\end{aligned} \tag{2.6}$$

As in all models the couplings between the mediator and the Standard Model fields have generation indices ($y_{ud}^{R\,ij}$ and $y_{ud}^{L\,ij}$). NLO QCD corrections for single production of scalar triplet diquarks are presented in [20, 21] (scalar) and [22] (vector). For pair production of the mediator NLO corrections are calculated in [23, 24] and can be obtained using `NLL-fast v3.1` [25]. NLO corrections for pair production of X can be obtained running `Top++ v2.0` [26] with replacing the top mass value. Given this Lagrangian we can calculate the decay widths of the new unstable particles X and M, these are

$$\begin{aligned}
\Gamma\left(\mathrm{M} \to \bar{u}_i \bar{d}_i\right) =& \frac{m_{\mathrm{M}}}{8\pi}\Bigg[\left((y_{ud}^L)^2 + (y_{ud}^R)^2\right)(1-\tau_{u_i}-\tau_{d_i}) \\
& - 4 y_{ud}^L y_{ud}^R \sqrt{\tau_{u_i}\tau_{d_i}}\sqrt{(\tau_{u_i}-1)^2 + \tau_{u_i}^2 - 2\tau_{d_i}(1+\tau_{u_i})}\Bigg] \\
\Gamma\left(\mathrm{M} \to \mathrm{DM}\,\mathrm{X}\right) =& \frac{y_D^2}{8\pi} m_{\mathrm{M}}\left(1-\Delta^2\tau_{\mathrm{DM}}\right)^{\frac{1}{2}}\left(1-(2+\Delta)^2\tau_{\mathrm{DM}}\right)^{\frac{3}{2}}.
\end{aligned} \tag{2.7}$$

2.3 Diquark (Sextet)

The sextet diquark model is based on SE1 in the codex, we have

$$\mathrm{DM} \equiv (1,1,0)_{\mathrm{M}} \qquad \mathrm{X} \equiv (6,1,\tfrac{8}{3})_{\mathrm{F}} \qquad \mathrm{M} \equiv (6,1,\tfrac{8}{3})_{\mathrm{S}}. \tag{2.8}$$

The Lagrangian reads

$$\begin{aligned}
\mathcal{L}_{\rm DM} &= \frac{i}{2}\overline{\rm DM}\partial\!\!\!/ {\rm DM} - \frac{m_{\rm DM}}{2}\overline{\rm DM}\,{\rm DM}\\
\mathcal{L}_{\rm X} &= i\overline{\rm X}D\!\!\!\!/\,{\rm X} - m_{\rm X}\overline{\rm X}\,{\rm X}\\
\mathcal{L}_{\rm M} &= (D_\mu {\rm M})^\dagger\,(D^\mu {\rm M}) - m_{\rm M}^2{\rm M}^\dagger\,{\rm M}\\
\mathcal{L}_{\rm vis} &= y_{uu}K^u_{ij}{\rm M}^u\,\bar{u}_i P_L (u^c)_j + \text{h.c.}\\
\mathcal{L}_{\rm dark} &= -y_D\overline{\rm X}\,{\rm DM}\,{\rm M} + \text{h.c.}\,.
\end{aligned} \tag{2.9}$$

As in all models the couplings between the mediator and the Standard Model fields have generation indices (y^{ij}_{uu}). NLO QCD corrections for single production of scalar sextet diquarks are presented in [20, 21] (scalar) and [22] (vector). Given this Lagrangian we can calculate the decay widths of the new unstable particles X and M, these are

$$\begin{aligned}
\Gamma\left({\rm M}\to u_i u_i\right) =& \frac{(y^{ii}_{uu})^2}{8\pi} m_{\rm M}\sqrt{1-4\tau_{u_i}}\,(1-2\tau_{u_i})\\
\Gamma\left({\rm M}\to {\rm DM}\,{\rm X}\right) =& \frac{y_D^2}{8\pi} m_{\rm M}\left(1-\Delta^2\tau_{\rm DM}\right)^{\frac{1}{2}}\left(1-(2+\Delta)^2\tau_{\rm DM}\right)^{\frac{3}{2}}.
\end{aligned} \tag{2.10}$$

