

Section 1

Collider simulation of the MDM model

In this appendix, we explain the procedure we have adopted to implement the MDM model into the numerical calculation performed in Sec. ???. We first make the **FeynRules** v2.3 [?] model file for the MDM model by modifying the SM model file *sm.fr*.^{h1} By running **FeynRules**, we can convert the model file to the Universal **FeynRules** Format (UFO) [?], which can be used as a model file for **MadGraph5**.^{h2}

In the Listing 1, we show a part of our **FeynRules** model file *mdm.fr*. This corresponds to the lines that contain additions and modifications to *sm.fr* to take account of the 5-plet fermion as an example of the MDM. In the following, ... denotes a description that is the same as *sm.fr* and thus omitted in the listing.

Listing 1: *mdm.fr*

```

1 (* *****)
2 (* ***** SU(2)L representation matrix ***** *)
3 (* *****)
4
5 replaceMDM = {repMDM[a_,b_,c_] :>
6   {{0,1,0,0,0},{1,0,Sqrt[3/2],0,0},{0,Sqrt[3/2],0,Sqrt[3/2],0},{0,0,
7     Sqrt[3/2],0,1},{0,0,0,1,0}},
8   {{0,-I,0,0,0},{I,0,-I Sqrt[3/2],0,0},{0,I Sqrt[3/2],0,-I Sqrt
9     [3/2],0},{0,0,I Sqrt[3/2],0,-I},{0,0,0,I,0}},
10  {{2,0,0,0,0},{0,1,0,0,0},{0,0,0,0,0},{0,0,0,-1,0},{0,0,0,0,-2}}}[[a
11    [[2]],b[[2]],c[[2]]]]
12 };
13
14
15 M$GaugeGroups = {
16   U1Y == {...},
17   SU2L == {
18     Abelian -> False,
19     CouplingConstant -> gw,
20     GaugeBoson -> Wi,
21     StructureConstant -> Eps,
22     Representations -> {{Ta,SU2D},{TM,SU2M}},

```

^{h1}Model files for the SM and several relatively simple extensions of the SM are found in the model database equipped in the official wiki [?].

^{h2}The use of collider physics public codes such as **FeynRules** and **MadGraph5** can be systematically learned by referring the well-summarized lecture notes provided by Sho Iwamoto [?].

```

23     Definitions -> {Ta[a_,b_,c_]->PauliSigma[a,b,c]/2, FSU2L[i_,j_,k_]:>
      I Eps[i,j,k], TM[a_,b_,c_]->repMDM[a,b,c]}
24 },
25 SU3C == {...}
26 };
27
28 (* ***** *)
29 (* ***** Indices ***** *)
30 (* ***** *)
31
32 IndexRange[Index[SU2W ]] = Unfold[Range[3]];
33 IndexRange[Index[SU2D ]] = Unfold[Range[2]];
34 IndexRange[Index[SU2M ]] = Unfold[Range[5]];
35 IndexRange[Index[Gluon ]] = NoUnfold[Range[8]];
36 IndexRange[Index[Colour ]] = NoUnfold[Range[3]];
37 IndexRange[Index[Generation]] = Range[3];
38
39 IndexStyle[SU2W, j];
40 IndexStyle[SU2D, k];
41 IndexStyle[SU2M, l];
42 IndexStyle[Gluon, a];
43 IndexStyle[Colour, m];
44 IndexStyle[Generation, f];
45
46 (* ***** *)
47 (* ***** Particle classes ***** *)
48 (* ***** *)
49
50 M$ClassesDescription = {
51   ...
52
53 (* Physical MDM Dirac components *)
54 F[5] == {
55   ClassName -> chi0,
56   SelfConjugate -> True,
57   WeylComponents -> chi0w,
58   Mass -> {mMDM0, 1000},
59   Width -> 0,
60   MajoranaPhase -> 0,
61   PropagatorLabel -> "chi0",
62   PropagatorType -> Straight,
63   PropagatorArrow -> None,
64   ParticleName -> "chi0",
65   FullName -> "chi0"
66 },
67 F[6] == {
68   ClassName -> chi1,
69   SelfConjugate -> False,
70   WeylComponents -> {chi1pw, chi1mwbar},
71   Mass -> {mMDM1, 1000},

```

```

72     Width -> 0,
73     MajoranaPhase -> 0,
74     QuantumNumbers -> {Q -> 1},
75     PropagatorLabel -> "chi1",
76     PropagatorType -> Straight,
77     PropagatorArrow -> Forward,
78     ParticleName -> "chi+",
79     AntiParticleName -> "chi-",
80     FullName -> "chi1"
81 },
82 F[7] == {
83     ClassName -> chi2,
84     SelfConjugate -> False,
85     WeylComponents -> {chi2pw, chi2mwbar},
86     Mass -> {mMDM2, 1000},
87     Width -> 0,
88     MajoranaPhase -> 0,
89     QuantumNumbers -> {Q -> 2},
90     PropagatorLabel -> "chi2",
91     PropagatorType -> Straight,
92     PropagatorArrow -> Forward,
93     ParticleName -> "chi++",
94     AntiParticleName -> "chi--",
95     FullName -> "chi2"
96 },
97
98 (* Fermions: unphysical fields *)
99 F[11] == {
100     ClassName -> LL,
101     Unphysical -> True,
102     Indices -> {Index[SU2D], Index[Generation]},
103     FlavorIndex -> SU2D,
104     SelfConjugate -> False,
105     QuantumNumbers -> {Y -> -1/2},
106     Definitions -> { LL[sp1_,1,ff_] :> Module[{sp2}, ProjM[sp1,sp2] v1[
        sp2,ff]], LL[sp1_,2,ff_] :> Module[{sp2}, ProjM[sp1,sp2] l[sp2,ff
        ]] }
107 },
108 F[12] == {
109     ClassName -> lR,
110     Unphysical -> True,
111     Indices -> {Index[Generation]},
112     FlavorIndex -> Generation,
113     SelfConjugate -> False,
114     QuantumNumbers -> {Y -> -1},
115     Definitions -> { lR[sp1_,ff_] :> Module[{sp2}, ProjP[sp1,sp2] l[sp2,
        ff]] }
116 },
117 F[13] == {
118     ClassName -> QL,

