MadDM 3.0 EW

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Contents

Abstract

This documents summarises the status of the studies of the discrepancies found in the energy spectra provided in the PPPC4DMID tables (labelled **PPPC4DMIDew** in MadDM v.3.0) and the spectra produced with MadDM 3.0.

1 Introduction

All the information, including the model used and the input cards (`run_card.dat` ,`param_card.dat`) can be found at:
https://github.com/fambrogi/MadDM

2 PPPC Electroweak Corrections

In this section the energy spectra for the Cosmic Rays $CRs = e^+, \nu_e, \gamma$ extracted from the `PPPC4DMID` and `PPPC4DMID_ew` Tables are compared, to get an idea of the effect of the EW correction (according the `PPPC4DMID`collaboration).

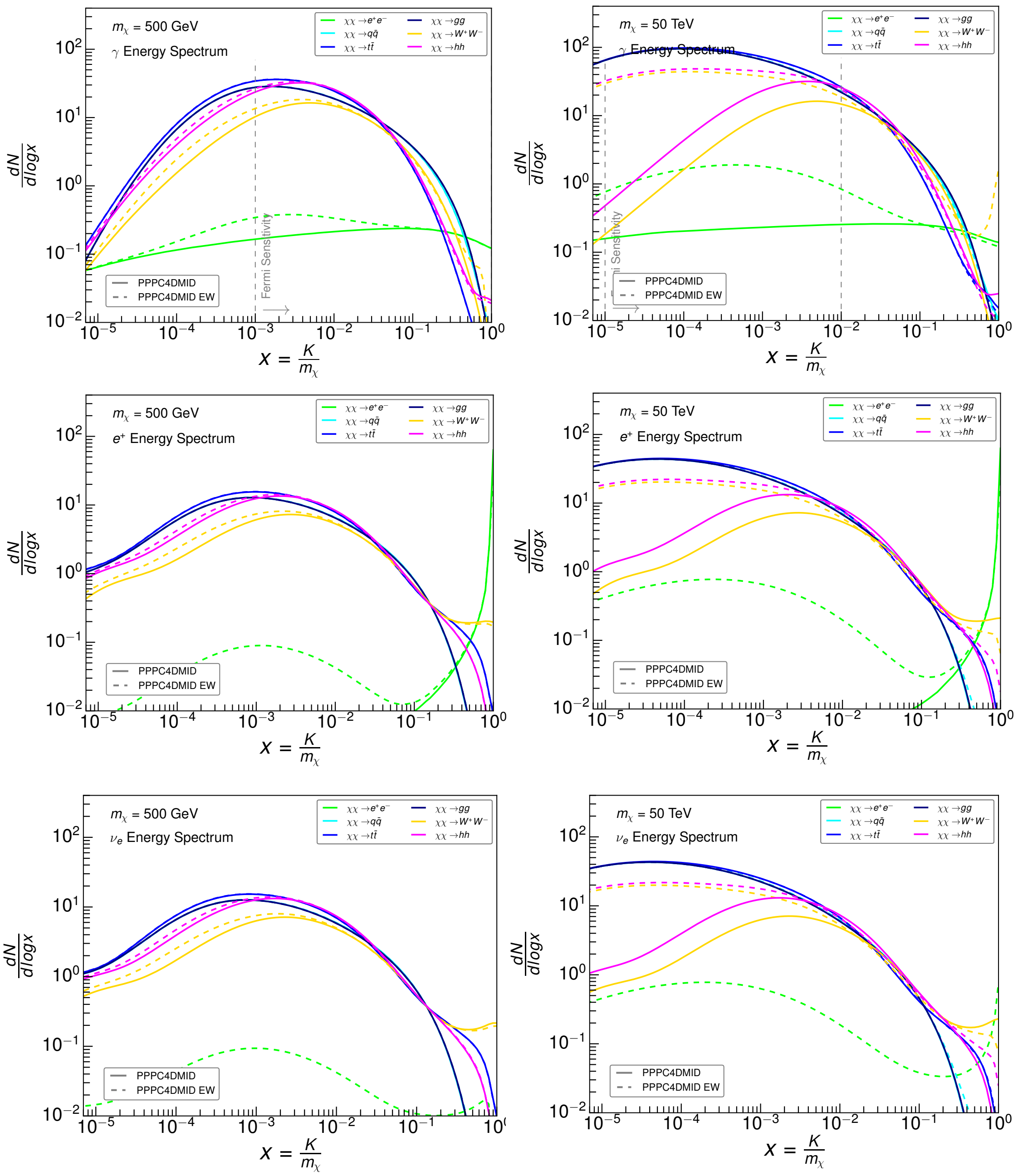

Figure 1. Energy spectra (γ, e^+, ν_e) for m_χ =500 GeV (left) and 50 TeV (right) extracted from the `PPPC4DMID` and `PPPC4DMID_ew` tables, for selected annihilation channels.

3 EW with MadGraph5_aMC@NLO

3.1 Processes

The processes used for the production of the samples with emission of extra electroweak bosons (Higgs, W and Z bosons) are the following:

```
import model DMsimp_s_spin0_EW
define X = W- W+ Z h
generate xd xd~ > w- w+
add process xd xd~ > w- w+ X
add process xd xd~ > w- w+ X X
add process xd xd~ > w- w+ X X X
```

Note that the short notation e.g. "XXW" includes the lower order processes (in this case only the tree level xdxd>WW) and up to one extra "X" boson, and likewise for the higher order processes.

Syntax for excluding diagrams with photons:

```
import model DMsimp_s_spin0_EW
define X = W- W+ Z h
generate xd xd~ > w- w+ /a
add process xd xd~ > w- w+ X  /a
add process xd xd~ > w- w+ X X  /a
add process xd xd~ > w- w+ X X X  /a
```

Relevant parameters in the `run_card.dat` :

```
*** run_card
1001.0     = ebeam1
10001.0    = ebeam1
100001.0    = ebeam1
```

for m_{χ_D}=1 , 10, 100 TeV respectively, and the `param_card.dat` :

```
*** param_card
52 1.00000e+03 # MXd
54 2.00000e+03 # MY0  (= 2 x MXd )
```

3.2 Cross Sections Comparison

In Tab. 1 the cross sections in [pb] obtained with different runs are shown.

$\mathbf{m_{\chi_D}}$	$\chi_{\mathbf{D}}\chi_{\mathbf{D}} \rightarrow \mathbf{WW}$	$\chi_{\mathbf{D}}\chi_{\mathbf{D}} \rightarrow \mathbf{WWX}$	$\chi_{\mathbf{D}}\chi_{\mathbf{D}} \rightarrow \mathbf{WWXX}$	$\chi_{\mathbf{D}}\chi_{\mathbf{D}} \rightarrow \mathbf{WWXXX}$
1.0 TeV (Old)	474	130*	600	600
1.0 TeV (Old, no γ)	474	676	704	-
1.0 TeV (New)	173	215	219	-
1.0 TeV (New,AUTO)	147.3	148.2	-	-
1.0 TeV (Chiara)	147.3	148.2	148.2	-
10.0 TeV (Old)	15.1×10^3	30.501×10^3	37.018×10^3	-
10.0 TeV (Old,no γ)	15.1×10^3	2.7×10^7	1.5×10^{10}	-
10.0 TeV (New)	15.1×10^3	30.542×10^3	-	-
100.0 TeV (Old)	4.7×10^5	-	-	-

Table 1. Cross sections in [pb] for various processes extracted from the LHE files. The "New" cross sections were computed with N_{Events}=10,000, while the "Old" ones with N_{Events}=100,000. Need to verify the value 130*.

3.3 Spectra for $\chi_D \chi_D \to e^- e^+$

The following spectra in Fig. 2 are obtained with:

```
import model /home/federico/Desktop/Tools/MadGraph5/MG5_aMC_v2_6_5/mod\
els/DMsimp_s_spin0_leptons
generate xd xd~ > e- e+
add process xd xd~ > e- e+ z
add process xd xd~ > e- ve~ w+
add process xd xd~ > e+ ve w-
```

in order to test the EW correction produced ba `MadGraph5_aMC@NLO` on the electron-positron pairs. Chiara modified the models to include direct couplings of the mediator to the leptons. However it seems that including the additional processes in `MadGraph5_aMC@NLO` does not affect at all the spectra. Indeed, in the lhe files there are no neutrinos, W or Z bosons (100k events generated). I additionally tested the $n_1 n_1 \to e^- e^+$ production (i.e. MSSM) to check that the spectra are indeed the same.