2.4 Scalar Octet

The scalar octet model is based on SO4 in the codex, we have the following new fields

$$\text{DM}\equiv(1,1,0)_{\rm M}\qquad \text{X}\equiv(8,2,1)_{\rm F}\qquad \text{M}\equiv(8,2,1)_{\rm S}. \tag{2.11}$$

The Lagrangian reads

$$\begin{aligned}
\mathcal{L}_{\rm DM} &= \frac{i}{2}\overline{\rm DM}\partial\!\!\!/ {\rm DM} - \frac{m_{\rm DM}}{2}\overline{\rm DM}\,{\rm DM}\\
\mathcal{L}_{\rm X} &= i\overline{\rm X}D\!\!\!\!/\,{\rm X} - m_{\rm X}\overline{\rm X}\,{\rm X}\\
\mathcal{L}_{\rm M} &= (D_\mu {\rm M}^a)^\dagger\,D^\mu {\rm M}^a - m_{\rm M}^2{\rm M}^a{\rm M}^a\\
\mathcal{L}_{\rm vis} &= -y_{Qu}\epsilon{\rm M}^{a\dagger}\,\overline{Q_L}T^a u_R - y_{Qd}{\rm M}^a\,\overline{Q_L}T^a d_R + \text{h.c.}\\
\mathcal{L}_{\rm dark} &= -y_D\overline{{\rm X}^a}\,{\rm DM}\,{\rm M}^a + \text{h.c.}\,.
\end{aligned} \tag{2.12}$$

As in all models the couplings between the mediator and the Standard Model fields have generation indices (y^{ij}_{Qu} and y^{ij}_{Qd}). The dark sector Yukawa y_D couples M with DM and X. NLO QCD corrections for pair production of scalar octets are presented in [27]. See [16, 17] for flavor story and SM side implementation. Given this Lagrangian we can calculate the decay widths of the new unstable particles X and M, these are

$$\begin{aligned}
\Gamma\left(\mathrm{M}^{(1)} \to u_i\, \bar{d}_i\right) =& \frac{m_{\mathrm{M}}}{32\pi}\Bigg[\left((y_{Qu})^2 + (y_{Qd})^2\right)(1-\tau_{u_i}-\tau_{d_i}) \\
&- 4 y^L_{Qu} y^R_{Qd}\sqrt{\tau_{u_i}\tau_{d_i}}\sqrt{(\tau_{u_i}-1)^2+\tau_{u_i}^2-2\tau_{d_i}(1+\tau_{u_i})}\Bigg] \\
\Gamma\left(\mathrm{M}^{(2)} \to q_i\, \bar{q}_i\right) =& \frac{y_{Qq}^2}{32\pi} m_{\mathrm{M}}\sqrt{1-4\tau_q}\,(1-2\tau_q) \\
\Gamma\left(\mathrm{M}^{(n)} \to \mathrm{DM}\,\mathrm{X}^{(n)}\right) =& \frac{y_D^2}{8\pi} m_{\mathrm{M}}\left(1-\Delta^2\tau_{\mathrm{DM}}\right)^{\frac{1}{2}}\left(1-(2+\Delta)^2\tau_{\mathrm{DM}}\right)^{\frac{3}{2}} .
\end{aligned} \tag{2.13}$$

2.5 Remarks

Note that in all the models the dark matter is a Majorana field. This is chosen such because the correct relic density would be obtained for lower dark matter masses.[3]

3 Model Validation

Model validation is an essential part and we have performed several checks to test our models. Naturally, the internal `FeynRules` checks have been used and all models satisfy these.[4] Furthermore, since the models are primarily designed to be used with `MadGraph`, we also run its implemented checks. In terms of `MadGraph` commands we run *check full process*, where *process* is replaced by several processes relevant for the phenomenology in our model. These processes are:

- Double mediator production (p p > m m)
- X X + jet production (p p > x x j)
- X decay (x > dm sm_1 sm_2)
- Single mediator production (p p > m [if $\mathrm{sm}_{1/2} \in$ p])
- Associated mediator production (p p > m $\mathrm{sm}_{1/2}$)

On top of the basic checks from `FeynRules` and `MadGraph` we also reproduce known results in the literature like production cross sections and decay rates. The are detailed on a process by process basis in the next sections. The chosen processes are based on the new signatures we propose. First we have pair production of the mediator with one mediator decaying to visible particles and the other mediator decaying to invisibale particles. To validate this process we reproduce the cross sections for pair production of the mediator. Secondly, a monojet plus missing transverse energy plus soft particles final state is considered. This

[3] Model files with Dirac dark matter can be provided on request.

