

MadDM 3.0 EW

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Abstract

This documents summarises the status of the studies of the discrepancies found in the energy spectra provided in the PPC4DMID 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 PPPC4DMIDcollaboration).

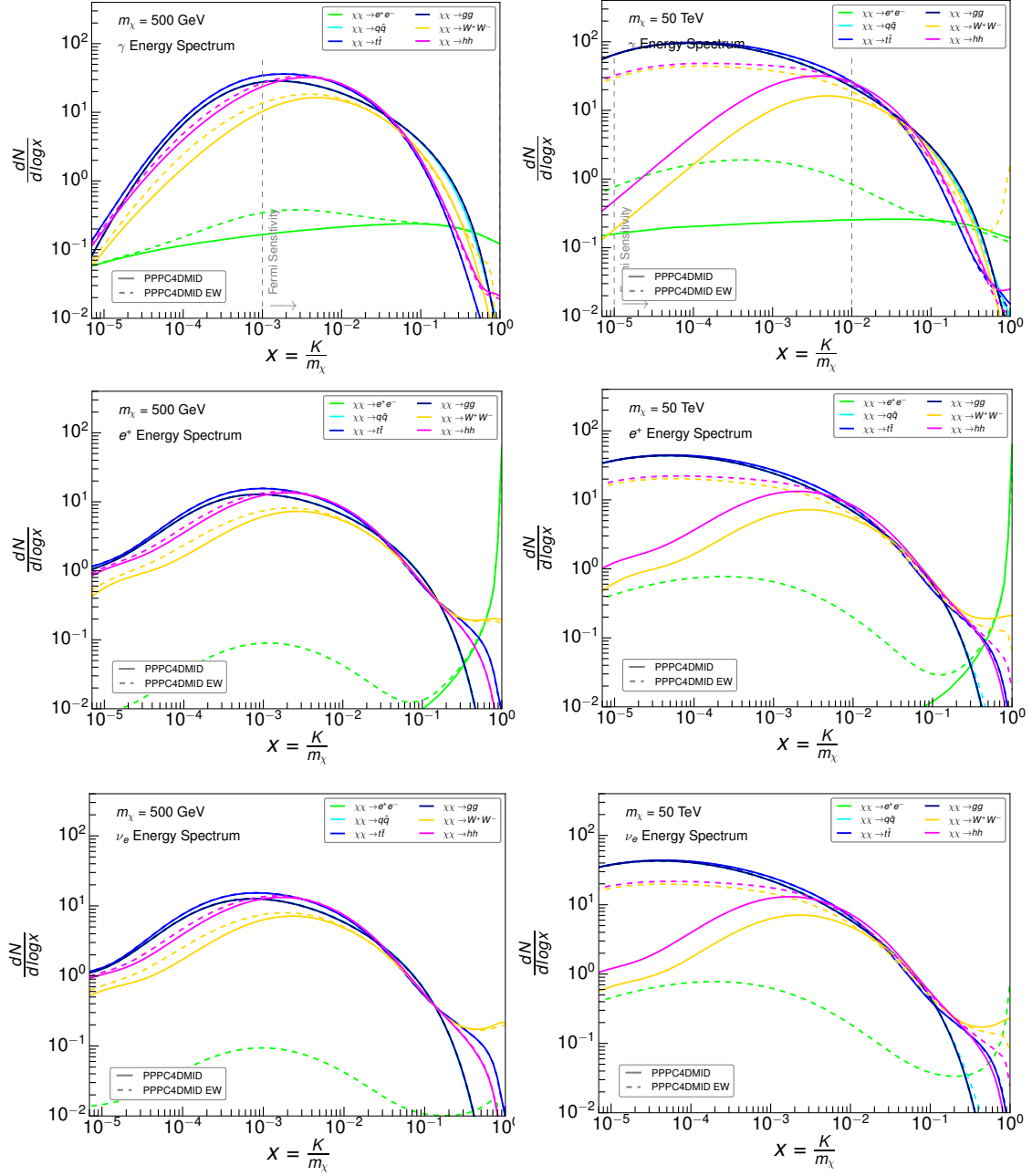


Figure 1. Energy spectra (γ, e^+, ν_e) for $m_\chi = 500$ GeV (left) and 50 TeV (right) extracted from the PPPC4DMID and PPPC4DMID_ew tables, for selected annihilation channels.

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 $xxd \rightarrow WW$) 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 $m_{\chi_D}=1, 10, 100$ 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.

m_{χ_D}	$\chi_D \chi_D \rightarrow \mathbf{WW}$	$\chi_D \chi_D \rightarrow \mathbf{WWX}$	$\chi_D \chi_D \rightarrow \mathbf{WWXX}$	$\chi_D \chi_D \rightarrow \mathbf{WWXXX}$
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 $\chi_D \chi_D \rightarrow e^- e^+$

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 by 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 $n_1 n_1 \rightarrow e^- e^+$ 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\
```

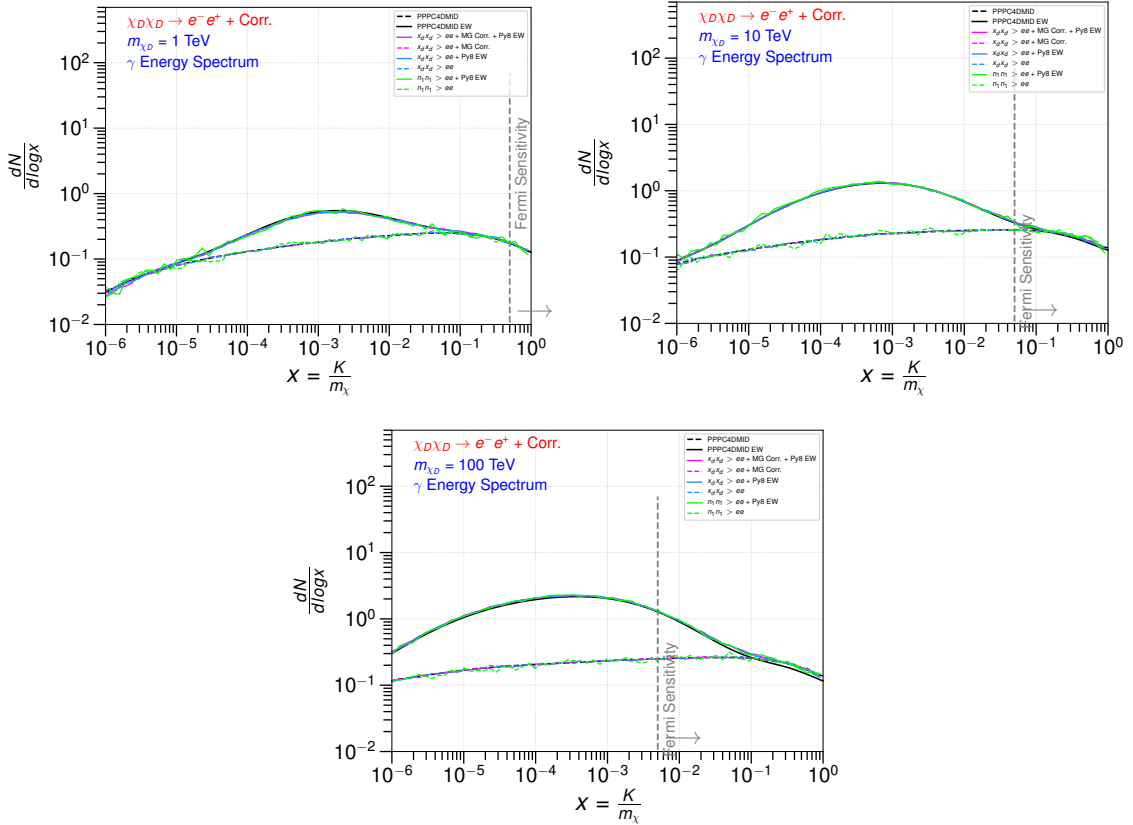


Figure 2. Energy Spectra for the channel $e^- e^+$ using the DM simplified model with couplings to leptons or the MSSM.


```
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 $\chi_D \chi_D \rightarrow WW$