For further test, shown in Fig. ??, I generated the samples:

```
import model /home/federico/Desktop/Tools/MadGraph5/MG5_aMC_v2_6_5/mod\
```

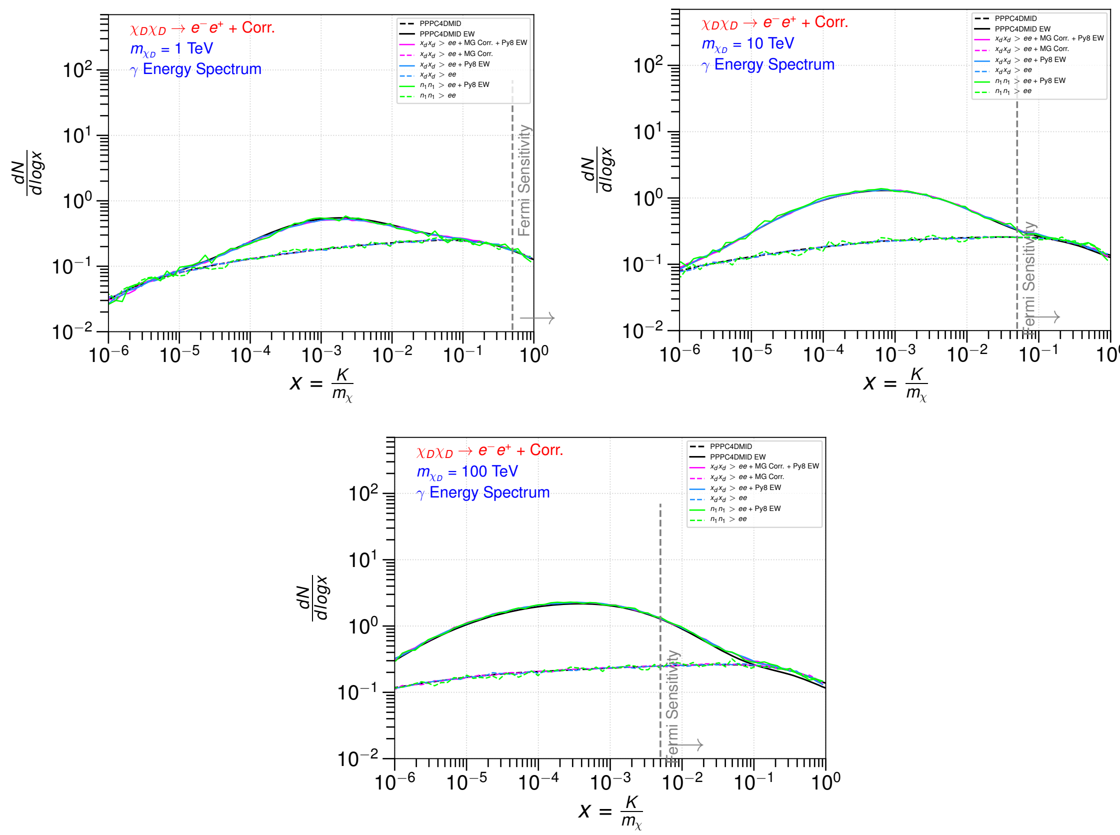

Figure 2. Energy Spectra for the channel $e^- e^p$ using the DM simplified model with couplings to leptons or the MSSM.

```
els/DMsimp_s_spin0_leptons
generate xd xd~ > e- e+ z
```

however MadGraph5_aMC@NLO returns zero events (i.e. cross section equals zero).

3.4 Spectra for $\chi_D \chi_D \to WW$

3.4.1 $m_{\chi_D} = 1$ TeV

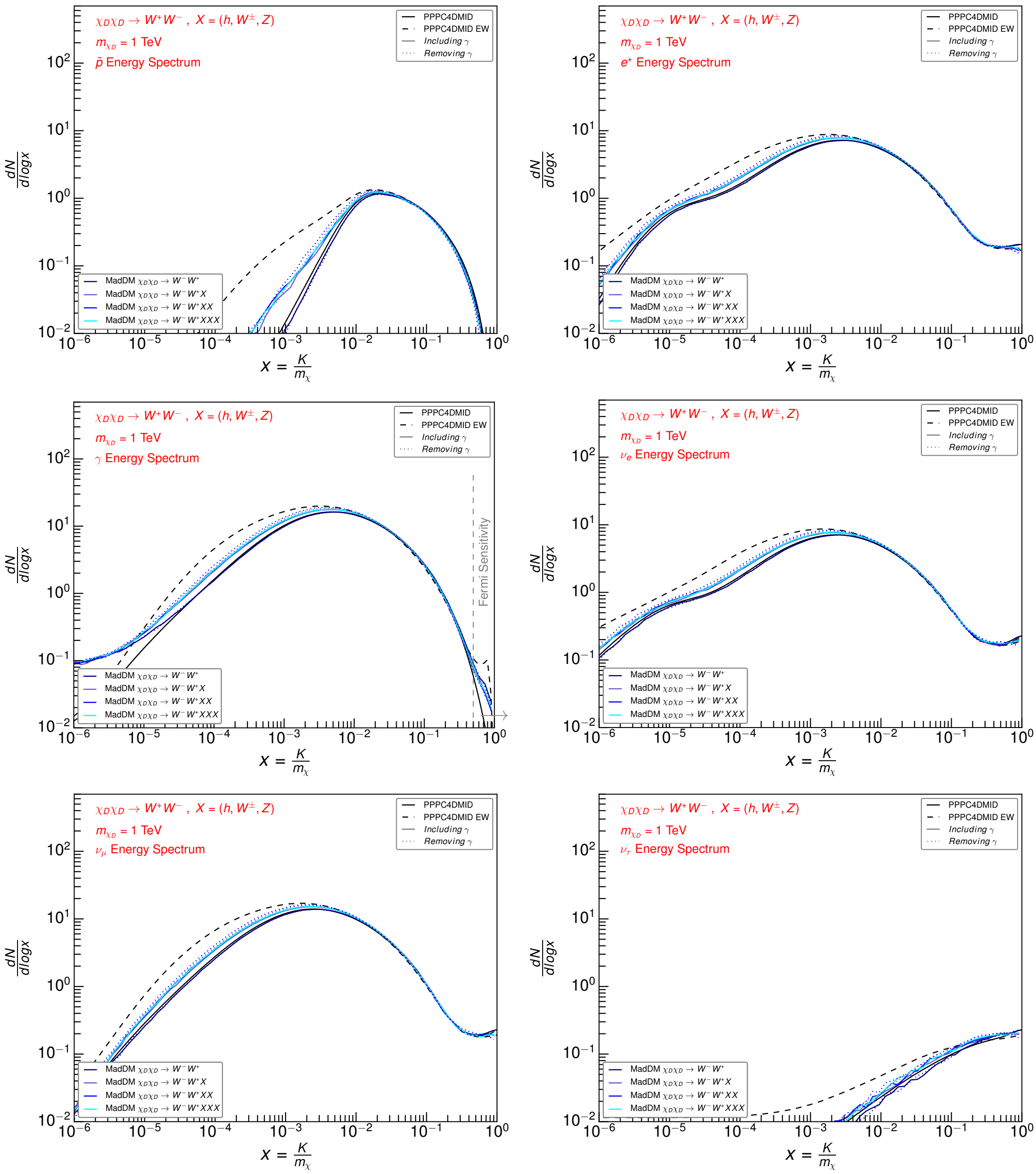

Figure 3. Energy Spectra for $m_{\chi_D} = 1$ TeV

3.4.2 "Old" $m_{\chi_D} = 100$ TeV

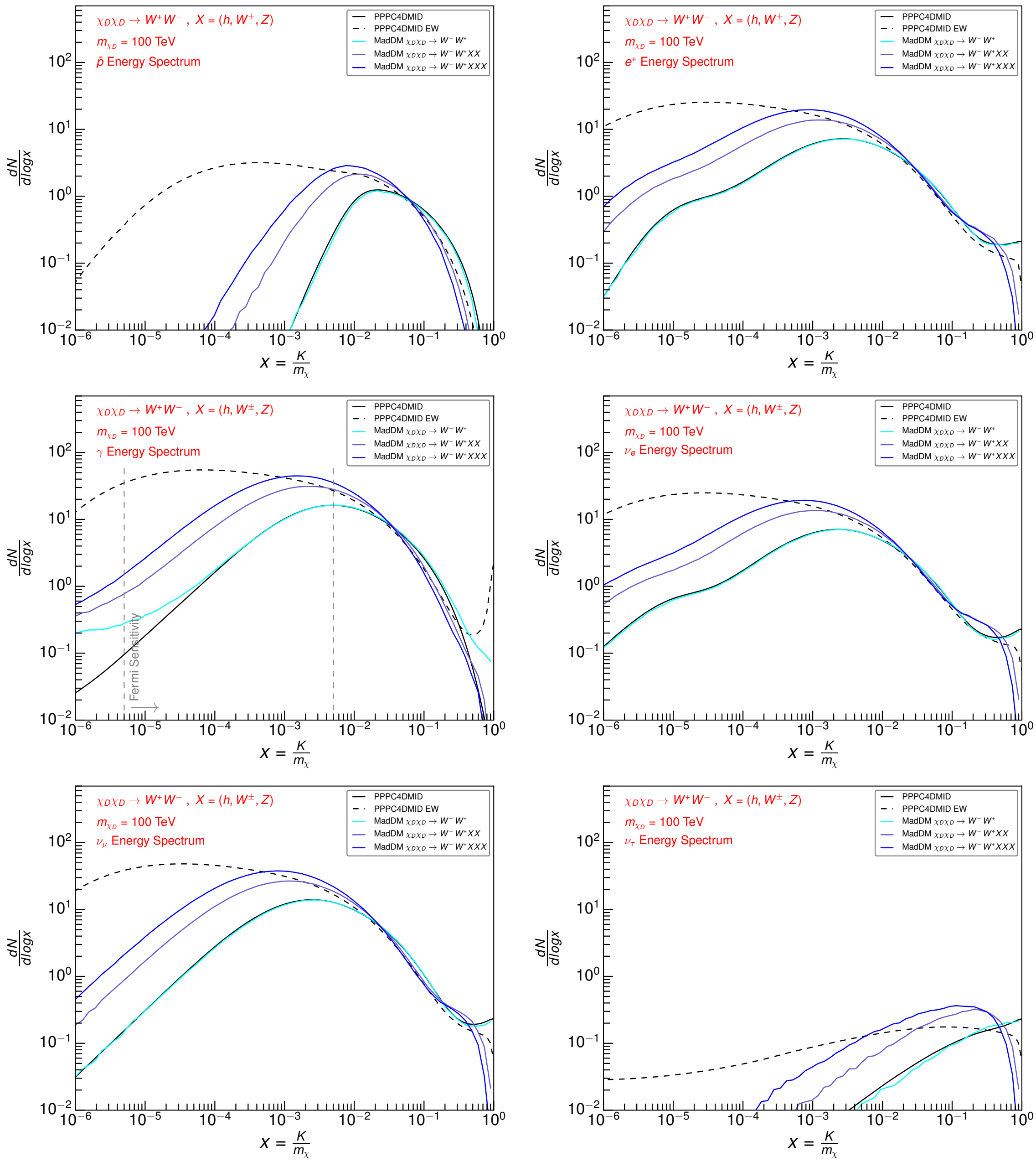

Figure 4. Energy Spectra for $m_{\chi_D} = 100$ TeV (Old data)

3.5 Spectra for $\chi_D\chi_D \to Y0 \to FFFF$

Here the spectra for the process $\chi_D\chi_D \to Y0 \to FFFF$ are shown for $m_{\chi_D} = 1$ TeV, compared to the PPPC4DMIDand PPPC4DMID_ew spectra. To produce the sample, the EW model was modified adding masses to the light quarks and muons, otherwise there is a problem in MadGraph5_aMC@NLO when evaluating the cross sections (re-using the same diagrams with masless particles?). I used the value of the muon mass (0.105 GeV) for the light quarks, and 4.5 GeV for the bottoms.
Note that this process include also Z bosons, since I did not remove their contribution explicitly form the diagrams, and that all the bosons contributing to the diagrams are on-shell. The presence of the Z/H bosons can account for some of the differences wrt the WW spectra from PPPC4DMIDor PPPC4DMID_ew .