[4] The employed `FeynRules` checks are: `CheckHermiticity`, `CheckDiagonalKineticTerms`, `CheckDiagonalMassTerms`, `CheckDiagonalQuadraticTerms`, `CheckKineticTermNormalisation` and `CheckMassSpectrum`.

process is generated by either ISR or FSR from the process of pair production of X. We therefore validate pair production of X by comparing to theoretical results in the literature. Finally in section 3.4 we validate the relic density calculations in these models by reproducing basic features as well as cross sections for the annihilation and coannihilation processes.

3.1 Mediator Pair-Production

We compare the pair production cross sections of the mediator in our models to the literature. The latest computations for LHC cross sections can be found in references [19, 28] (leptoquark), [] (diquark-triplet), [] (diquark-sextet) and [27] (scalar octet). In figure 1 we show the leading-order QCD pair production cross sections at 8 TeV for the different models we present here.

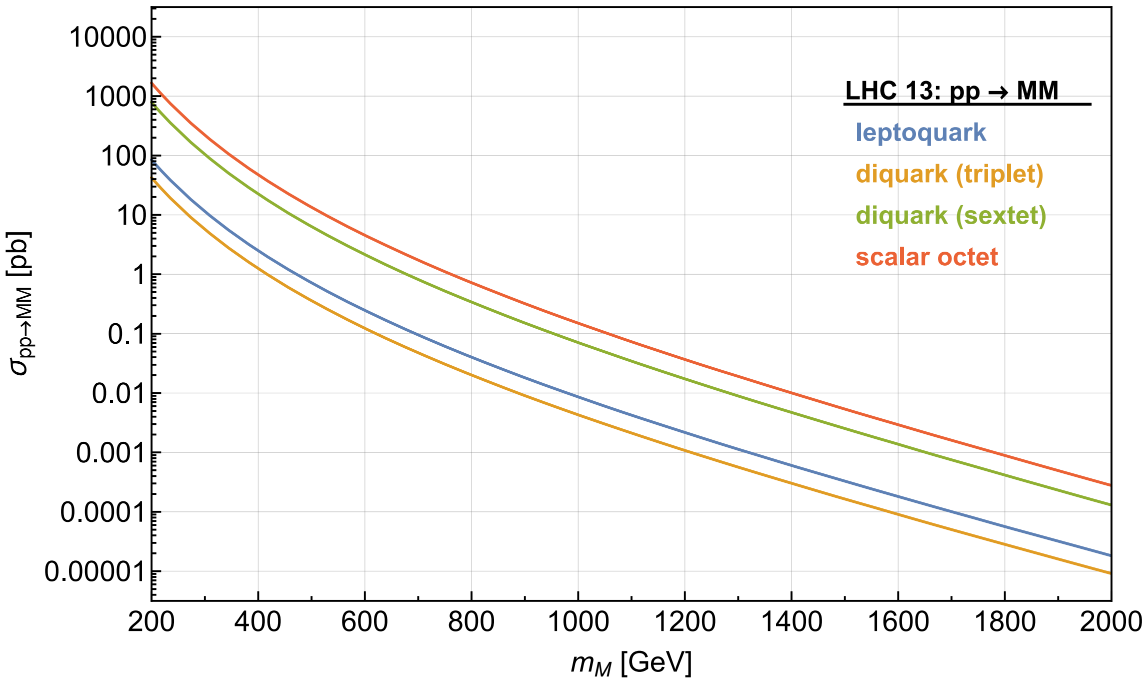

Figure 1. Production cross sections for M pairs at the 13 TeV LHC for the simplified models with a strong interaction via their kinetic terms. For the mediators in a non-trivial representation of $SU(2)_L$ the production of all components is considered.

