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*.[♮1] 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`.[♮2]

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,
         Sqrt[3/2],0,1},{0,0,0,1,0}},
7    {{0,-I,0,0,0},{I,0,-I Sqrt[3/2],0,0},{0,I Sqrt[3/2],0,-I Sqrt
         [3/2],0},{0,0,I Sqrt[3/2],0,-I},{0,0,0,I,0}},
8    {{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
         [[2]],b[[2]],c[[2]]]]]
9  };
10
11 (* ************************* *)
12 (* ****** Gauge groups ****** *)
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}},
```

[♮1]Model files for the SM and several relatively simple extensions of the SM are found in the model database equipped in the official wiki [**?**].

[♮2]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] vl[
           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 -> "MDM mass"
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
            chi1bar.chi1 - mmm chi2bar.chi2,
225    FlavorExpand->{SU2W,SU2M}]/.replaceMDM//WeylToDirac];
226
227  Lagrangian:= LGauge + LFermions + LMDM + LHiggs + LYukawa + LGhost;
```