The model can be found at https://github.com/fambrogi/MadDM/tree/master/EW_Study/EW_Model_FermionMass, while the complete banner can be found in https://github.com/fambrogi/MadDM/blob/master/EW_Study/Banners/xdxd_Y0_FFFF_1TeV_banner.dat .

MadGraph5_aMC@NLO Process:

```
import model DMsimp_s_spin0_EW_MM
define F = ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ t t~ u c d s b u~ c~ d~ \
s~ b~ ta- ta+
generate xd xd~ > y0 > F F F F
output xdxd_Y0_FFFF
```

Pythia8 cards commands:

```
TimeShower:weakShower = on (or off)
WeakShower:singleEmission = off
```

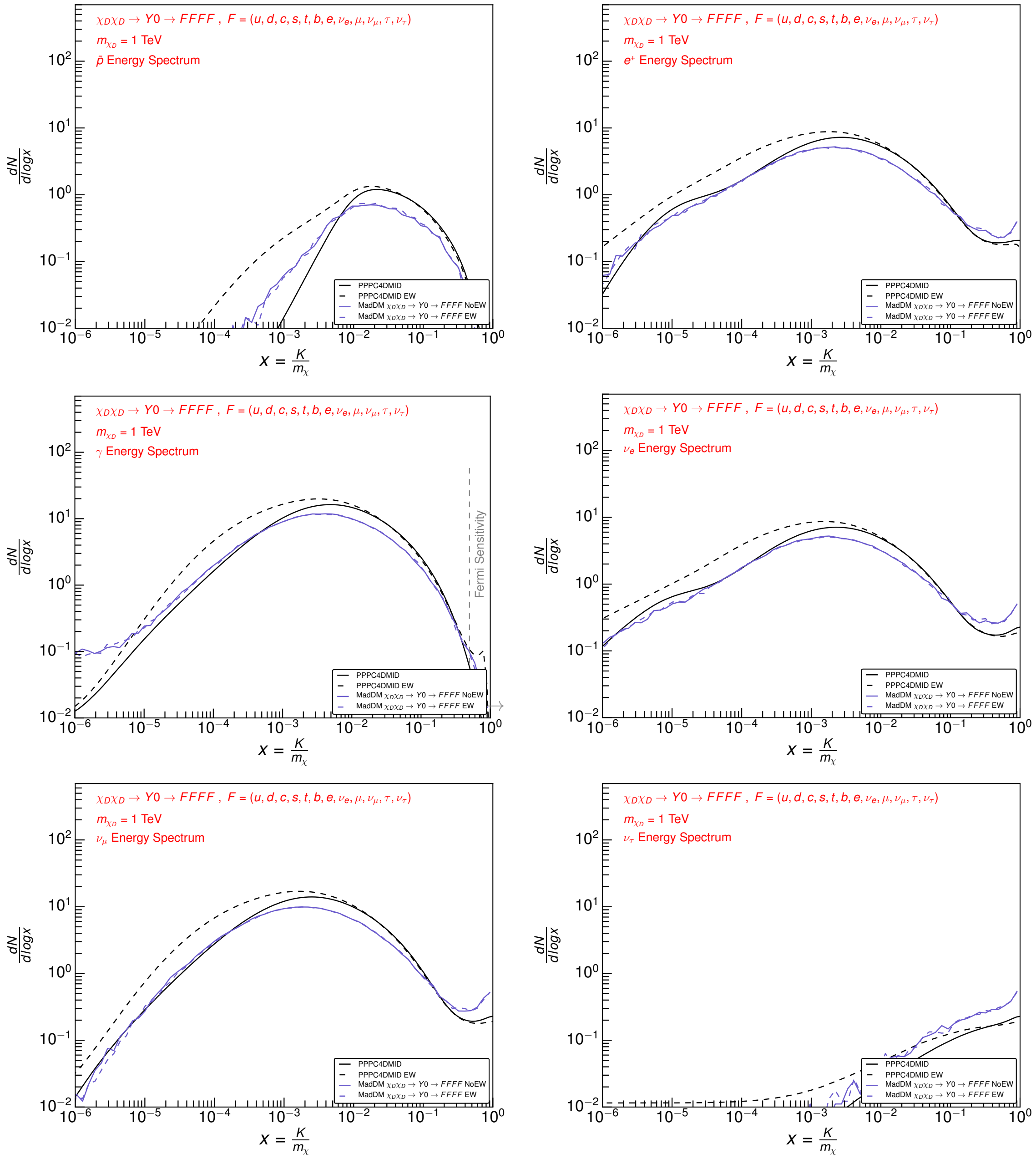

Figure 5. Energy Spectra for $m_{\chi_D} = 1$ TeV for the process $\chi_D\chi_D \to Y0 \to FFFF$. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

3.6 Spectra for $\chi_D \chi_D \to Y0 \to FFFF$ with off-shell W and no Z

The spectra in Fig. 6,7,10 were produced with the following MadGraph5_aMC@NLO processes:

```
import model DMsimp_s_spin0_EW_WithMass
define F = ve vm vt e- mu- ve~ vm~ vt~ e+ mu+ t t~ u c d s b u~ c~ d~ \
s~ b~ ta- ta+
generate xd xd~ > F F F F $ w- w+ / z
output xdxd_FFFF_WoffNoZ
```

so, differently from the previous case, the $W^{\pm}$ bosons are required to be off-shell, and the Z bosons are removed from the diagrams. In addition, the spectra obtained with the removal of intermediate Z bosons only are shown.

3.6.1 $m_{\chi_D} = 1$ TeV

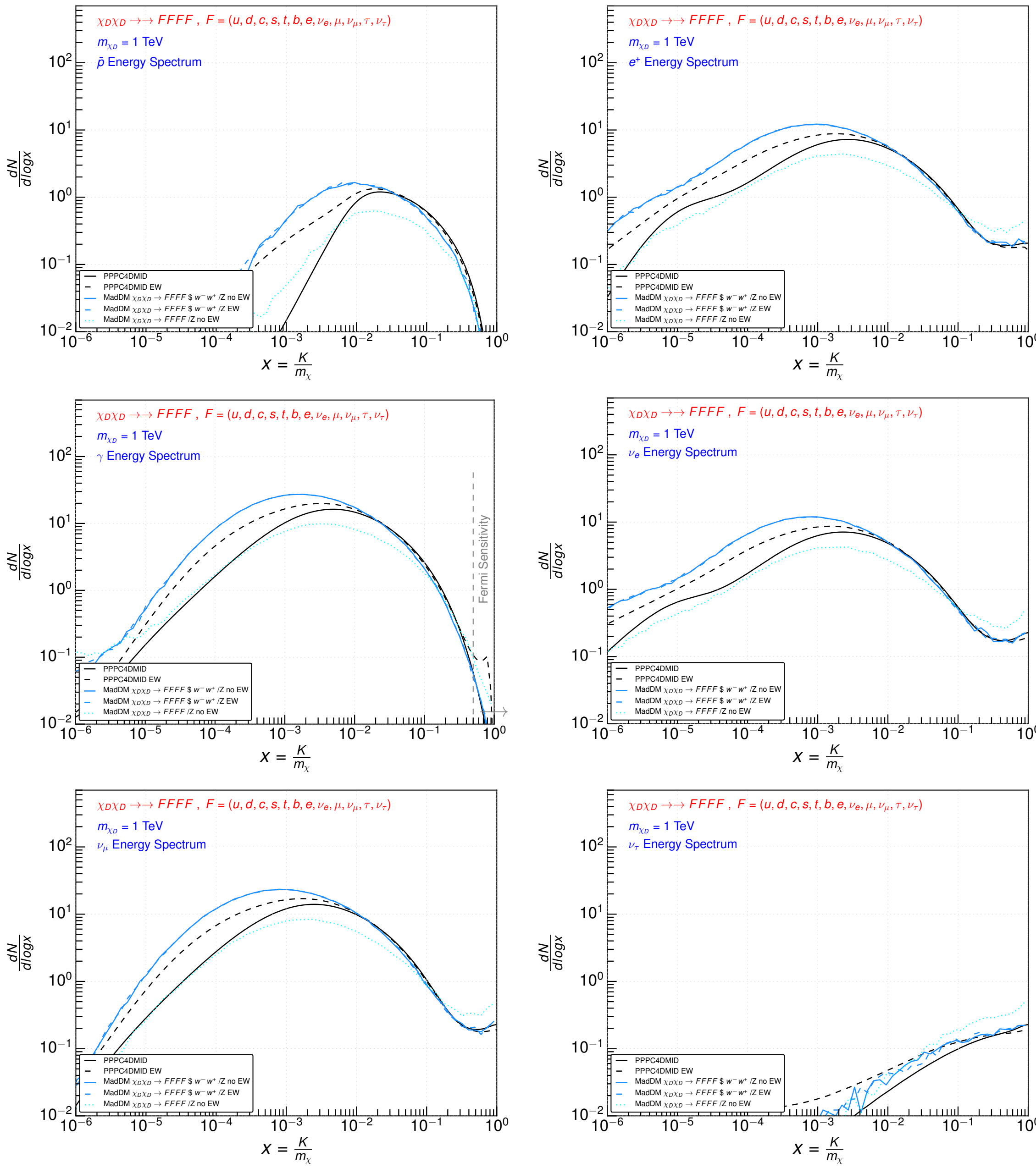

Figure 6. Energy Spectra for $m_{\chi_D} = 1$ TeV for the process $\chi_D\chi_D \to Y0 \to FFFF\$w^{-}w^{+}/Z$, for $m_{\chi_D} = 1$ TeV. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