The pair-production cross section for a pair of colored complex scalars equals from gluon

gluon and quark anti-quark annihilation equals [16, 29, 30]

$$\begin{aligned}\sigma\left(g\, g \to S\, S\right) =& \frac{2\pi\alpha_s^2}{s^2}\frac{d_R C_2(R)}{d_A^2}\left[\frac{1}{6}\beta\left(6C_2(R)(4m_S^2+s)+C_2(A)(10m_S^2-s)\right)\right.\\ &\left.-\frac{4m_S^2}{s}\left(C_2(A)m_S^2+C_2(R)(s-m_S^2)\right)\log\frac{1+\beta}{1-\beta}\right]\\ \sigma\left(q\,\bar{q} \to S\, S\right) =& \frac{\pi\alpha_s^2}{3s}\frac{d_A}{d_F^2}C(F)C(R)\beta^3,\end{aligned} \tag{3.1}$$

where $\beta = \sqrt{1-4m_S^2/s}$ and the color factors from the quarks and the gluons are $d_F = 3$, $d_A = 8$, $C(F) = \frac{1}{2}$ and $C_2(A) = 3$. For the representation of the scalar R, we have d_R representing the dimension of that representation and the Casimirs $C(R) = \frac{1}{2}, \frac{5}{2}, 3$ and $C_2(R) = \frac{4}{3}, \frac{10}{3}, 3$ for the 3, the 6 and the 8 of $SU(3)$ respectively. For the models we check that simulations of these parton level processes with `MadGraph` reproduce the analytic cross sections in equation (3.1) within a margin of 1% for several choices of m_S and s.

3.2 X Pair-Production

Since in all of the models X is a Dirac fermion we would expect the double production of X in the different models to be equal up to color factors.

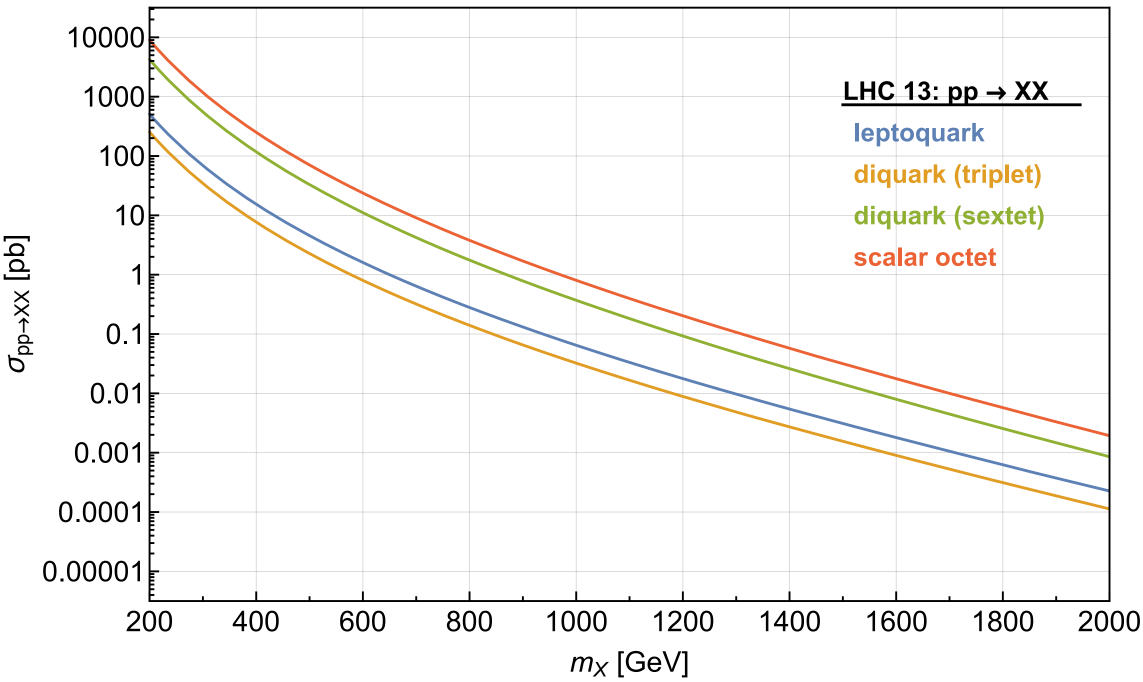

Figure 2. Production cross sections for X pairs at the 13 TeV LHC for the simplified models with a strong interaction via their kinetic terms. For the coannihilation partners in a non-trivial representation of $SU(2)_L$ the production of all components is considered.