3.4.1 $m_{\chi_D} = 1$ TeV

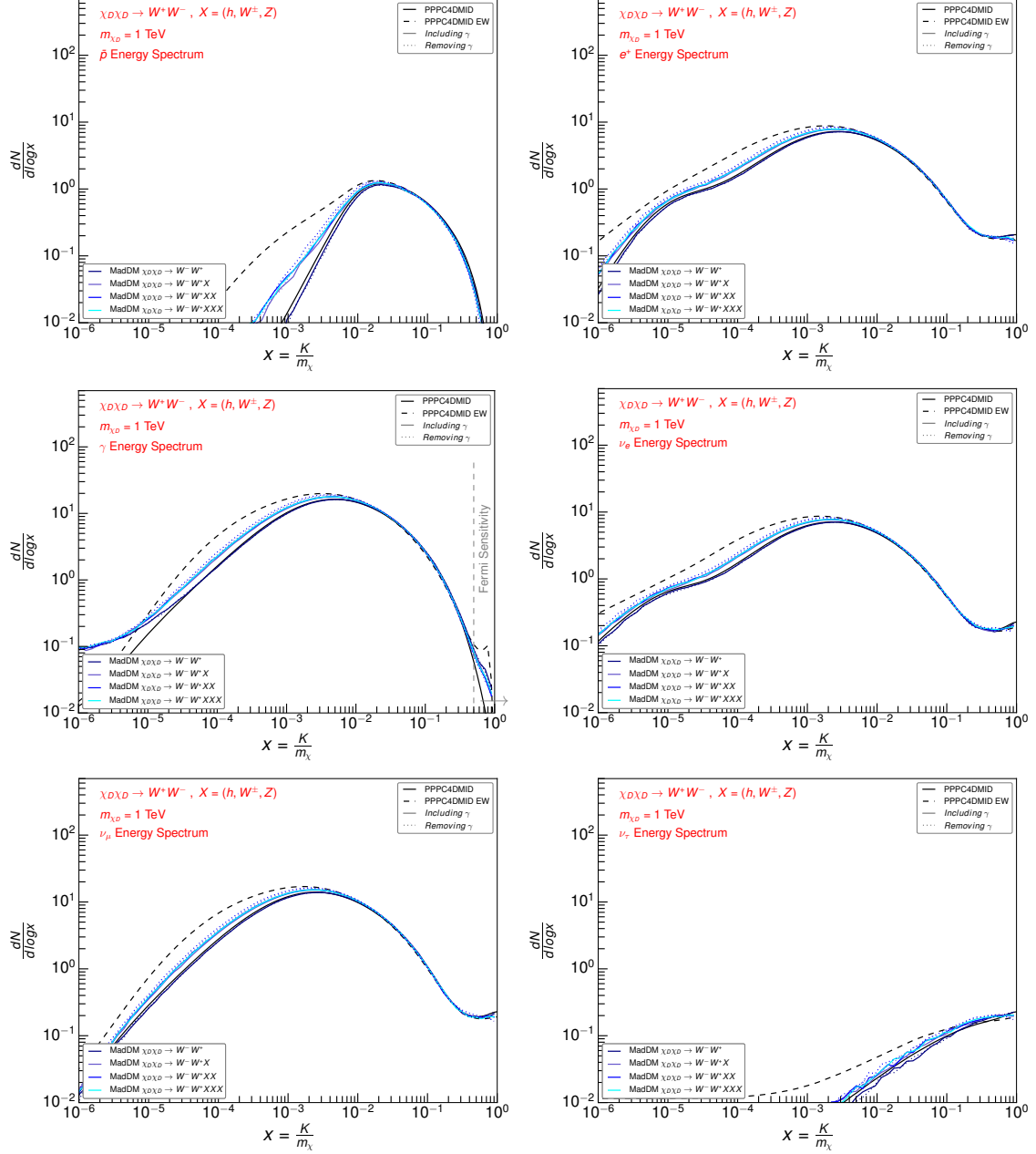


Figure 3. Energy Spectra for $m_{\chi_D} = 1$ TeV

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

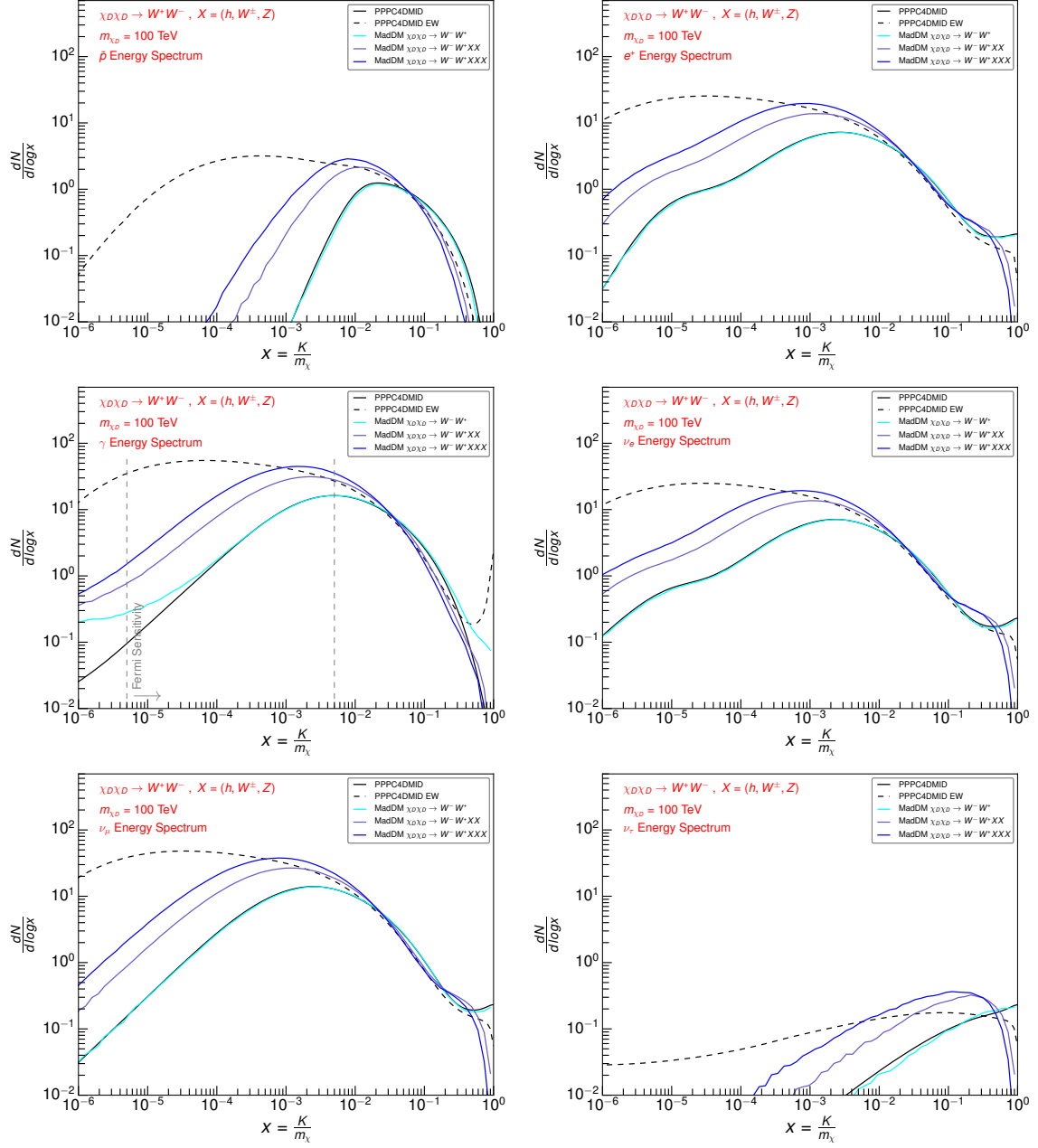


Figure 4. Energy Spectra for $m_{\chi_D} = 100$ TeV (Old data)