3.6.2 $m_{\chi_D} = 10$ TeV

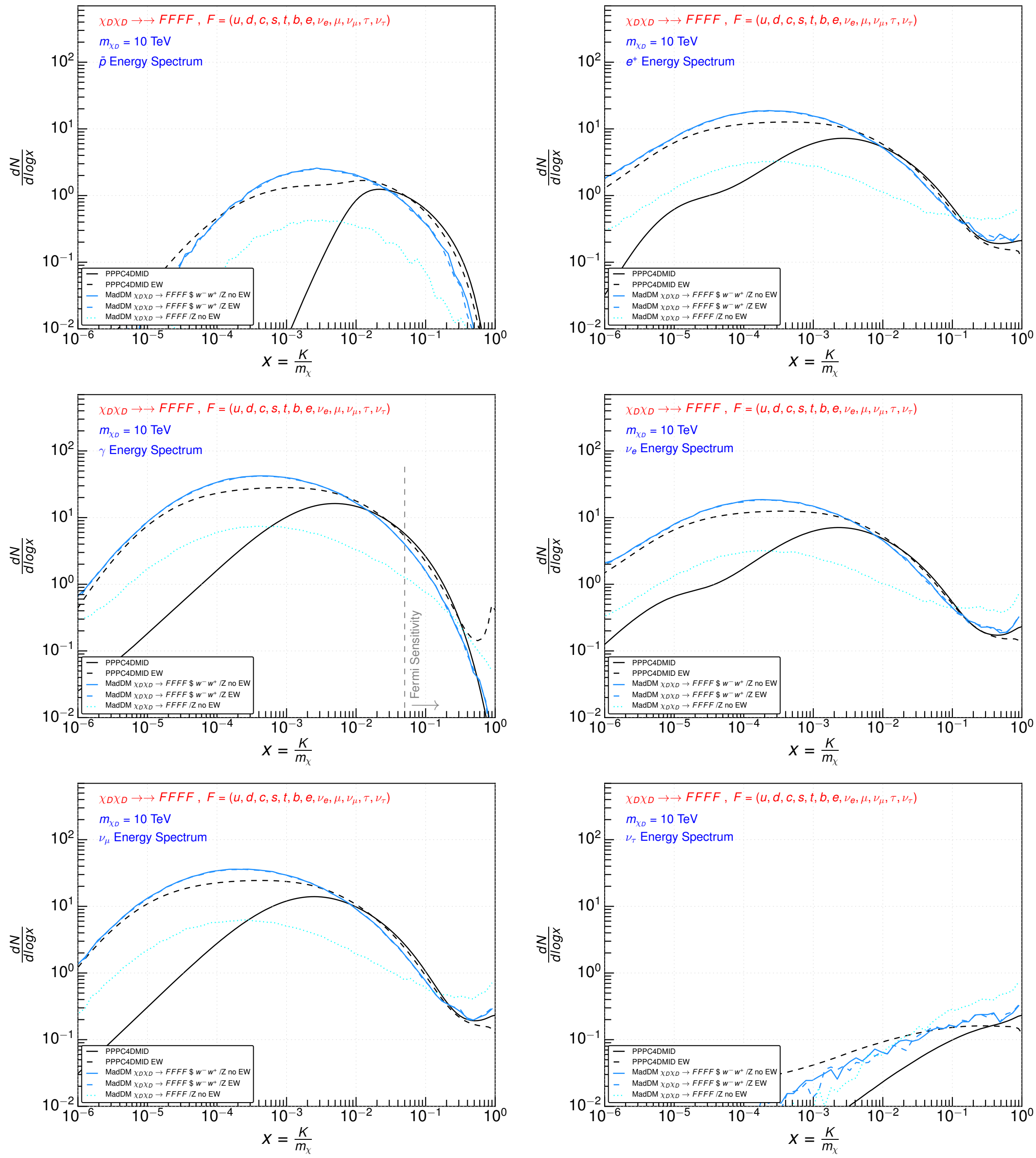

Figure 7. Energy Spectra for $m_{\chi_D} = 10$ TeV for the process $\chi_D\chi_D \to Y0 \to FFFF\$w^-w^+/Z$, for $m_{\chi_D} = 1$ TeV. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

3.6.3 m_{χ_D} = 100 TeV

For large m_{χ_D} masses, the spectra produced with the decays from off-shell W bosons look very similar to the ones from the `PPPC4DMID_ew` . However also note that the electroweak corrections from Pythia 8 don't seem to have any effect at all, i.e. they are not calculated for the 4 fermions.

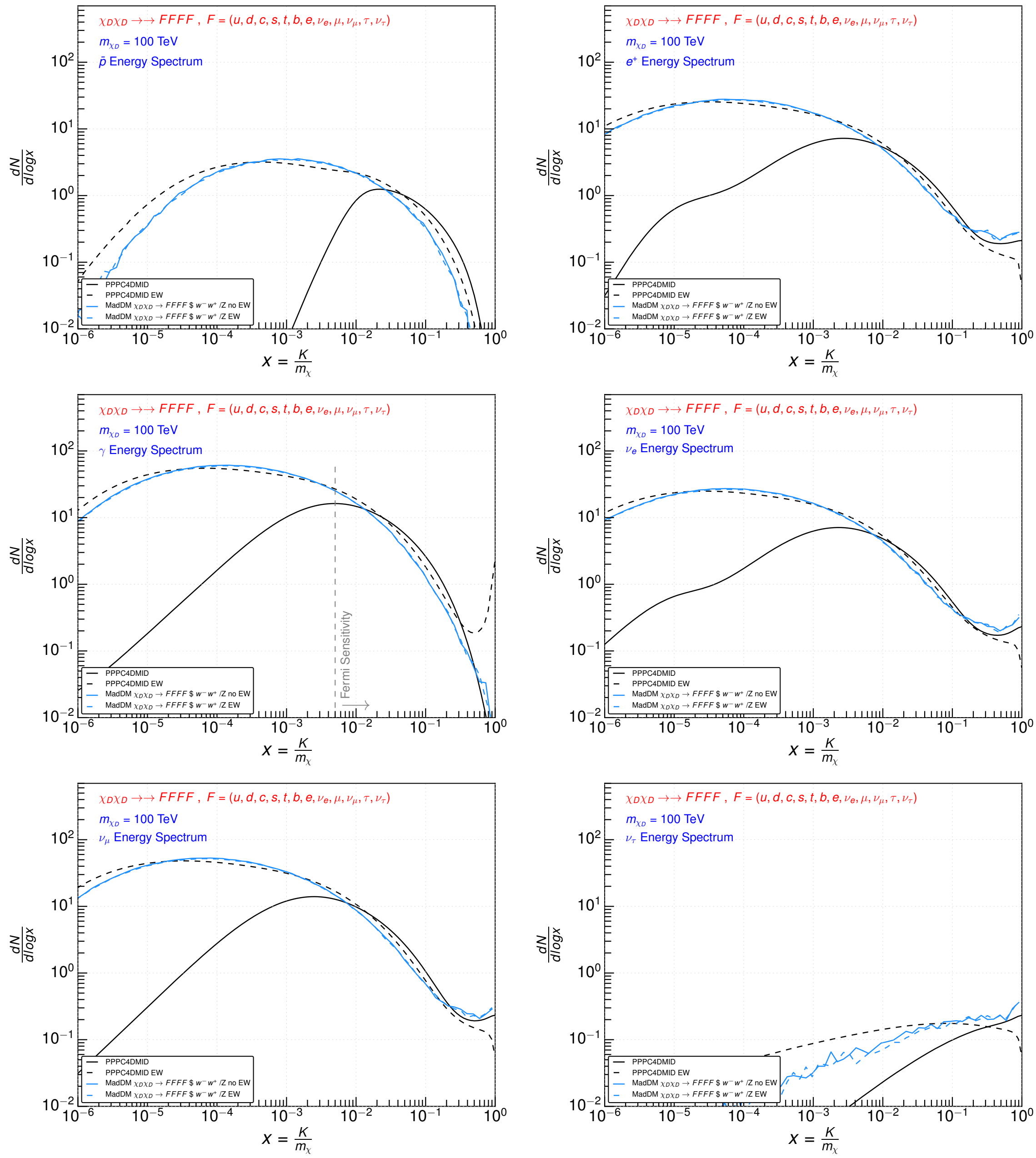

Figure 8. Energy Spectra for m_{χ_D} = 100 TeV for the process $\chi_D\chi_D \to Y0 \to FFFF\$w^-w^+/Z$, for $m_{\chi_D} = 1$ TeV. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

4 MG EW Corrections for $x_d x_d \to e^- e^+$

Process implemented in `MadGraph5_aMC@NLO`:

```
import model DMsimp_s_spin0_leptons
generate xd xd~ > e- e+
add process xd xd~ > e- e+ z
add process xd xd~ > e+ ve w-
add process xd xd~ > e- ve~ w+
output xdxd_ee_eez_evew
```

The corresponding Feynman diagrams, for reference, are shown in Fig. 9.