The pair-production cross section of two Dirac fermions from gluon gluon and quark anti-quark annihilation equals [31, 32]

$$\begin{aligned}\sigma\left(g\,g\to\psi\,\bar\psi\right) =& -\frac{4\pi\alpha_s^2}{3s^3}\frac{d_R C_2(R)}{d_A^2}\left[C_2(A)\left(5m^2 s\beta+s^2\beta-12m^4\log\frac{1+\beta}{1-\beta}\right)\right.\\ &\left.+3C_2(R)\left(4m^2 s\beta+s^2\beta+(8m^4-4m^2 s-s^2)\log\frac{1+\beta}{1-\beta}\right)\right]\\ \sigma\left(q\,\bar q\to\psi\,\bar\psi\right) =&\frac{4\pi\alpha_s^2}{3s}\frac{d_A}{d_F^2}C(F)C(R)\,\beta\left(1+\frac{2m_\psi^2}{s}\right),\end{aligned}\tag{3.2}$$

where now $\beta=\sqrt{1-4m_\psi^2/s}$. The color factors are the same as those defines in defined in section 3.2. For the models we check that simulations of these parton level processes with `MadGraph` reproduce the analytic cross-setions in equation (3.2) within a margin of 1% for several choices of m_ψ and s.

3.3 Mediator Single Production

The mediator can be singly produced and then decay to visible states through the M–SM$_1$–SM$_2$ interaction. The cross sections for these processes we checked are (using the narrow-width approximation)

$$\begin{aligned}\sigma\left(ue^+\to \mathrm{M}_{\mathrm{LQ}}^{5/3}\to ue^+\right) =&\frac{y_{Q\ell}^4}{64\pi}\frac{s}{(s-m^2)+m^2\Gamma^2}\\ \sigma\left(ud\to \mathrm{M}_{\mathrm{DQ3}}^{*}\to ud\right) =&\frac{\left({y_{ud}^L}^2+{y_{ud}^R}^2\right)^2}{48\pi}\frac{s}{(s-m^2)+m^2\Gamma^2}\\ \sigma\left(uu\to \mathrm{M}_{\mathrm{DQ6}}\to uu\right) =&\frac{y_{uu}^4}{12\pi}\frac{s}{(s-m^2)+m^2\Gamma^2}\\ \sigma\left(u\bar u\to \mathrm{M}_{\mathrm{SO}}^{0}\to u\bar u\right) =&\frac{y_{Qu}^4}{288\pi}\frac{s}{(s-m^2)+m^2\Gamma^2}.\end{aligned}\tag{3.3}$$

Simulations of these parton level processes with `MadGraph` reproduce the analytic cross sections in equation (3.3) within a margin of 1% for several choices of m and s and the couplings.

3.4 Relic Density

Since these models are not only designed for LHC searches we also validate the calculation of the relic density of dark matter. We use the programs `MicrOMEGAs` [10] and `MadDM v2.0` [15] to reproduce the basic features of these coannihilation models. In the models where the mediator and the coannihilation partner are charged under QCD we expect large annihilation cross sections from the process X X $\to g\,g$. We therefore set $\Delta=0.1$ to have access to this cross section in the relic density computations. Furthermore we would expect the resonance coannihilation diagram to dominate around $m_{\rm DM}(2+\Delta) = m_{\rm M}$, for non-zero $y_D = y_{\rm vis} = 0.5$. Additional channels open up when $m_{\rm DM}, m_{\rm X} > m_{\rm M}$, where there is annihilation to the mediator, which further decays to Standard Model particles.[5] The relic density in our models is shown as a function of the dark matter mass in figure 3 and the described features are all present. Note that the relic density of all models would be higher if DM would be of Dirac nature.