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

Here the spectra for the process $\chi_D \chi_D \rightarrow Y0 \rightarrow FFFF$ are shown for $m_{\chi_D} = 1$ TeV, compared to the `PPPC4DMID` and `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 massless 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 includes also Z bosons, since I did not remove their contribution explicitly from 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 `PPPC4DMID` or `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
```

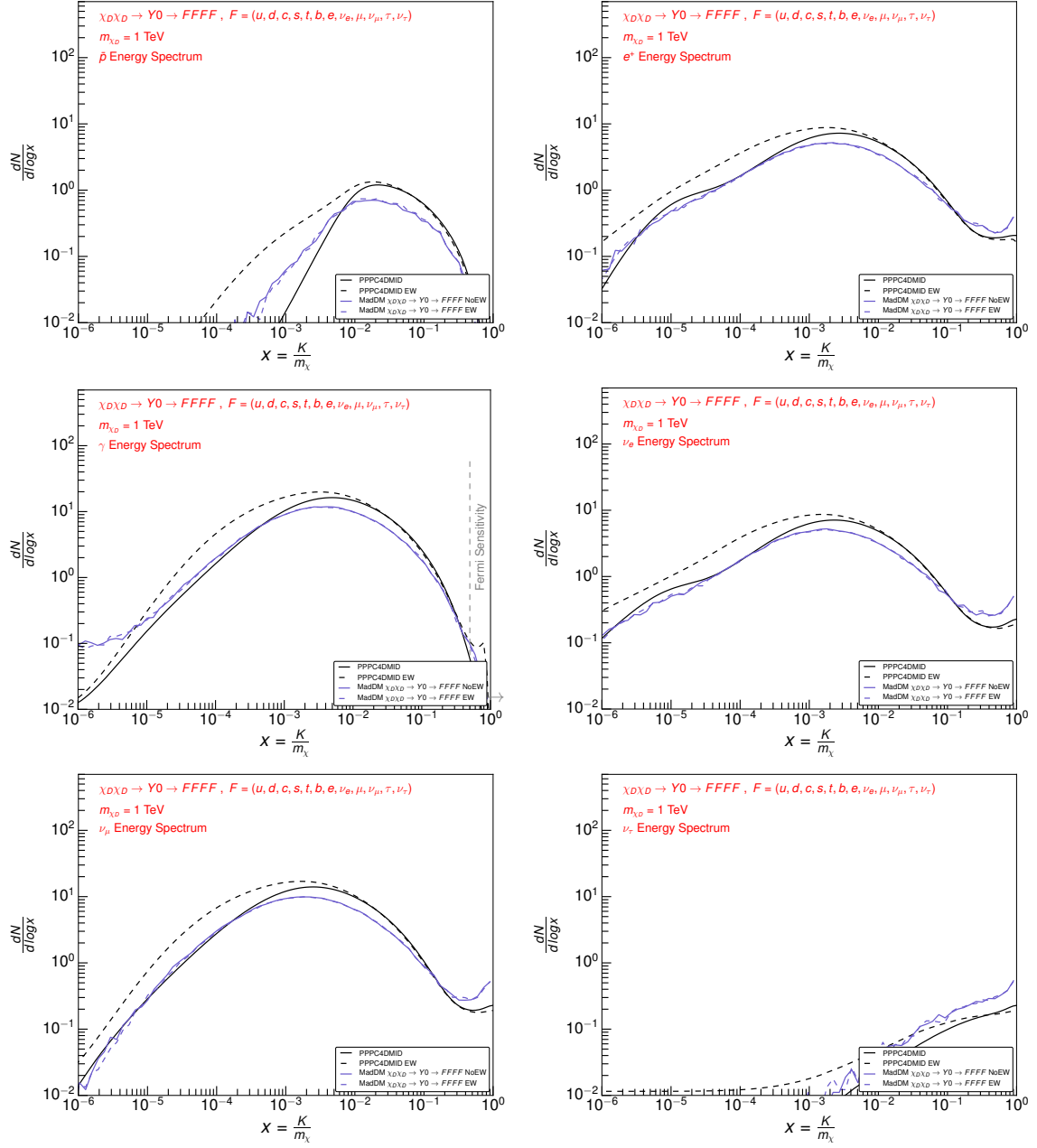


Figure 5. Energy Spectra for $m_{\chi_D} = 1$ TeV for the process $\chi_D \chi_D \rightarrow Y0 \rightarrow FFFF$. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

3.6 Spectra for $\chi_D \chi_D \rightarrow Y0 \rightarrow FFFF$ 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 xdx_d_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 $m_{\chi_D} = 1 \text{ TeV}$

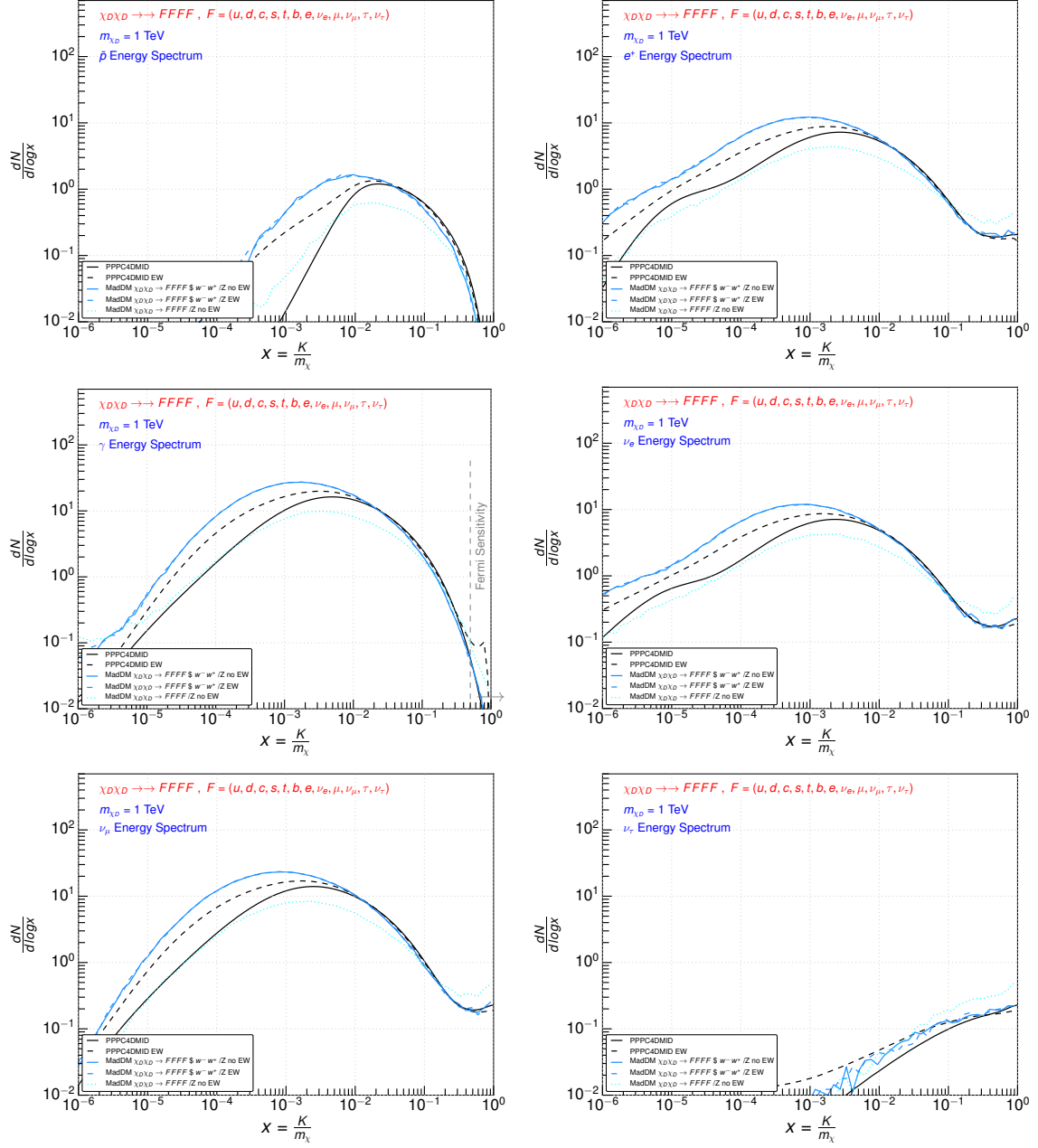


Figure 6. Energy Spectra for $m_{\chi_D} = 1 \text{ TeV}$ for the process $\chi_D \chi_D \rightarrow Y0 \rightarrow FFFF w^- w^+ / Z$, for $m_{\chi_D} = 1 \text{ TeV}$. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

3.6.2 $m_{\chi_D} = 10 \text{ TeV}$

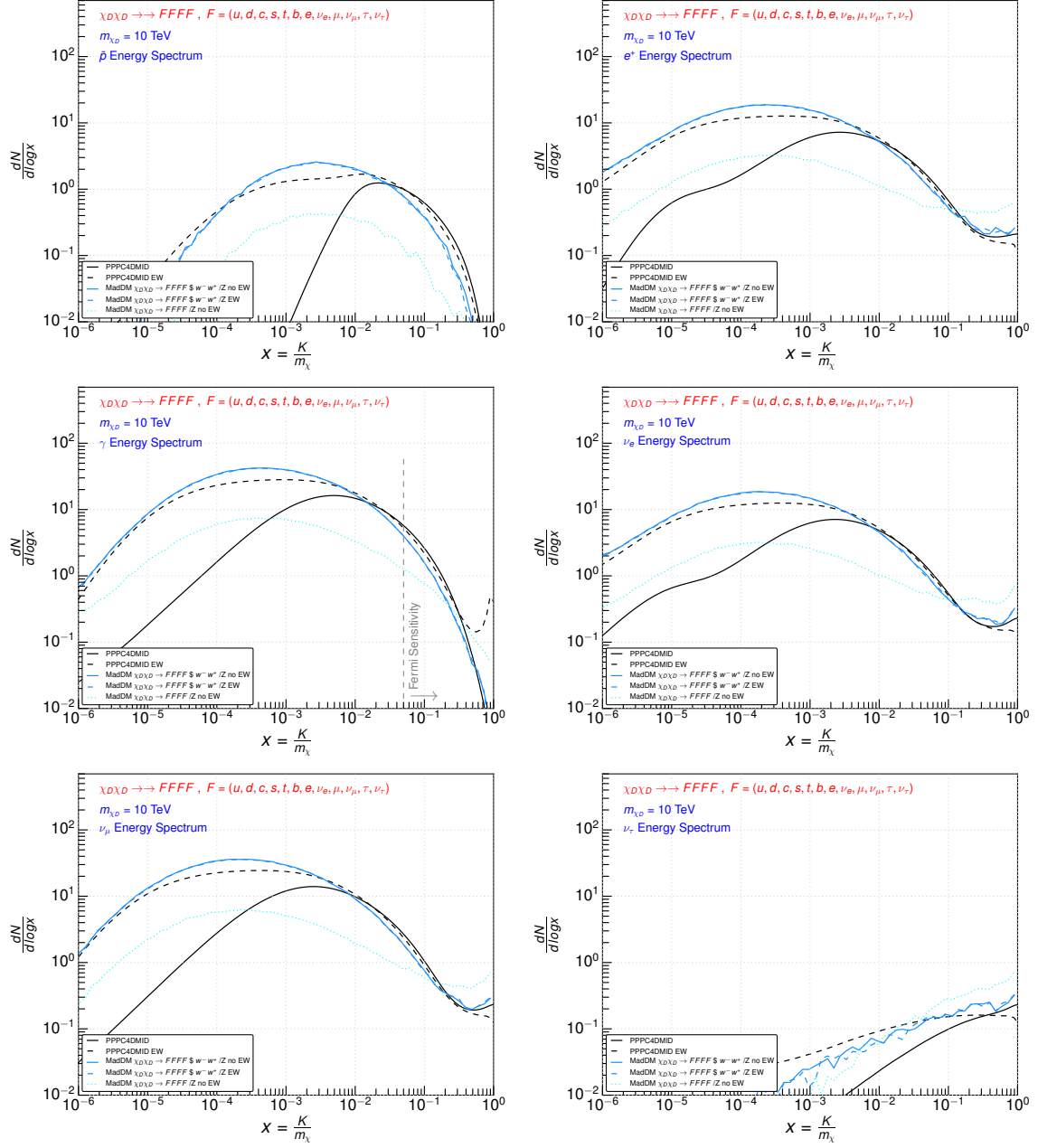


Figure 7. Energy Spectra for $m_{\chi_D} = 10 \text{ TeV}$ for the process $\chi_D \chi_D \rightarrow Y0 \rightarrow FFFF w^- w^+ / Z$, for $m_{\chi_D} = 1 \text{ TeV}$. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

3.6.3 $m_{\chi_D} = 100$ 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.

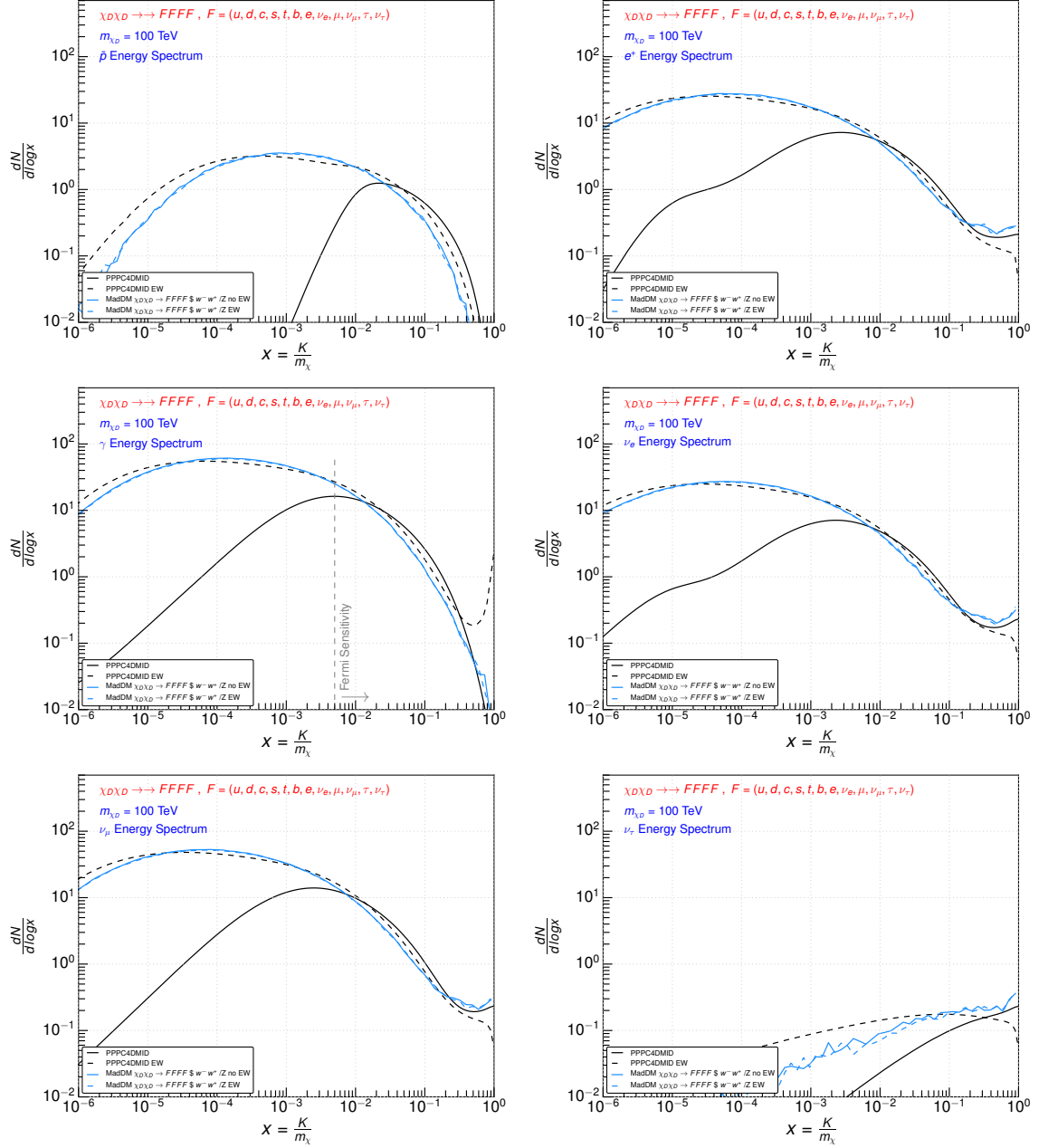


Figure 8. Energy Spectra for $m_{\chi_D} = 100$ TeV for the process $\chi_D \chi_D \rightarrow Y0 \rightarrow FFFF w^- w^+ / Z$, for $m_{\chi_D} = 1$ TeV. The label "EW" and "NoEW" in the MadDM samples mean respectively samples produced with or without the EW corrections in Pythia8.

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

Process implemented in MadGraph5_aMC@NL0:

```
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 xdx_d_ee_eez_evev
```

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

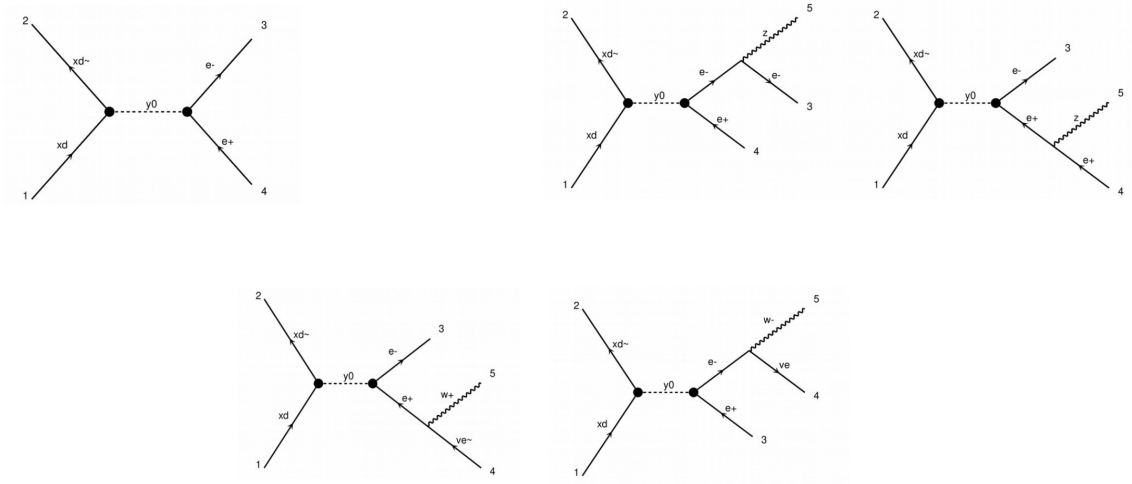


Figure 9. Feynman diagrams.

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" $x_d x_d \rightarrow ee$; 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 $m_{x_d} = 1$).

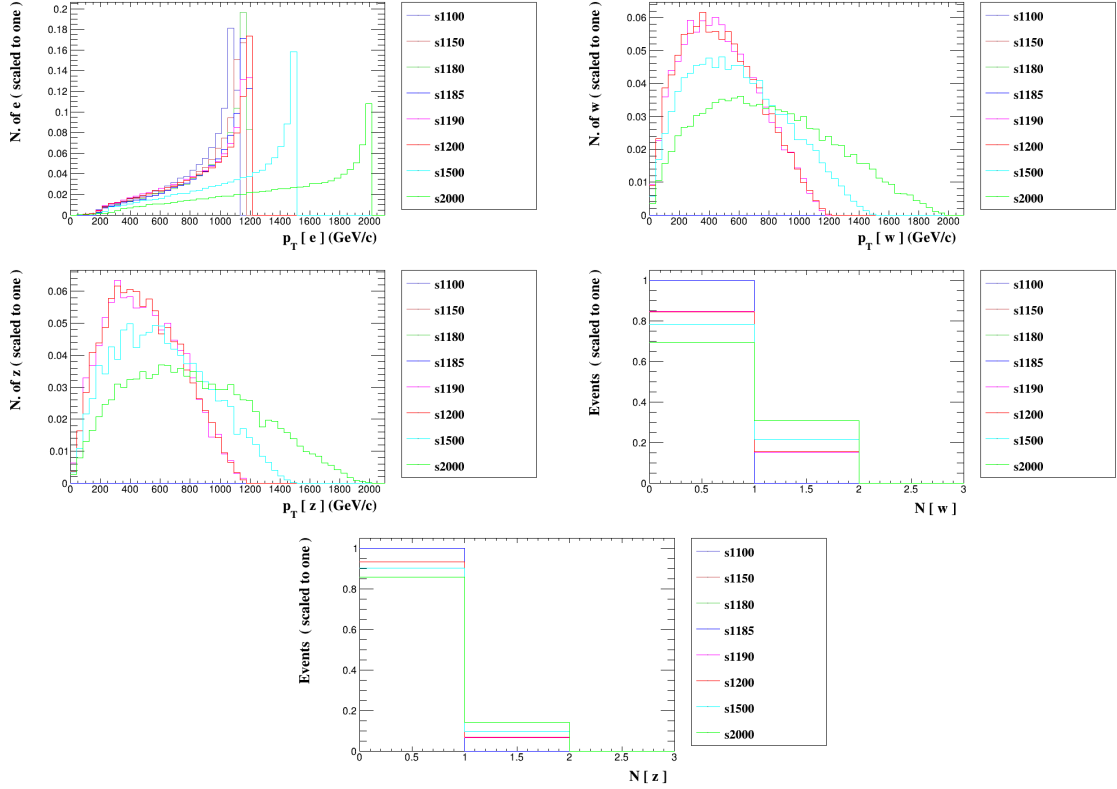


Figure 10. Kinematic distributions of the e, W and Z p_T , and W and Z multiplicities, for different beams energy ($m_{x_d} = 1$ TeV)

4.2 Spectra for $m_{xd}=1$ TeV

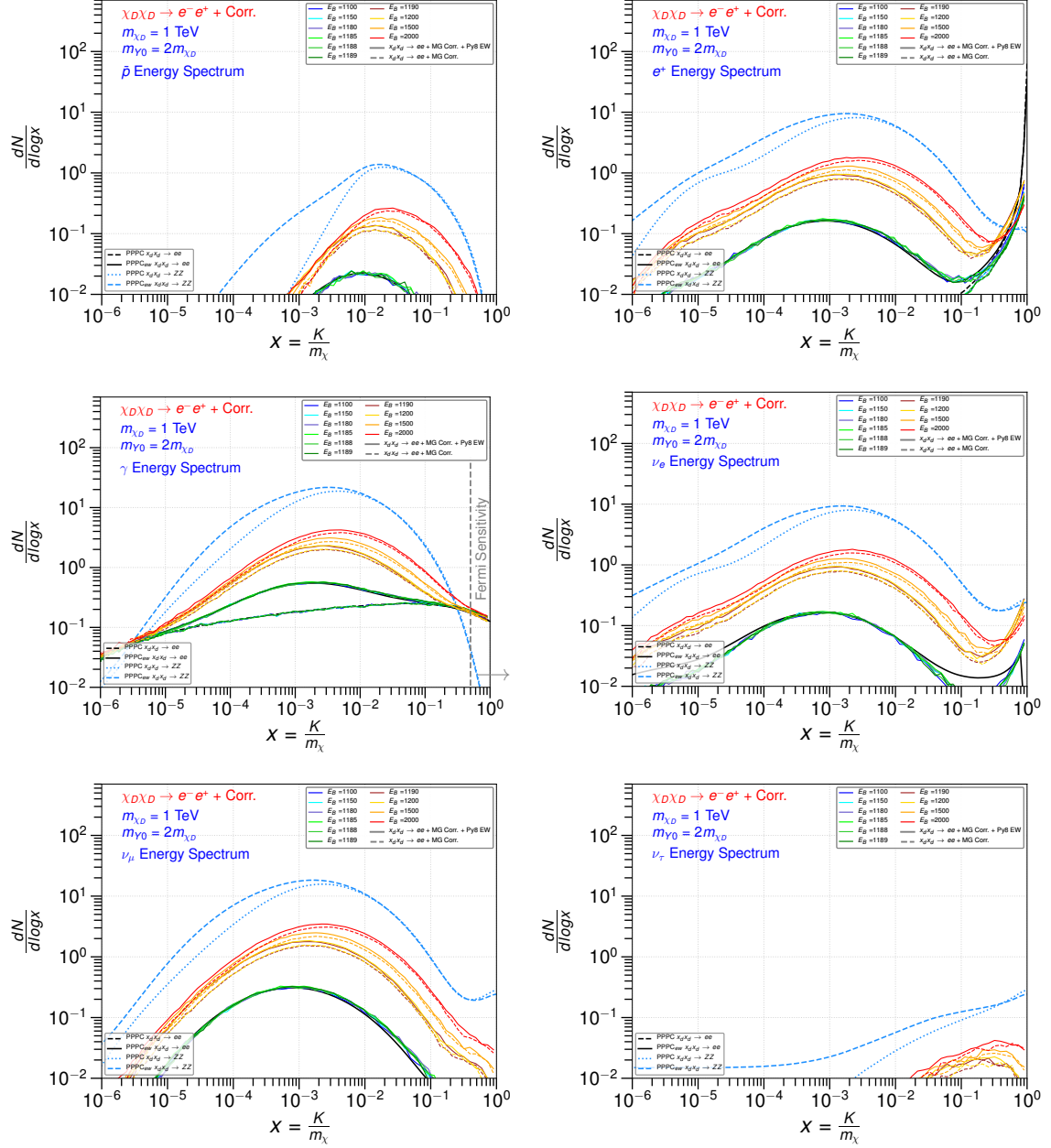


Figure 11. Energy spectra for different beam energies for $m_{xd}=1$ TeV. The process considered is $x_d x_d \rightarrow e^- e^+$, with the addition of the EW emission implemented in MadGraph5_aMC@NLO. For reference also the spectra for $x_d x_d \rightarrow ZZ$ from the PPC4DMID and PPC4DMID_ew are shown.

4.3 Spectra for $m_{xd}=10$ TeV

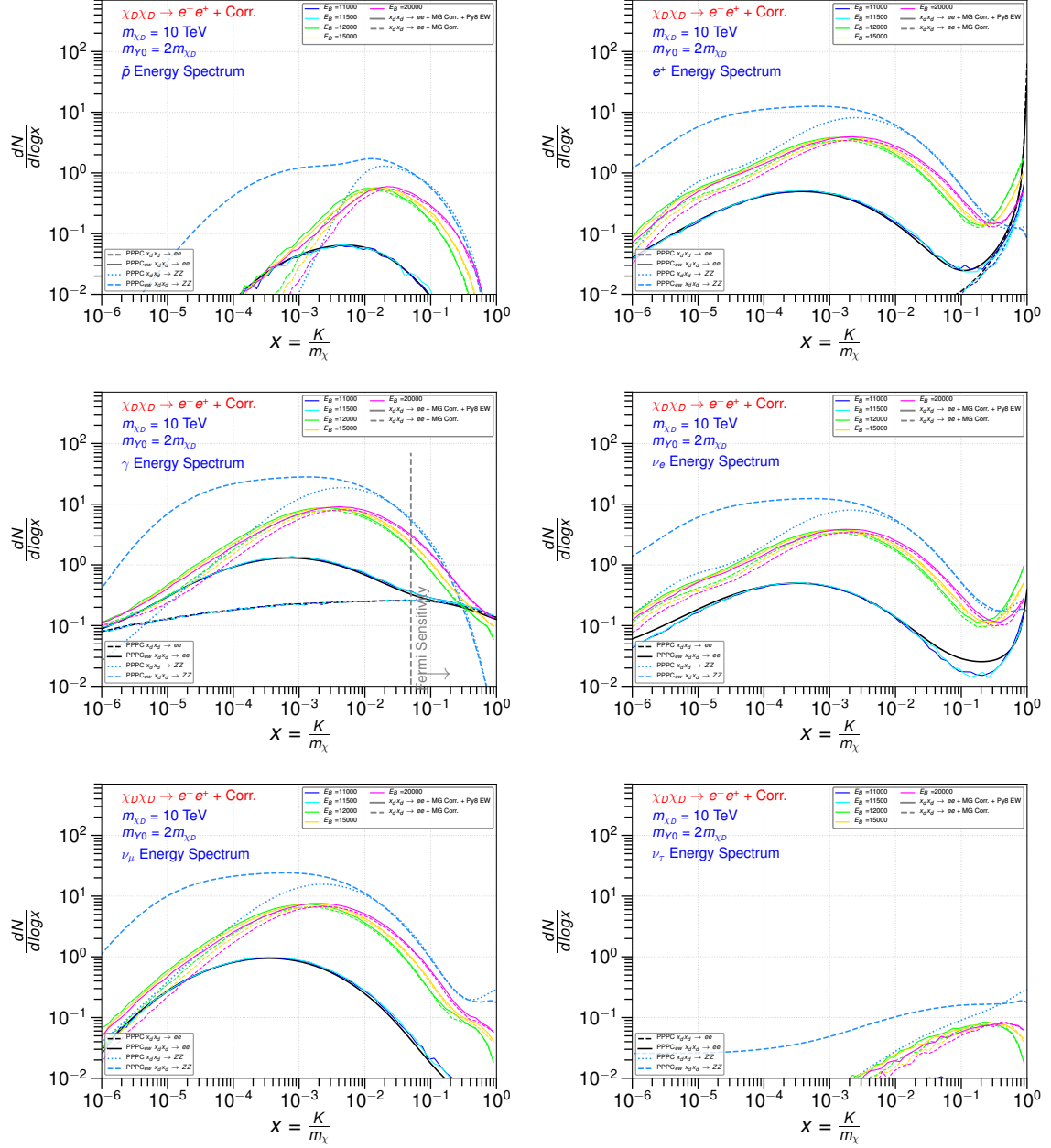


Figure 12. Same as 11 for $m_{\tilde{\chi}_D}=10$ TeV

4.4 Spectra for $m_{xd}=100$ TeV

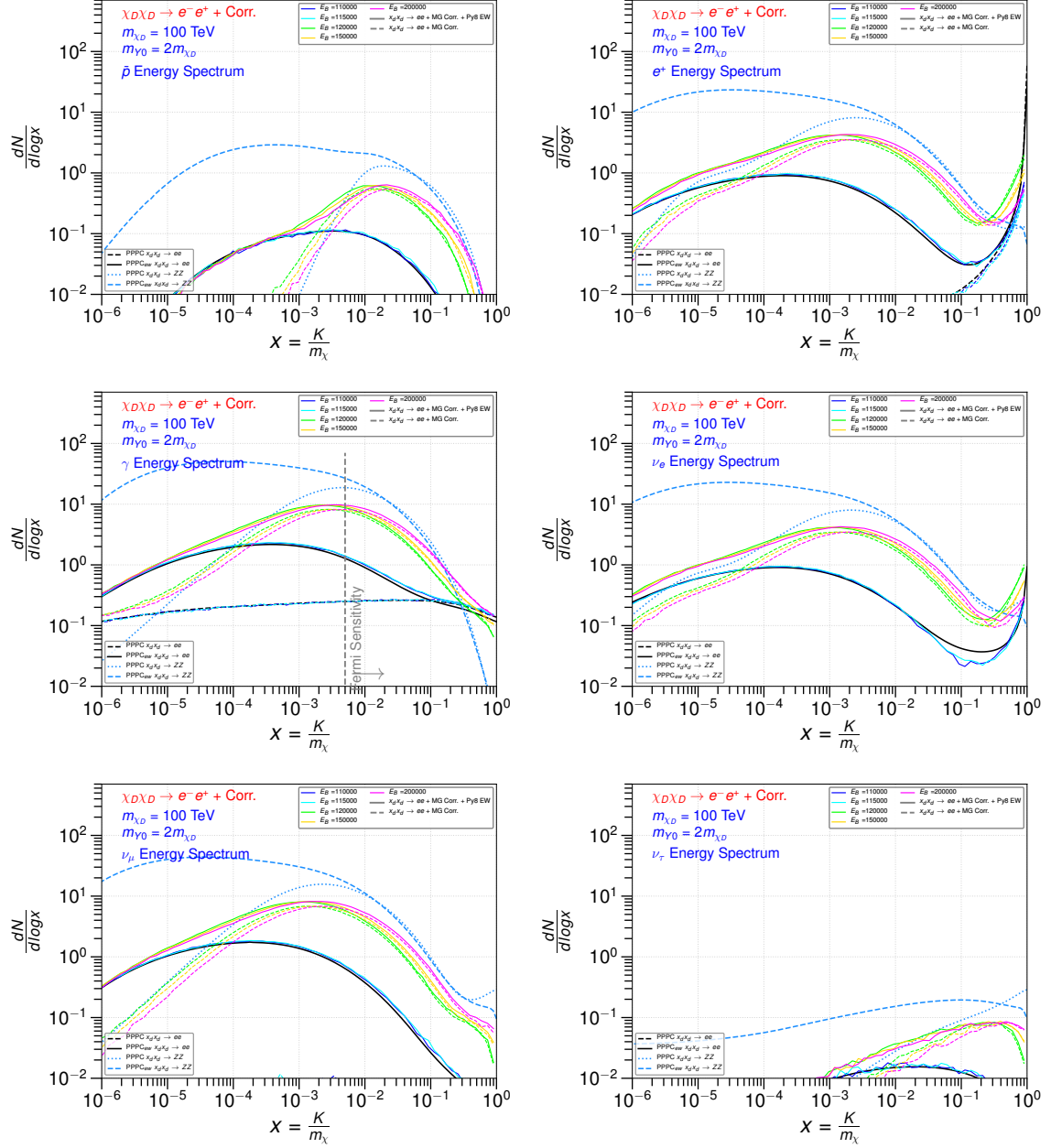


Figure 13. Same as 11 for $m_{\chi_D}=100$ TeV

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 $\chi_D \chi_D \rightarrow WWX$ does not include the contribution of the "tree level" process $\chi_D \chi_D \rightarrow WW$.