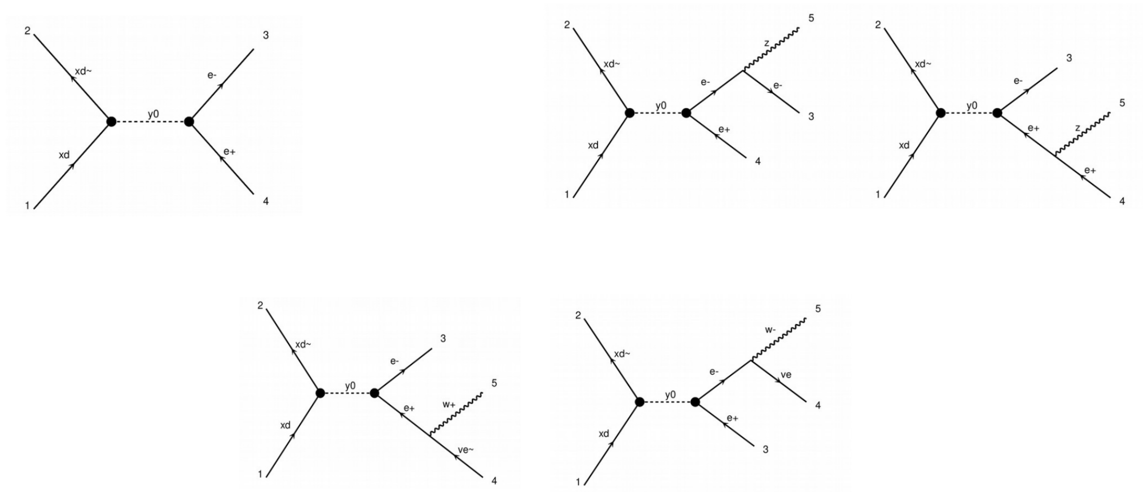

Figure 9. Feynman diagrams.

4.1 Kinematic Distributions

Kinematic distributions of the e,W and Z p_T, W and Z boson multiplicities for $m_{x_d} = 1$ TeV. Below a certain E_{beam} threshold, the cross section for the processes are zero except for the "tree-level" $x_d x_d \to ee$; this was tested with e.g. the process

```
import model DMsimp_s_spin0_leptons
generate xd xd~ > e- e+ z
```

, which was the reason why I started using higher energy beams than what we usually set (e.g. 1001 or 1010 for $m_{x_d} = 1$).

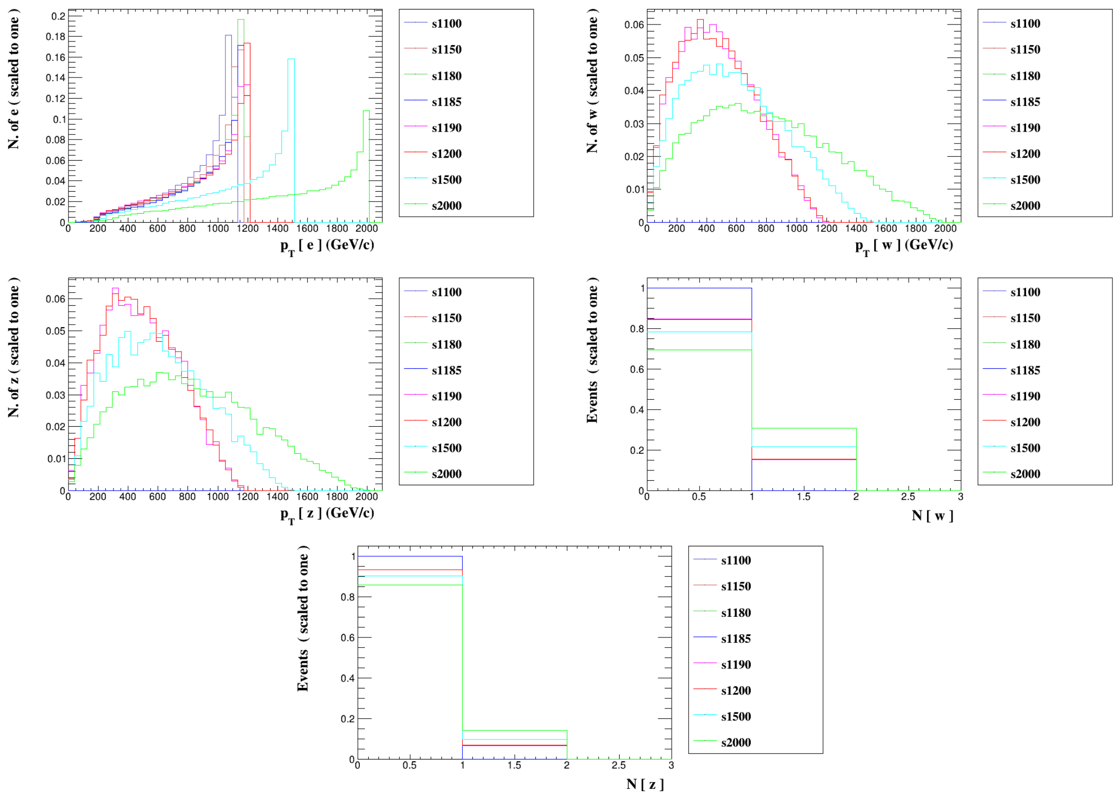

Figure 10. Kinematic distributions of the e,W and Z p_T, and W and Z multiplicities, for different beams energy ($m_{x_d} = 1$ TeV)

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4.2 Spectra for m_{xd} =1 TeV

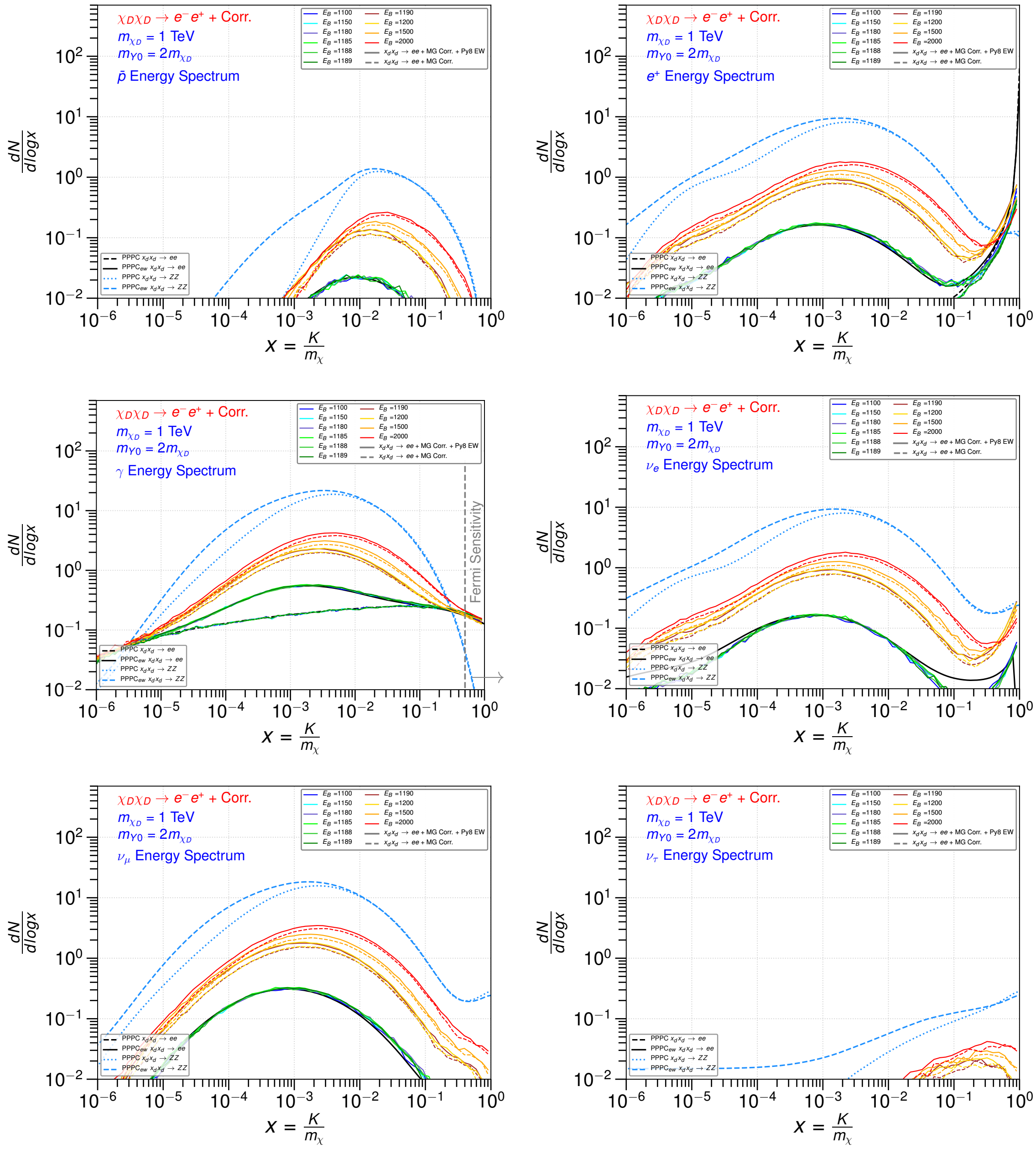

Figure 11. Energy spectra for different beam energies for $m_/xd$ =1 TeV. The process considered is $x_d x_d \to e^- e^+$, with the addition of the EW emission implemented in MadGraph5_aMC@NLO . For reference also the spectra for $x_d x_d \to ZZ$ from the PPPC4DMIDand PPPC4DMID_eware shown.