```

```

119     Unphysical -> True,
120     Indices -> {Index[SU2D], Index[Generation], Index[Colour]},
121     FlavorIndex -> SU2D,
122     SelfConjugate -> False,
123     QuantumNumbers -> {Y -> 1/6},
124     Definitions -> {
125         QL[sp1_,1,ff_,cc_] -> Module[{sp2}, ProjM[sp1,sp2] uq[sp2,ff,cc]],
126         QL[sp1_,2,ff_,cc_] -> Module[{sp2,ff2}, CKM[ff,ff2] ProjM[sp1,sp2]
            dq[sp2,ff2,cc]] }
127 },
128 F[14] == {
129     ClassName -> uR,
130     Unphysical -> True,
131     Indices -> {Index[Generation], Index[Colour]},
132     FlavorIndex -> Generation,
133     SelfConjugate -> False,
134     QuantumNumbers -> {Y -> 2/3},
135     Definitions -> { uR[sp1_,ff_,cc_] -> Module[{sp2}, ProjP[sp1,sp2] uq[
            sp2,ff,cc]] }
136 },
137 F[15] == {
138     ClassName -> dR,
139     Unphysical -> True,
140     Indices -> {Index[Generation], Index[Colour]},
141     FlavorIndex -> Generation,
142     SelfConjugate -> False,
143     QuantumNumbers -> {Y -> -1/3},
144     Definitions -> { dR[sp1_,ff_,cc_] -> Module[{sp2}, ProjP[sp1,sp2] dq[
            sp2,ff,cc]] }
145 },
146
147 (* Unphysical MDM multiplet *)
148 W[1] == {
149     ClassName -> MDM,
150     Unphysical -> True,
151     Chirality -> Left,
152     SelfConjugate -> False,
153     Indices -> {Index[SU2M]},
154     FlavorIndex -> SU2M,
155     Definitions -> {
156         MDM[sp1_,1] -> chi2pw[sp1],
157         MDM[sp1_,2] -> chi1pw[sp1],
158         MDM[sp1_,3] -> chi0w[sp1],
159         MDM[sp1_,4] -> chi1mw[sp1],
160         MDM[sp1_,5] -> chi2mw[sp1] }
161 },
162
163 (* Unphysical MDM Weyl components *)
164 W[2] == {
165     ClassName -> chi0w,

```

```

166     Unphysical -> True,
167     Chirality -> Left,
168     SelfConjugate -> False
169 },
170 W[3] == {
171     ClassName -> chi1pw,
172     Unphysical -> True,
173     Chirality -> Left,
174     SelfConjugate -> False,
175     QuantumNumbers -> {Q -> 1}
176 },
177 W[4] == {
178     ClassName -> chi1mw,
179     Unphysical -> True,
180     Chirality -> Left,
181     SelfConjugate -> False,
182     QuantumNumbers -> {Q -> -1}
183 },
184 W[5] == {
185     ClassName -> chi2pw,
186     Unphysical -> True,
187     Chirality -> Left,
188     SelfConjugate -> False,
189     QuantumNumbers -> {Q -> 2}
190 },
191 W[6] == {
192     ClassName -> chi2mw,
193     Unphysical -> True,
194     Chirality -> Left,
195     SelfConjugate -> False,
196     QuantumNumbers -> {Q -> -2}
197 }
198 };
199
200 (* ***** *)
201 (* ***** Parameters ***** *)
202 (* ***** *)
203
204 M$Parameters = {
205     ...
206
207     mmm == {
208         ParameterType -> External,
209         BlockName -> MDMBLOCK,
210         OrderBlock -> 1,
211         Value -> 1000,
212         TeX -> Subscript[m, MDM],
213         Description -> "MDMmass"
214     }
215 };

```

```

216
217 (* ***** *)
218 (* ***** Lagrangian ***** *)
219 (* ***** *)
220
221 ...
222
223 LMDM := Block[{mu},
224   ExpandIndices[I MDMbar.sibar[mu].DC[MDM, mu] - mmm/2 chi0bar.chi0 - mmm
225     chi1bar.chi1 - mmm chi2bar.chi2,
226   FlavorExpand->{SU2W,SU2M}]/.replaceMDM//WeylToDirac];
227 Lagrangian:= LGauge + LFermions + LMDM + LHiggs + LYukawa + LGhost;

```