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.

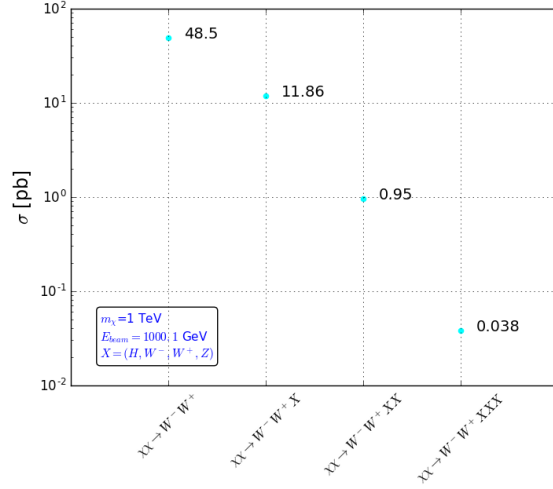


Figure 14. Cross sections for the processes $\chi_D \chi_D \rightarrow WW$ with up to three additional vector bosons $X = W^\pm HZ$. Note that only the cross section is relative only to the specific process as indicated by the label is considered (i.e. not the cumulative cross section). The parameters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

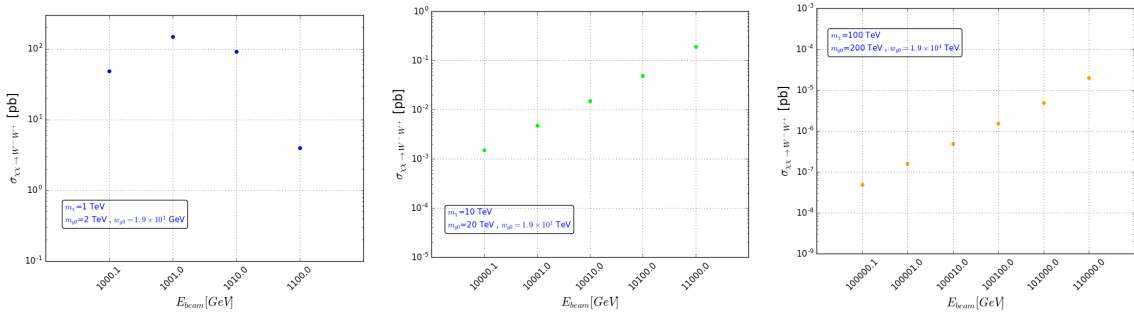


Figure 15. Cross section of the process $\chi_D \chi_D \rightarrow WW$, for $m_{\chi_D} = 1, 10, 100$ TeV, for different energies of the beams. The mass of the mediator is set to double the mass of the DM particle.

6 Width of the mediator Y_0

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 Y_0 becomes stable. Note that also the cross section scales with Λ .

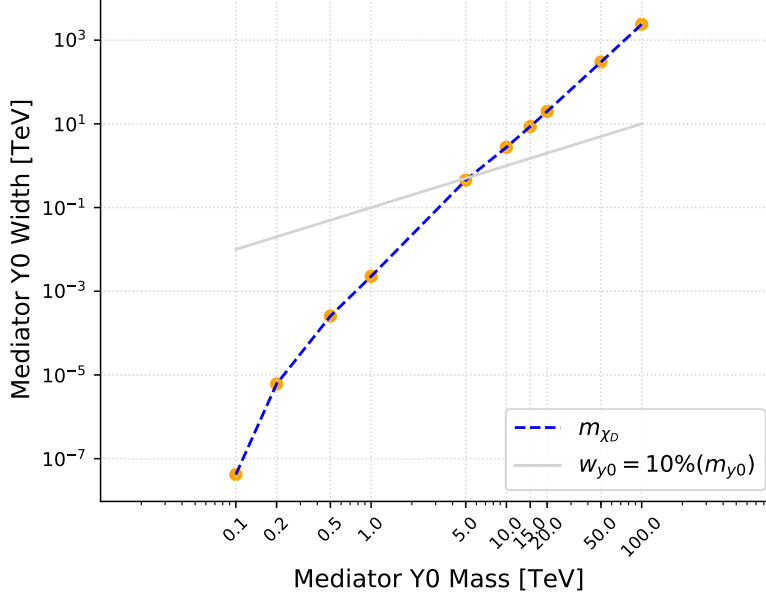


Figure 16. Values of the width of the mediator Y_0 as calculated by `MadGraph5_aMC@NLO`. A value of 10% of the mediator mass m_{Y_0} is shown by the gray line as a comparison.

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:

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

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

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