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4.3 Spectra for m_{xd} =10 TeV

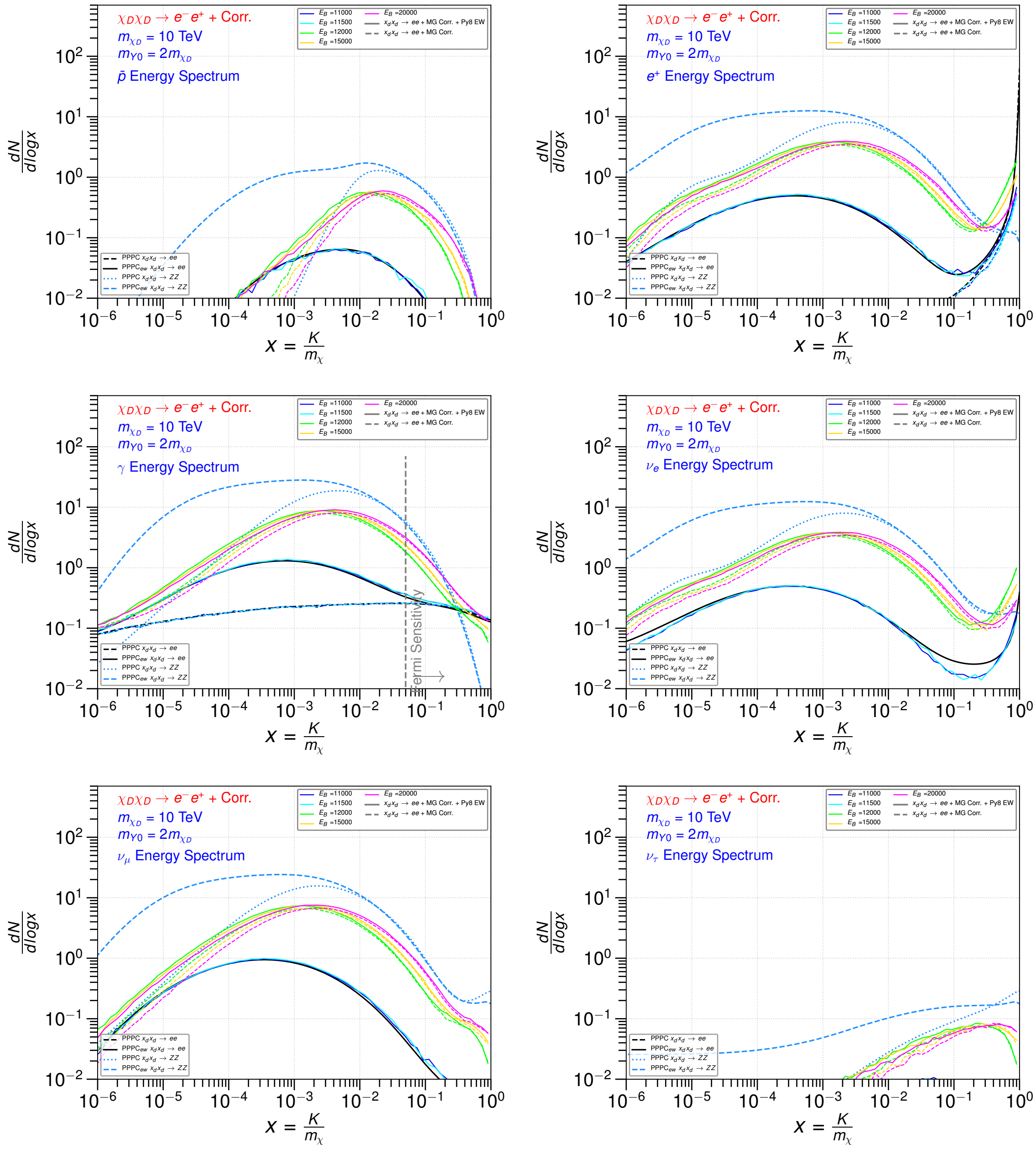

Figure 12. Same as 11 for $m_/xd$ =10 TeV

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4.4 Spectra for m_{xd} =100 TeV

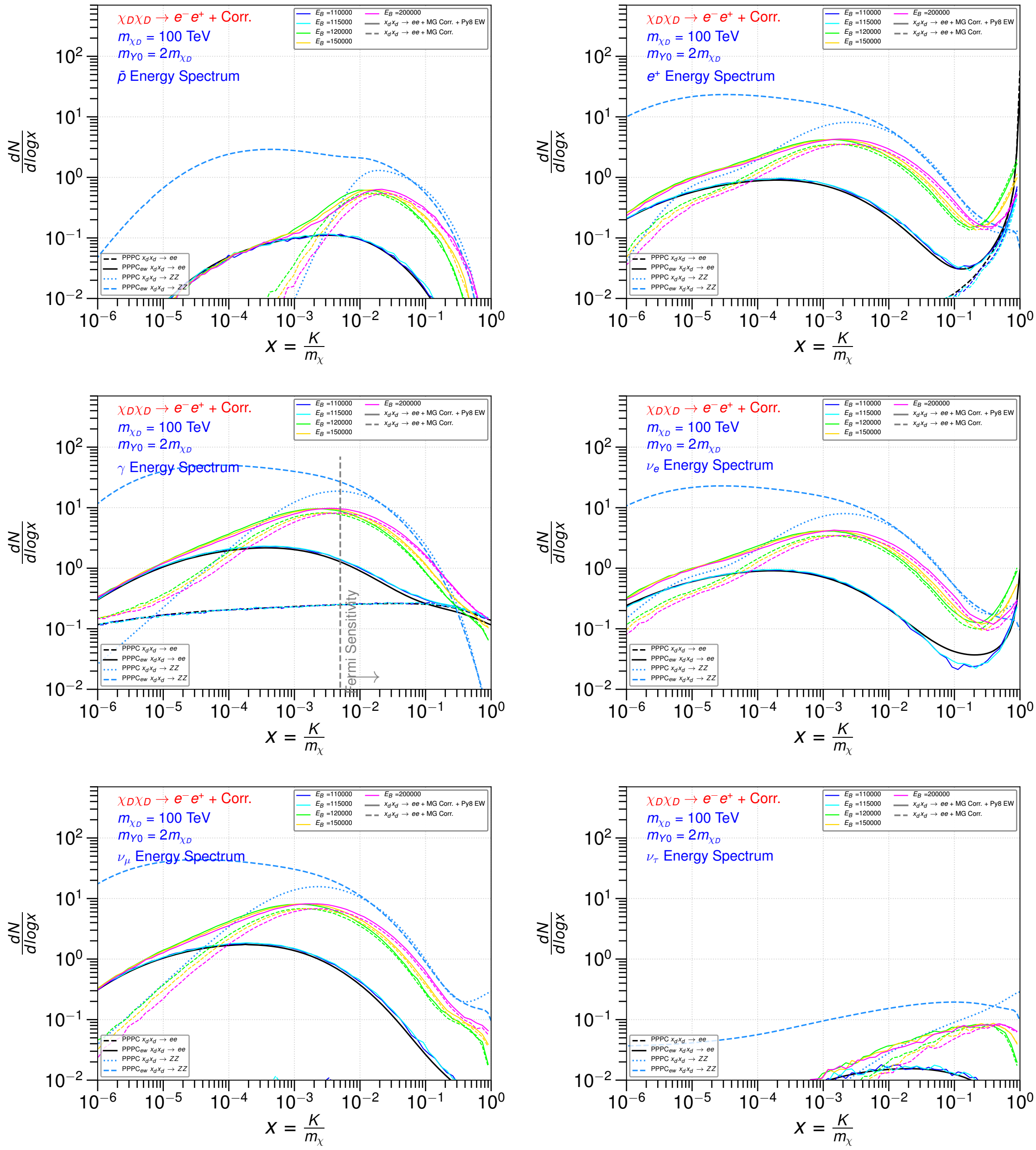

Figure 13. Same as 11 for $m_/xd$ =100 TeV

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5 Cross Sections

The results of the calculation of various processes cross section are presented. In Fig. 14 the cross section for different processes are shown. In this case, only the process indicated by the label contributes to the value of the cross section, meaning that e.g. the process $\chi_D\chi_D \to WWX$ does not include the contribution of the "tree level" process $\chi_D\chi_D \to WW$.

Since cross sections depend also on the total energy in the centre-of-mass of the DM annihilation i.e. on the parameter E_{beam} in `MadGraph5_aMC@NLO` , Fig. 15 shows the cross section values for different energies of the simulated beams.

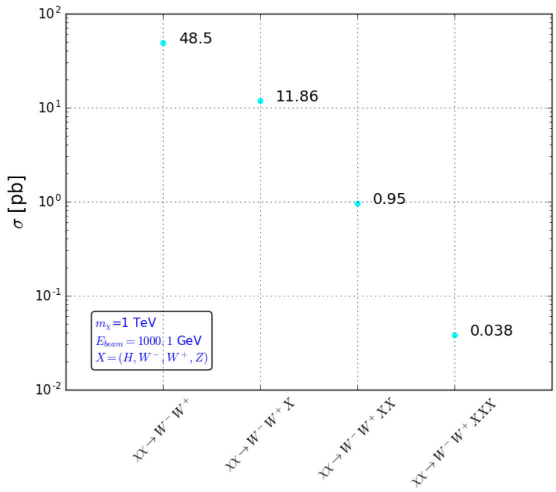

Figure 14. Cross sections for the processes $\chi_D\chi_D \to WW$ with up to three additional vector bosons $X = W^{\pm}HZ$. Note that only the cross section is relative only to the specific process as indicated by the label is considered (i.e. not the cumulative cross section). The parameters are set to $m_{\chi_D} = 1$ TeV , $m_{Y0} = 2$ TeV, $E_{Beam} = 2001$ TeV.

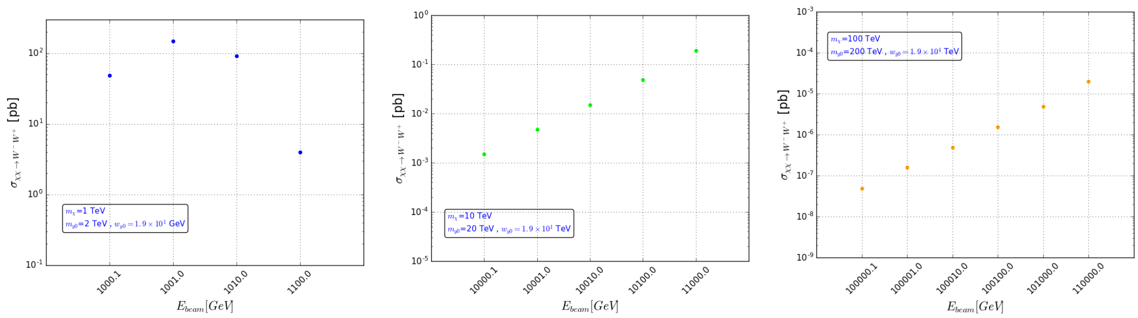

Figure 15. Cross section of the process $\chi_D\chi_D \to WW$, for $m_{\chi_D} = 1, 10, 100$ TeV, for different energies of the beams. The mass of the mediator is set to double the mass of the DM particle.