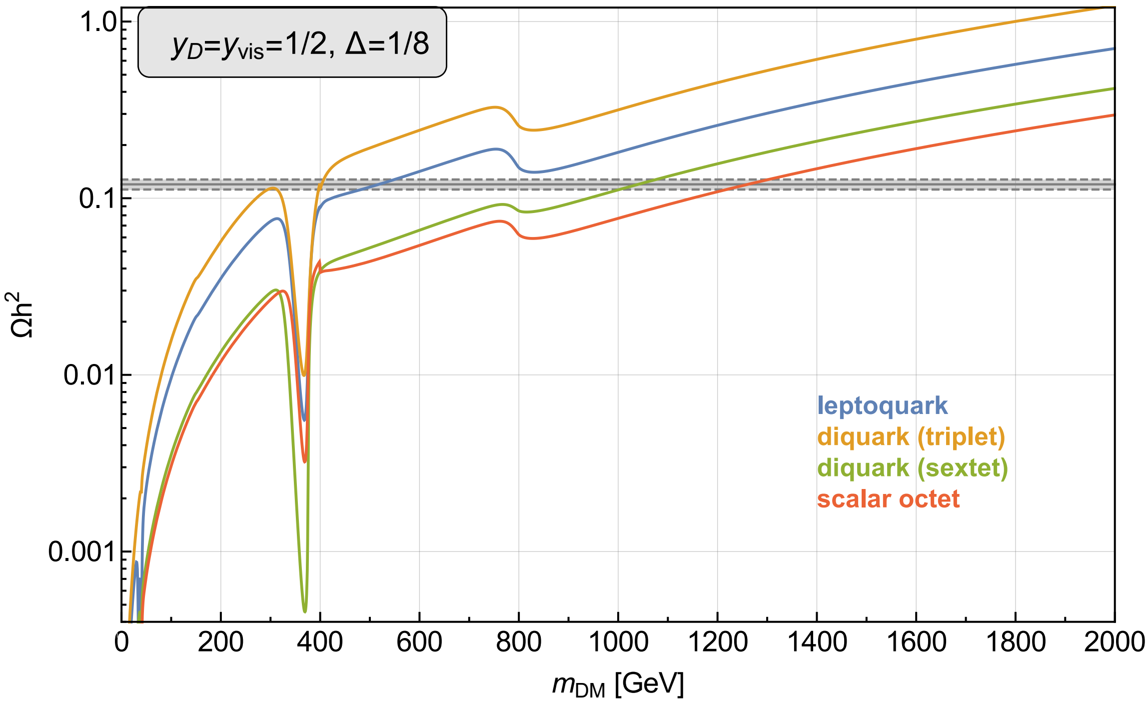

Figure 3. Relic density as a function of $m_{\rm DM}$ for the simplified models with a strong interaction via their kinetic terms. For the mediator to visible only the first generation couplings are non-zero.

We check the implementation of our models against the coannihilation diagrams occuring in processes relevant for the calculation of the relic density. These processes are X-annihilation (X X $\to g\,g$), the coannihilation channel (DM X $\to$ M $\to$ $\rm SM_1$ $\rm SM_2$) and DM and X annihilation to four SM particles (X X $\to$ M M, DM DM $\to$ M M). For all the models we check that simulations of these parton level processes with `MadGraph` reproduce the analytic cross sections within a margin of 1% for several choices of the relevant parameters.

4 Summary

In this note we have presented a set of simplified models of coannihilating dark matter implemented in `FeynRules` leading to resonance plus missing transverse energy signatures

[5]To enable this feature in `MadDM` be sure to generate the initial diagrams with model masses which kinematically allow these diagrams, which is ensured when $m_{\rm DM}, m_{\rm X} > m_{\rm M}, m_{\rm SM}$. Additionally X X $\to$ M M with subdominant mediation via a t-channel DM must be included explicitly into the calculation if y_D is comparable to g_s.

at the Large Hadron Collider. These models have been validated against several theoretical results and using available tools. The simplified models can thus be used by the experimental collaborations to as benchmarks to design novel searches with resonance signatures scattering of missing transverse energy.

A Model Usage

In this appendix we briefly detail how to use the different models within the programs for generating Monte Carlo events and calculating the relic density.

A.1 MadGraph

The different signatures can be generated using `MadGraph`, here we will detail which parameter values are needed and which generation steps need to be taken. The first step when `MadGraph` has been started consists of loading the model using the command `import model lq_met/dq3_met/dq6_met/so_met` for the various models in this note.

This assumes that the simplified model has been added to the models folder of `MadGraph`. The new fields in the models in `MadGraph` notation are `~dm` and `~dm~` for the dark matter candidate, `~x` and `~x~` for the coannihilation partner and `m` and `m~` for the mediator. If any of the new fields is an $SU(2)_L$ N-plet the different components are denoted by an additional index $i = 1, \cdots, N$, for example `m2~` for the second component of a triplet. As a reminder, the field with the lowest index will have the highest electric charge. The new couplings introduced in these models are given an interaction order equal to QED in `FeynRules`. This implies that if a topology can be mediated by QCD interactions as well as NP interactions, these new interactions are not considered in the diagram generation in `MadGraph` and have to be explicitly included.