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 $m_{\chi D} = 2m_{\chi}$, $m_{Y0} = 2m_{\chi D}$, and $E_{beam} \sim 2m_{\chi D}$. So for our standard choices the coupling is fine (set to 1 in the param card).

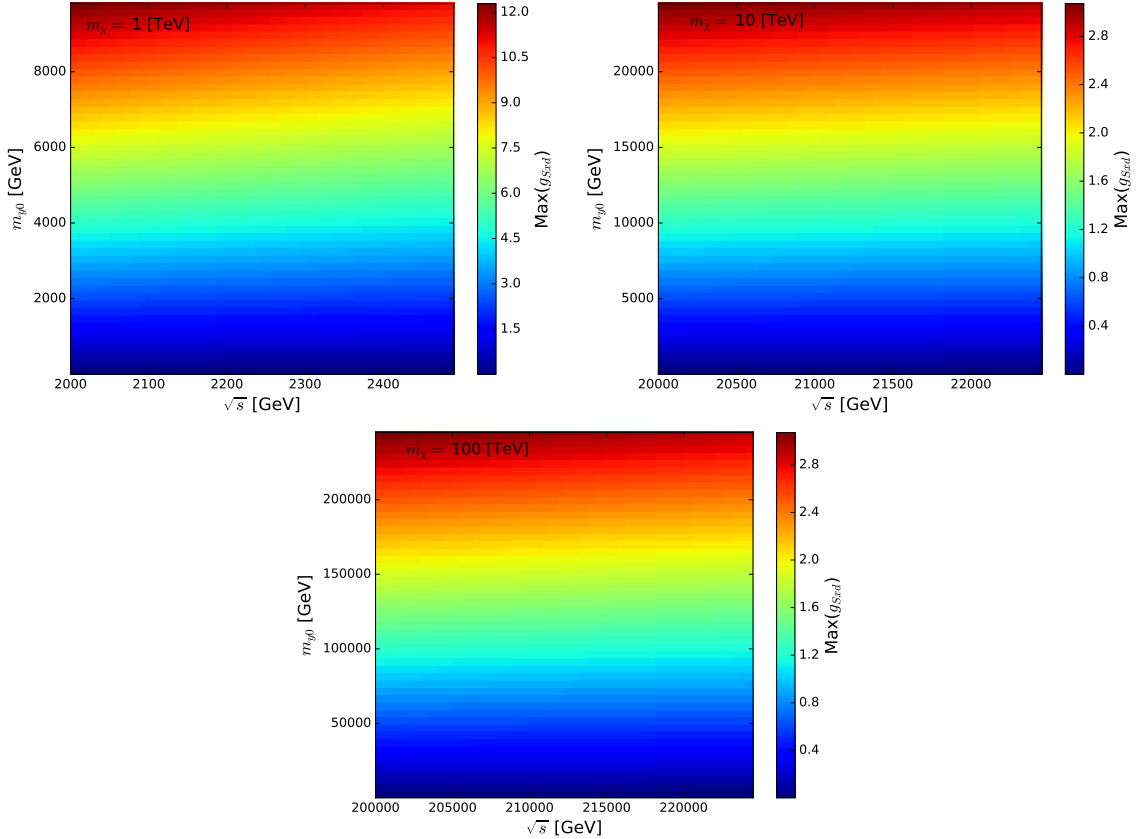


Figure 17. Upper limits on the values of the coupling constant g_{Sxd}

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 $x_d x_d \rightarrow \mu^- \mu^+ + \text{EW}$ arXiv:1001.3950

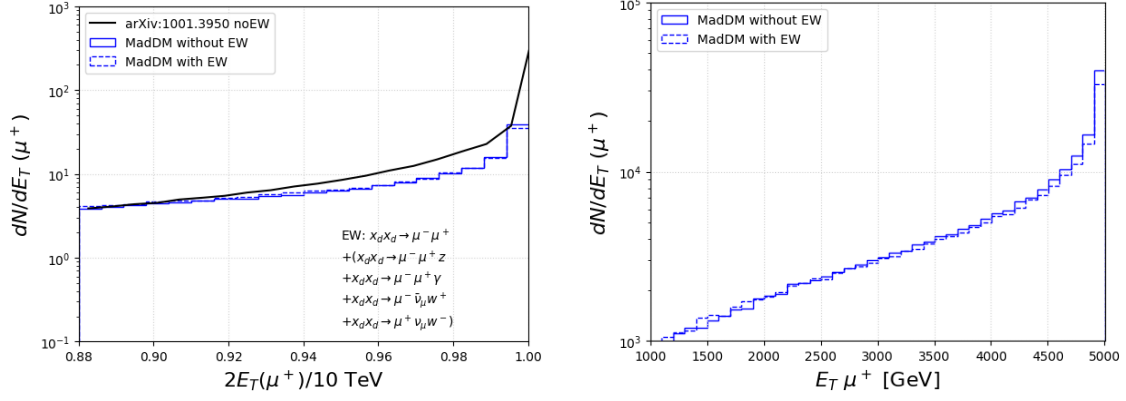


Figure 18.

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

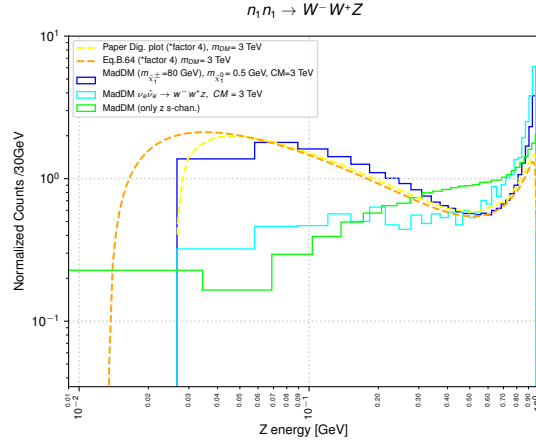


Figure 19.

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

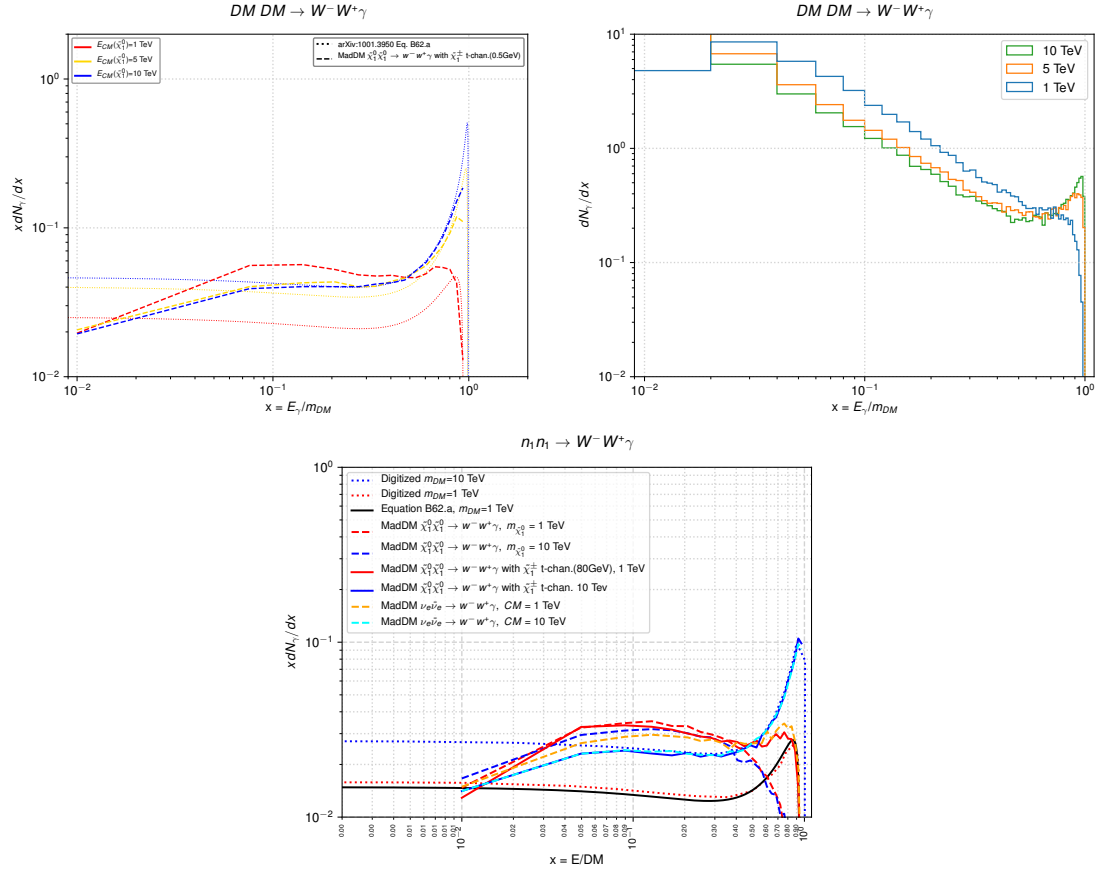


Figure 20.

10 Validation paper arXiv 1009.0224

In this section we present the validation of the results for the "Minimal Dark Matter" model introduced in [2]. 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 [2] and the results obtained with **MadDM 3.0** for the annihilation process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+ z$. 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.](#)

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.

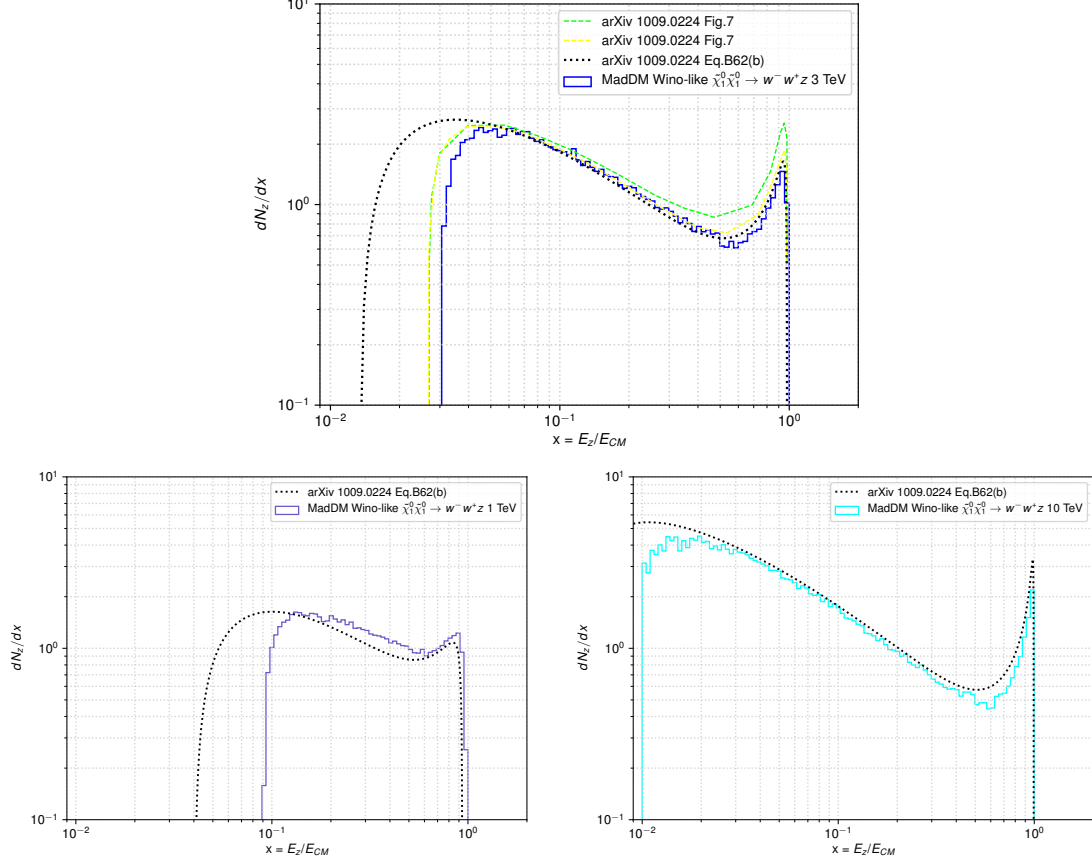