6 Width of the mediator $Y0$

When using the automatic computation of the width implemented in `MadGraph5_aMC@NLO` , problems start to arise when the mass of the mediator become large. In particular the width of the particle get to exceed largely the value of its own mass, as it show in Fig. 16. Note: this is solved if the parameter Λ i.e. the scale of the new physics is set to a value higher than the mass of the DM. If so, the width of the Y0 becomes stable. Note that also the cross section scales with Λ.

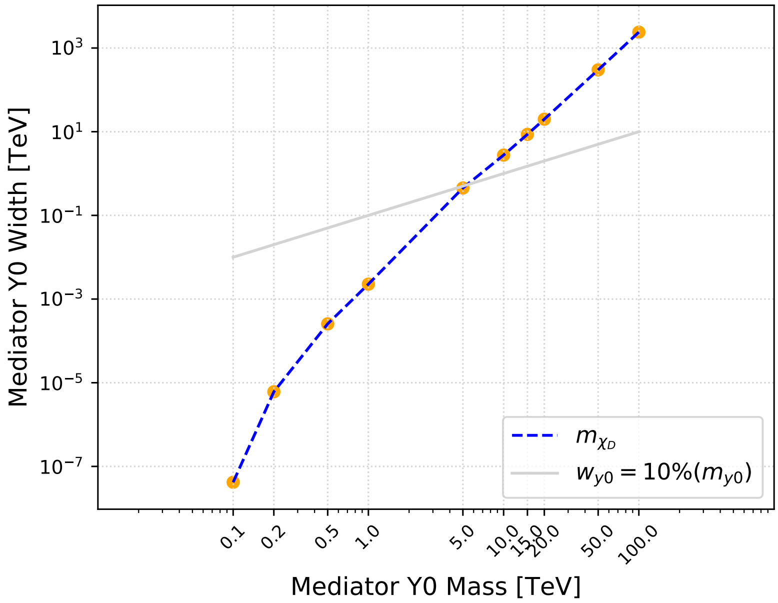

Figure 16. Values of the width of the mediatro $Y0$ as calculated by `MadGraph5_aMC@NLO` . A value of 10% of the mediator mass m_{Y0} is shown by the gray line as a comparison.

7 Unitarity

As pointed out in e.g. [1], DM simplified model can face the problem of unitarity violation for specific combinations of the parameters of the model and/or depending on the energy scale. In the cited article, they show that for unitarity to be preserved, the centre-of-mass energy must satisfy:

$$\sqrt{s} < \frac{\pi \ m_{Z'}^2}{(g_{DM}^A)^2 m_{DM})} \tag{7.1}$$

Using the same formula (which is not exactly applicable to our model), the upper limit on the DM coupling constant g_{wS} can be xtracted as:

$$g_{Sxd} < \sqrt{\frac{\pi \ m_{Y0}^2}{m_{\chi D}\sqrt{s}}} \tag{7.2}$$

The results in Fig.17 show the upper limit values of g_{Sxd} which preserve unitarity, for different DM and mediator masses and beam energies.

Basically the plots look the same since we always use mxd , my=2*mxd, and Ebeam $\sim$ 2*mxd. So for our standard choices the coupling is fine (set to 1 in the param card).

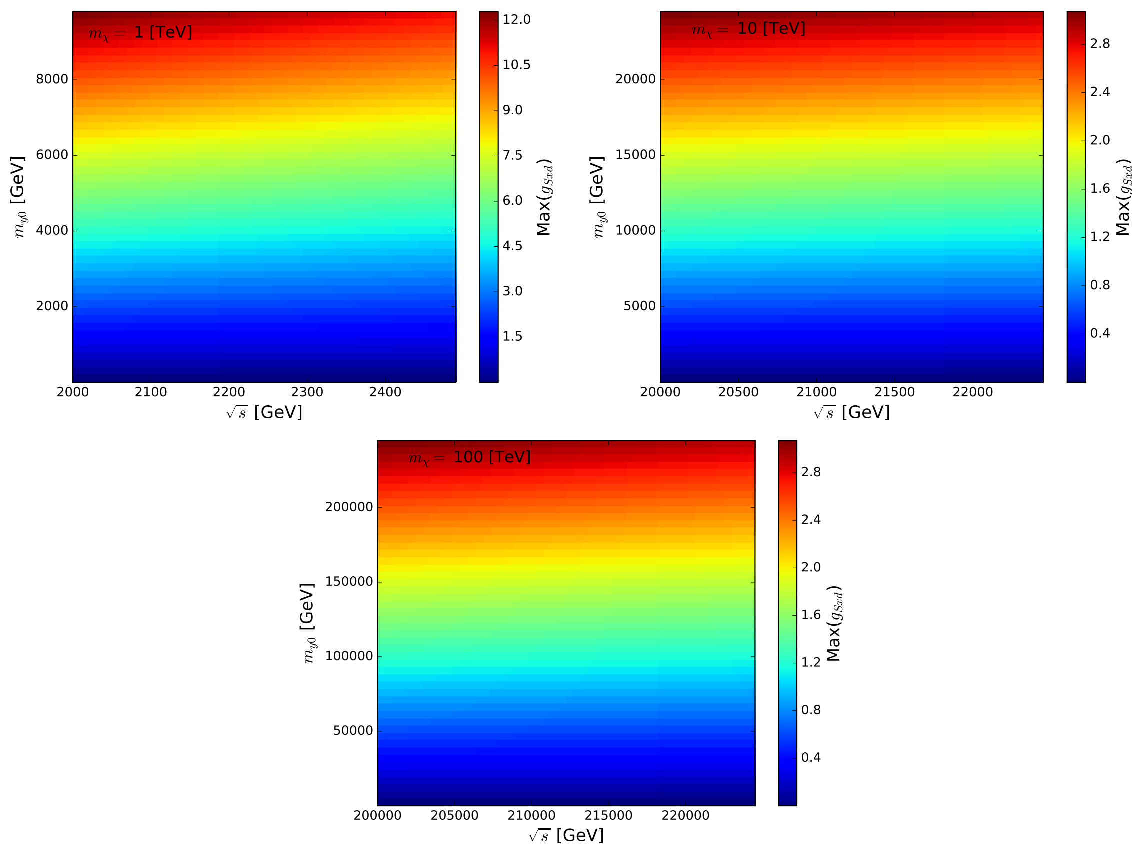

Figure 17. Upper limits on the values of the coupling constant g_{Sxd}

8 MG5 Issues

Sometimes, but not always, I get the following message:

```
INFO: Combining Events
INFO: fail to reach target 10000
  === Results Summary for run: run_01 tag: tag_1 ===

     Cross-section :   2.711e+06 +- 6.486e+04 pb
     Nb of events :  25
```

when generating events with extra bosons for $m_{\chi_D} = 100$ TeV. The `MadGraph5_aMC@NLO` version is 2.6.4 .

9 OLD Validation papers arXiv 1009.0224 and 1001.3950

9.1 Validation Minimal DM Model $x_d x_d \to \mu^- \mu^+$ + EW arXiv:1001.3950

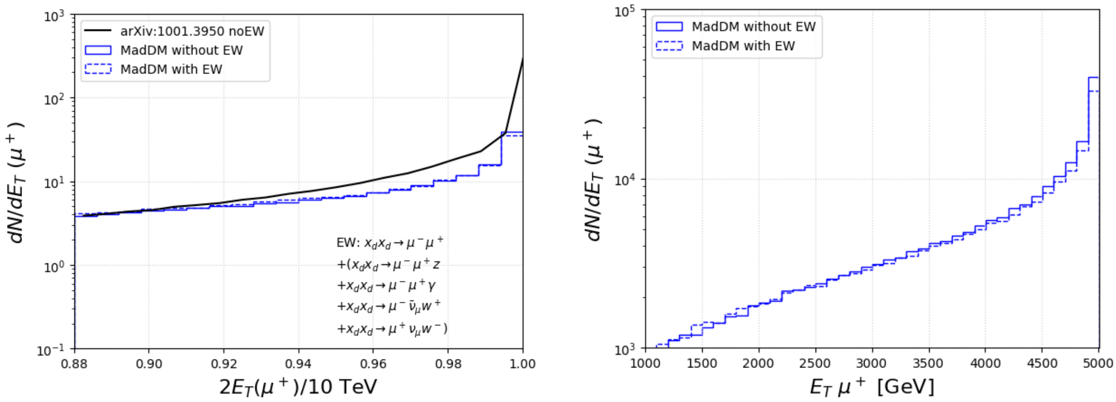

Figure 18.

9.2 Validation $n_1 n_1 \to w^- w^+ z$ arXiv:1009.0224

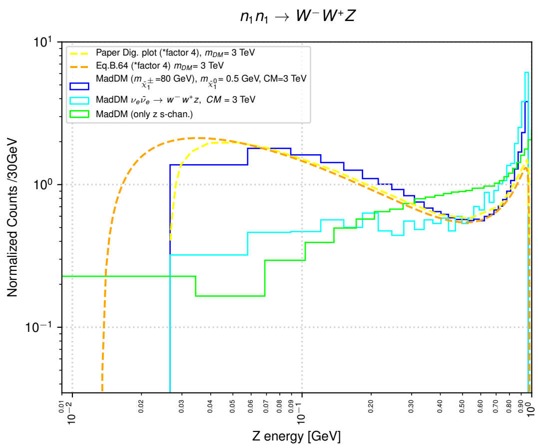

Figure 19.