The new physics couplings in these models have been assigned a new interaction order in `FeynRules` named NP. It has been given importance equal to QCD interactions, so that when generating process with `MadGraph` contribution from the new particles are included by default.

In order to make the use of our models as simple as possible we provide a separate text file with the commands to generate the most important processes in `MadGraph` for all of our models. These processes are

- Paired mediator production: $p\,p \to \mathrm{M\,M}$ with:
  - Visible decays: both mediators decay to SM particles $\mathrm{M} \to \mathrm{SM_1\,SM_2}$.
  - Mixed decays: one mediator decays as $\mathrm{M} \to \mathrm{SM_1\,SM_2}$ and the other as $\mathrm{M} \to \mathrm{DM\,X}$.
  - Invisible decays: both mediators decay to the dark sector $\mathrm{M} \to \mathrm{DM\,X}$.

- Paired X production: $p\,p \to \mathrm{X}\,\mathrm{X} + (n \text{ jets})$ with:
  - X has only the decay mode $\mathrm{X} \to \mathrm{DM}\,\mathrm{SM}_1\,\mathrm{SM}_2$.
- Single mediator production: $p\,p \to \mathrm{M} \to \mathrm{SM}_1\,\mathrm{SM}_2$.

A.2 MadDM

The relic density in these models can be computed using `MadDM` based on the `UFO` output. We refer to the `MadDM` manual [15] for more details.

A.3 MicrOMEGAs

An alternative program for performing relic density computations is `MircOMEGAs` which is based on the `CalcHEP` output. In conjunction with the `UFO` output for each model we also provide `CalcHEP` model files. We refer to the `MircOMEGAs` manual [10] for more details.

References

[1] M. J. Baker et al., *The Coannihilation Codex*, arXiv:1510.03434.

[2] N. D. Christensen and C. Duhr, *FeynRules - Feynman rules made easy*, *Comput. Phys. Commun.* **180** (2009) 1614–1641, [arXiv:0806.4194].

[3] A. Alloul, N. D. Christensen, C. Degrande, C. Duhr, and B. Fuks, *FeynRules 2.0 - A complete toolbox for tree-level phenomenology*, *Comput. Phys. Commun.* **185** (2014) 2250–2300, [arXiv:1310.1921].

[4] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, and T. Reiter, *UFO - The Universal FeynRules Output*, *Comput. Phys. Commun.* **183** (2012) 1201–1214, [arXiv:1108.2040].

[5] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **06** (2011) 128, [arXiv:1106.0522].

[6] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, [arXiv:1405.0301].

[7] T. Sjostrand, S. Mrenna, and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852–867, [arXiv:0710.3820].

[8] **DELPHES 3** Collaboration, J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lematre, A. Mertens, and M. Selvaggi, *DELPHES 3, A modular framework for fast simulation of a generic collider experiment*, *JHEP* **02** (2014) 057, [arXiv:1307.6346].

[9] A. Kaminska and M. de Vries, "FeynRules Model Database: Simplified Models for Coannihilating Dark Matter." https://feynrules.irmp.ucl.ac.be/wiki/SimplifiedDM.

[10] G. Blanger, F. Boudjema, A. Pukhov, and A. Semenov, *micrOMEGAs4.1: two dark matter candidates*, *Comput. Phys. Commun.* **192** (2015) 322–329, [arXiv:1407.6129].

[11] A. Belyaev, N. D. Christensen, and A. Pukhov, *CalcHEP 3.4 for collider physics within and beyond the Standard Model*, *Comput. Phys. Commun.* **184** (2013) 1729–1769, [arXiv:1207.6082].

[12] N. D. Christensen, P. de Aquino, C. Degrande, C. Duhr, B. Fuks, M. Herquet, F. Maltoni, and S. Schumann, *A Comprehensive approach to new physics simulations*, *Eur. Phys. J.* **C71** (2011) 1541, [arXiv:0906.2474].

[13] A. Semenov, *LanHEP: A Package for the automatic generation of Feynman rules in field theory. Version 3.0*, *Comput. Phys. Commun.* **180** (2009) 431–454, [arXiv:0805.0555].