Figure 21. Validation of the `MadDM 3.0` results with the theoretical prediction from [2], using the "Minimal Dark Matter" model for Wino-like MSSM $\tilde{\chi}_1^0 - \tilde{\chi}_1^\pm$, for the process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+ z$. Upper panel: comparison for $m_{\tilde{\chi}_1^0} = 3$ TeV, the theory predictions are shown in dashed yellow and green lines (line digitized from 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. Lower panels: comparison for $m_{\tilde{\chi}_1^0} = 1$ and 10 TeV.

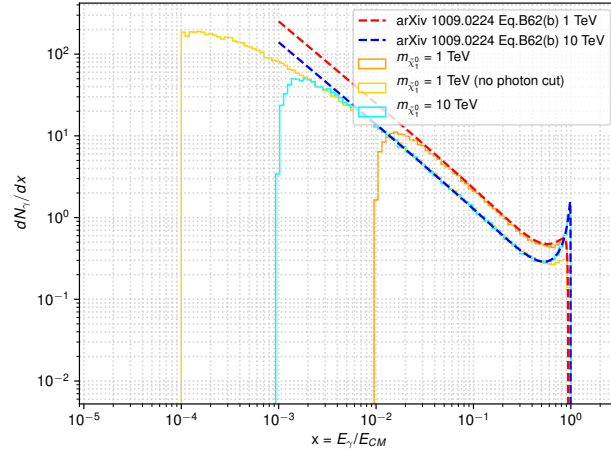


Figure 22. Same as Fig. 21 for the 3-body annihilation process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+ \gamma$. Note that the edges in the MadDM 3.0 distributions are due to the cut on the photon energy in the *run_card.dat*.

10.1 Single emission of Z boson with the minimal DM model (Wino-like LSP)

In this Section I analyse the single contribution of each process, i.e. $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+$, $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+ z$ and $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+ z z$, for $m_{\tilde{\chi}_1^0} = 1$ TeV. I set, in the param and run card, I set $m_{\tilde{\chi}_1^0} = 1$ TeV, $m_{\tilde{\chi}_1^\pm} = 1.0001$ TeV (almost mass degenerate), Ebeam = 1.0001 TeV. The emission of 3 Z bosons seems not necessary since the cross section for zz corrections is already a factor 100 smaller than the tree level. Then, I will add the emission of Higgses, photons and Ws to have the complete EW corrections; however, in the case of the DMSimp_s_spin0_EW model model in Fig. 3, there was no significant difference.