9.3 Validation $n_1 n_1 \to w^- w^+ \gamma$ arXiv:1009.0224

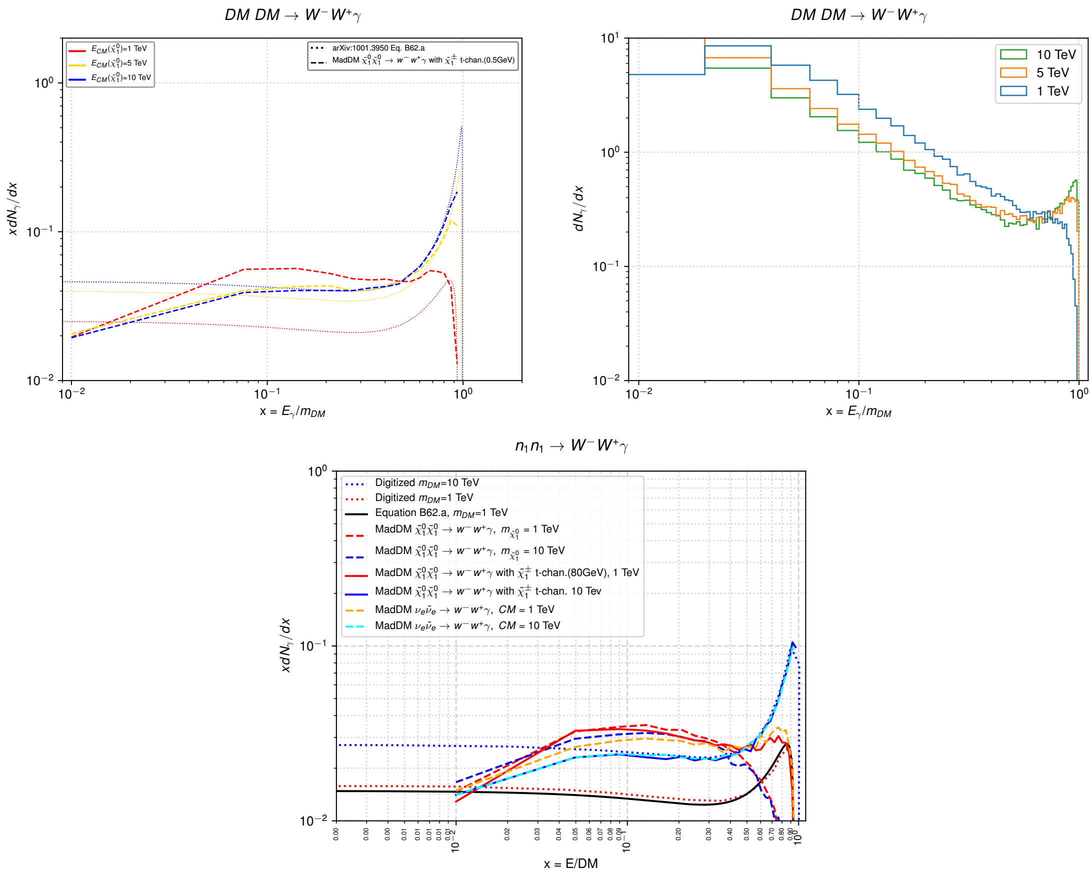

Figure 20.

10 Validation papers arXiv 1009.0224

In this section we present the validation of the results for the "Minimal Dark Matter" model introduced in [?]. In this DM only has electroweak interactions; we take the case of the parameter space of the MSSM where the DM candidate is a pure Wino-like $\tilde{\chi}_1^0$, and consequently mass degenerate with the lightest chargino $\tilde{\chi}_1^{\pm}$. The results are shown in Fig. 21. The plots show the comparison between the results in [?] and the results obtained with `MadDM 3.0` for the annihilation process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to w^- w^+ z$. The upper plots is obtained for $m_{\tilde{\chi}_1^0} = 3$ TeV. We see that the `MadDM 3.0` results are in good agreement with the theoretical predictions, which are calculated using different approximation methods. The lower plots compare the `MadDM 3.0` distributions with the spectra obtained using Eq.B62b for alternative DM mass of 1 and 10 TeV respectively. Note that Eq.B62b (case of extra Z boson radiation) and Eq.B62a (case of extra photon radiation) do not produce the correct kinematic boundaries in the low energy boundary of the spectra (according to the authors). Note that the theory predictions for $m_{\tilde{\chi}_1^0} = 1, 3, 10$ TeV were rescaled by multiplying for the arbitrary factors 5,10,3. I have no idea why but it is the only way to make them to the correct scale.

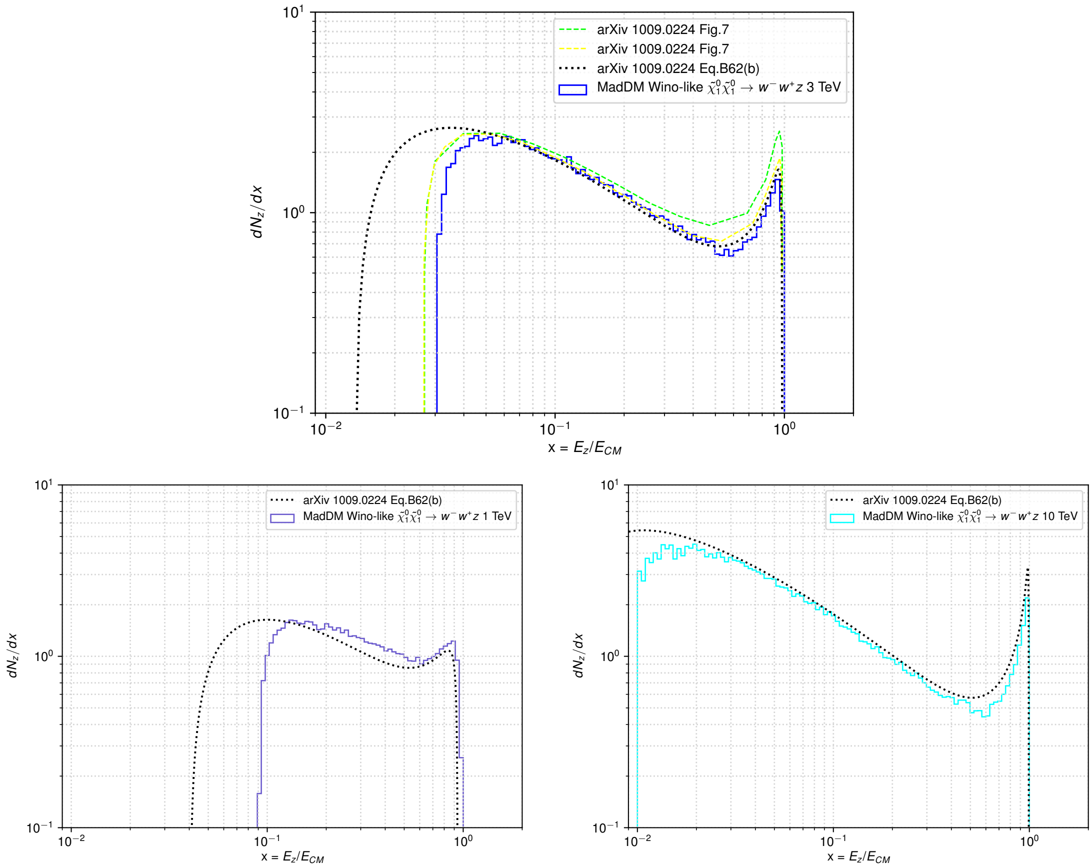

Figure 21. Validation of the `MadDM 3.0` results with the theoretical prediction from [?], using the "Minimal Dark Matter" model for Wino-like MSSM $\tilde{\chi}_1^0 - \tilde{\chi}_1^\pm$, for the process $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to w^- w^+ z$. Upper panel: comparison for $m_{\tilde{\chi}_1^0} = 3$ TeV, the theory predictions are shown in dashed yellow and green lines (line digitized form the original paper, corresponding to two different parametrization used in the analytical calculations) and black dotted (Eq.B62b). In particular, the prediction from the Eq.B62b does not reproduce correctly the low energy tail of the distributions. Lowe panels: comparison for $m_{\tilde{\chi}_1^0} = 1$ and 10 TeV.

Analogously, the process involving the radiation of one extra photons was validated in Fig. 21. Note that due to the cut in the photon energy in the *run_ card.dat*, the distributions have a sharp edge that does not correspond to actual kinematic boundaries.

Acknowledgments

Thanks

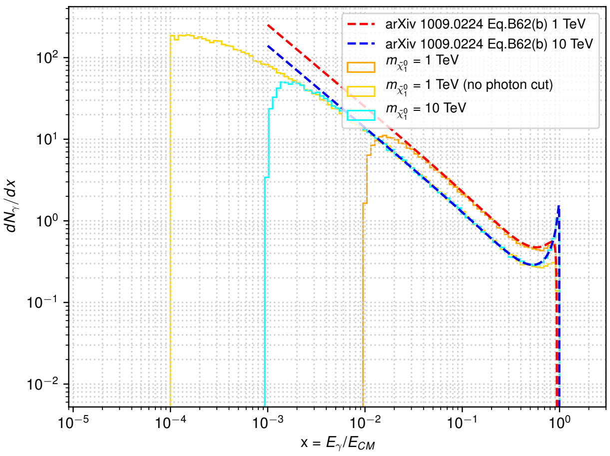

Figure 22. Same as Fig. 21 for the 3-body annihilation process $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to w^-w^+\gamma$. Note that the edges in the `MadDM 3.0` distributions are due to the cut on the photon energy in the *run_ card.dat*.

References

[1] F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, *Implications of unitarity and gauge invariance for simplified dark matter models*, *JHEP* **02** (2016) 016, [arXiv:1510.02110].