[14] A. Semenov, *LanHEP - a package for automatic generation of Feynman rules from the Lagrangian. Updated version 3.2*, *Comput. Phys. Commun.* **201** (2016) 167–170, [arXiv:1412.5016].

[15] M. Backovic, K. Kong, and M. McCaskey, *MadDM v.1.0: Computation of Dark Matter Relic Abundance Using MadGraph5*, *Physics of the Dark Universe* **5-6** (2014) 18–28, [arXiv:1308.4955].

[16] A. V. Manohar and M. B. Wise, *Flavor changing neutral currents, an extended scalar sector, and the Higgs production rate at the CERN LHC*, *Phys. Rev.* **D74** (2006) 035009, [hep-ph/0606172].

[17] M. I. Gresham and M. B. Wise, *Color octet scalar production at the LHC*, *Phys. Rev.* **D76** (2007) 075003, [arXiv:0706.0909].

[18] M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, *Pair production of scalar leptoquarks at the CERN LHC*, *Phys. Rev.* **D71** (2005) 057503, [hep-ph/0411038].

[19] T. Mandal, S. Mitra, and S. Seth, *Pair Production of Scalar Leptoquarks at the LHC to NLO+PS Accuracy*, arXiv:1506.07369.

[20] T. Han, I. Lewis, and T. McElmurry, *QCD Corrections to Scalar Diquark Production at Hadron Colliders*, *JHEP* **01** (2010) 123, [arXiv:0909.2666].

[21] Y. C. Zhan, Z. L. Liu, S. A. Li, C. S. Li, and H. T. Li, *Threshold resummation for the production of a color sextet (antitriplet) scalar at the LHC*, *Eur. Phys. J.* **C74** (2014) 2716, [arXiv:1305.5152].

[22] K. Das, S. Majhi, S. K. Rai, and A. Shivaji, *NLO QCD corrections to the resonant Vector Diquark production at the LHC*, *JHEP* **10** (2015) 122, [arXiv:1505.07256].

[23] W. Beenakker, S. Brensing, M. n. Kramer, A. Kulesza, E. Laenen, L. Motyka, and I. Niessen, *Squark and Gluino Hadroproduction*, *Int. J. Mod. Phys.* **A26** (2011) 2637–2664, [arXiv:1105.1110].

[24] W. Beenakker, C. Borschensky, M. Krmer, A. Kulesza, E. Laenen, S. Marzani, and J. Rojo, *NLO+NLL squark and gluino production cross-sections with threshold-improved parton distributions*, *Eur. Phys. J.* **C76** (2016), no. 2 53, [arXiv:1510.00375].

[25] A. Kulesza and C. Borschensky, "NLL-fast." http://pauli.uni-muenster.de/~akule_01/nllwiki/index.php/NLL-fast.

[26] M. Czakon and A. Mitov, "Top++." http://www.alexandermitov.com/software/115-top-versions-and-downloads.

[27] D. Goncalves-Netto, D. Lopez-Val, K. Mawatari, T. Plehn, and I. Wigmore, *Sgluon Pair Production to Next-to-Leading Order*, *Phys. Rev.* **D85** (2012) 114024, [arXiv:1203.6358].

[28] **ATLAS** Collaboration, G. Aad et al., *Searches for scalar leptoquarks in pp collisions at* $\sqrt{s}$ *= 8 TeV with the ATLAS detector*, arXiv:1508.04735.

[29] C.-R. Chen, W. Klemm, V. Rentala, and K. Wang, *Color Sextet Scalars at the CERN Large Hadron Collider*, *Phys. Rev.* **D79** (2009) 054002, [arXiv:0811.2105].

[30] M. V. Martynov and A. D. Smirnov, *Colored scalar particles production in pp-collisions and possible mass limits for scalar gluons from future LHC data*, *Mod. Phys. Lett.* **A23** (2008) 2907–2913, [arXiv:0807.4486].

[31] N. Kidonakis and B. D. Pecjak, *Top-quark production and QCD*, *Eur. Phys. J.* **C72** (2012) 2084, [arXiv:1108.6063].

[32] P. R. Harrison and C. H. Llewellyn Smith, *Hadroproduction of Supersymmetric Particles*, *Nucl. Phys.* **B213** (1983) 223. [Erratum: Nucl. Phys.B223,542(1983)].