

# 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*.<sup>†1</sup> 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**.<sup>†2</sup>

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. ... 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}},

```

<sup>†1</sup>Model files for the SM and several relatively simple extensions of the SM are found in the model database equipped in the official wiki [?].

<sup>†2</sup>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 [?].

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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},

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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,

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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,

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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;

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