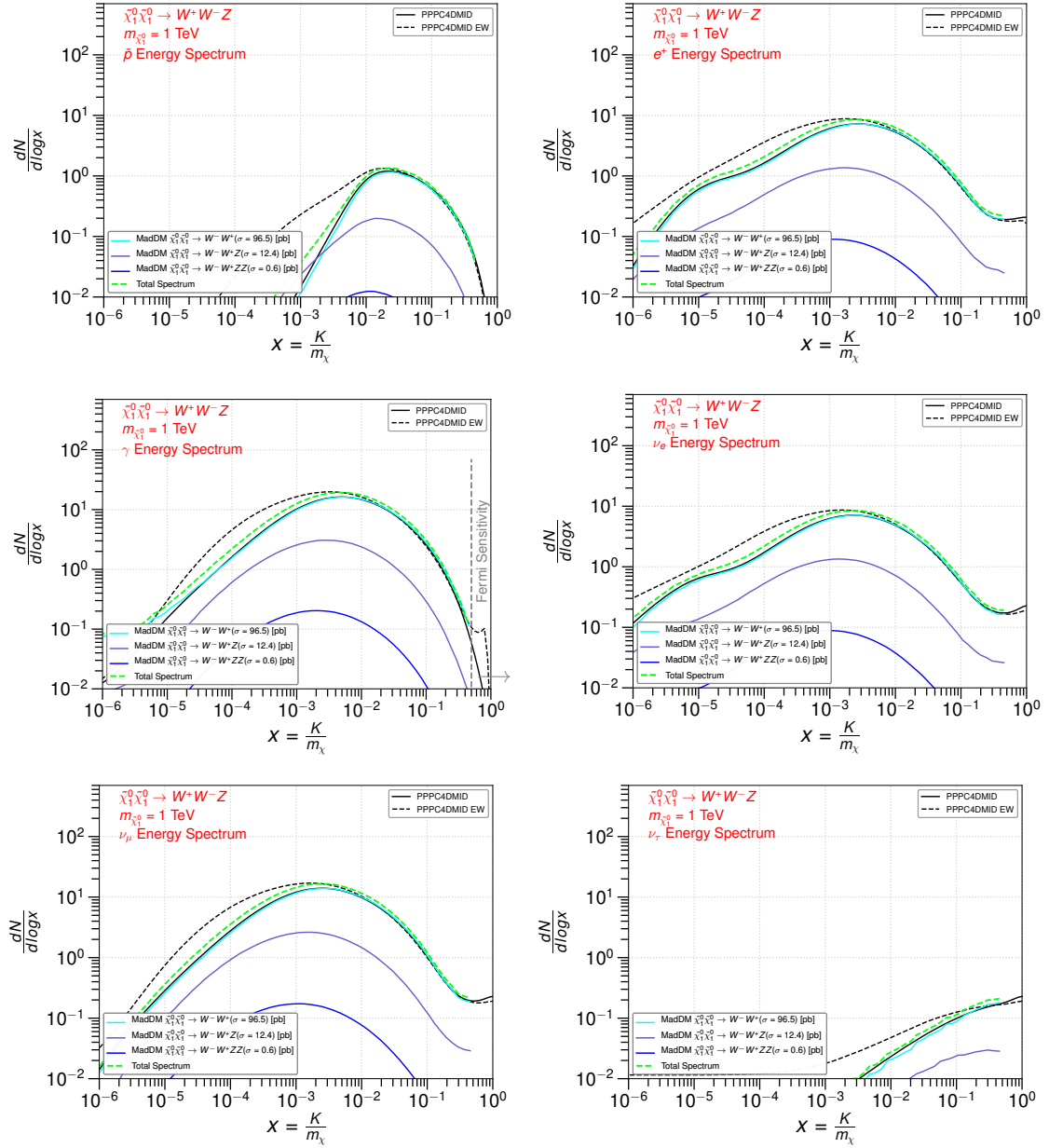


Figure 23. Emission of Z bosons in the minimal DM model (Wino-like LSP) for $m_{\tilde{\chi}_1^0} = 1$ TeV. We considered separately the processes $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+$, $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+ z$ and $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow w^- w^+ z z$. The corresponding cross section is reported in the legend, and it is used to normalize the spectrum with respect to the tree level process (since Pythia gives normalized spectra, I rescaled each process by multiplying by the ratio of the cross sections), e.g. the curve for the one z emission is rescaled by (tree level)/(one z emission). The lime line is obtained by adding the contribution of each process. Note that the PPC comparison is just for reference: the MadDM processes are not complete since the emission of photons, Higgses and Ws should also be included. Compare with Fig. 3 for the DMsimp_s_spin0_EW model.

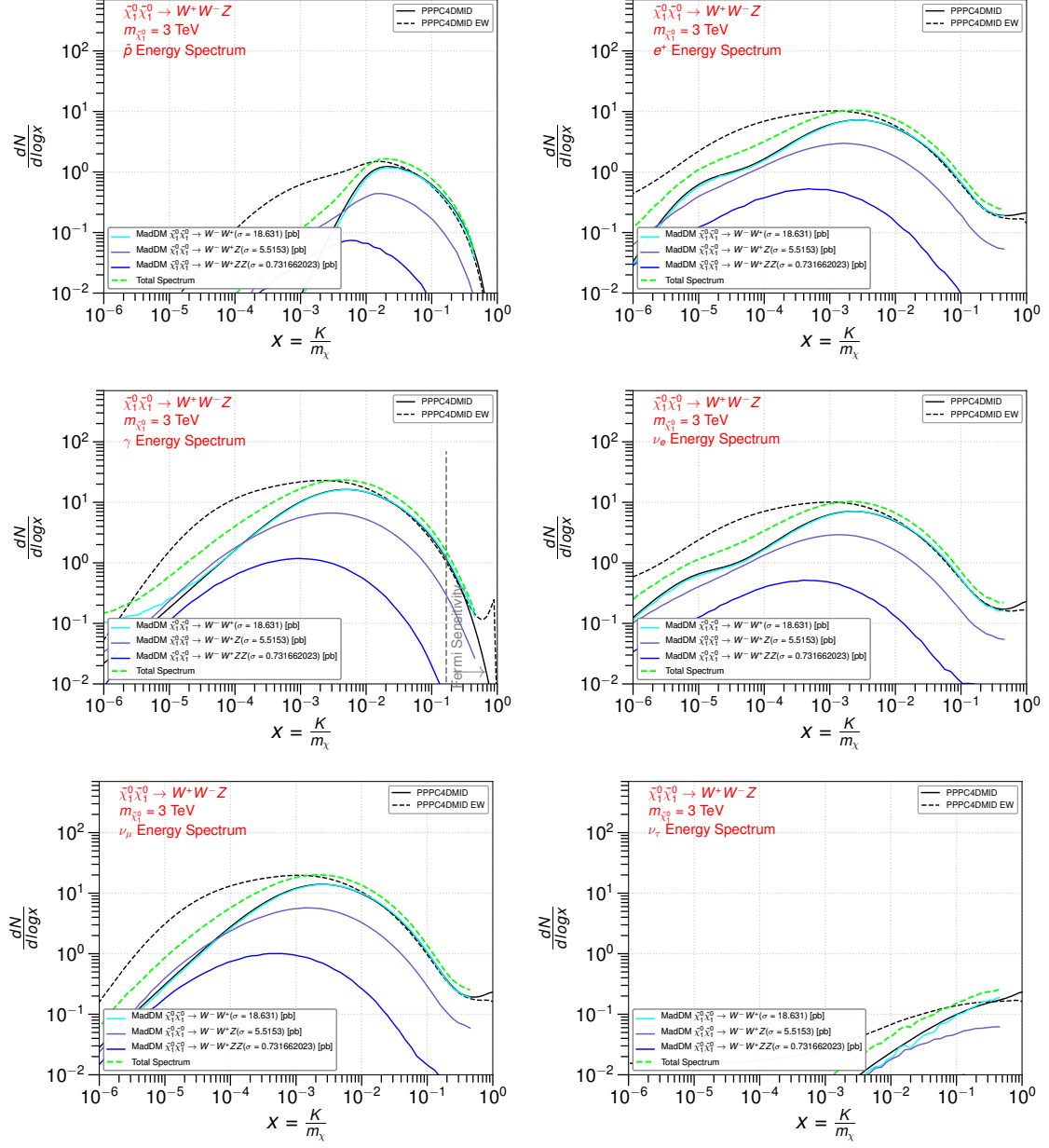


Figure 24. Same as Fig. 25 for $m_{\tilde{\chi}_1^0} = 3 \text{ TeV}$.

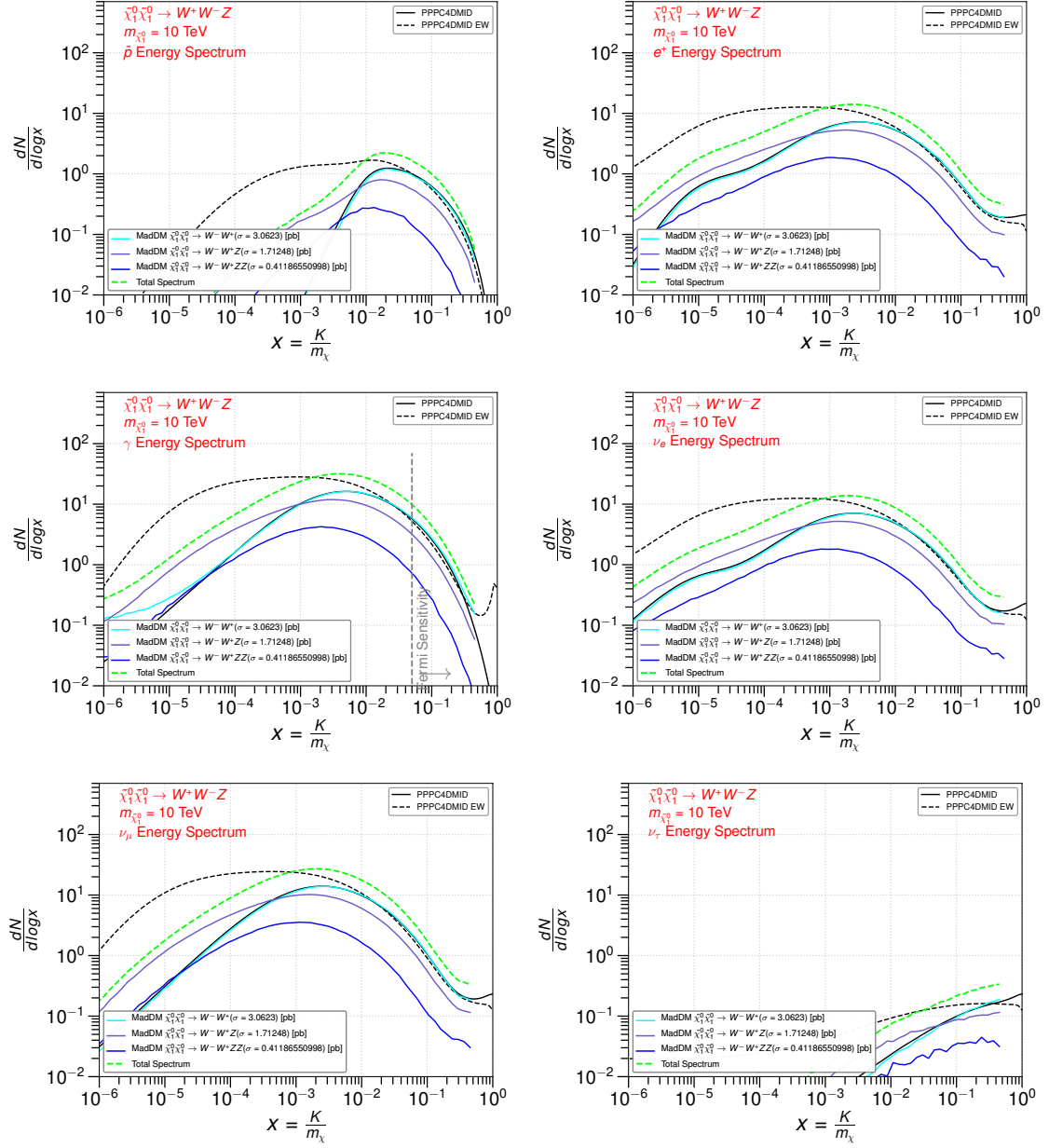


Figure 25. Same as Fig. 25 for $m_{\tilde{\chi}_1^0} = 10$ TeV.

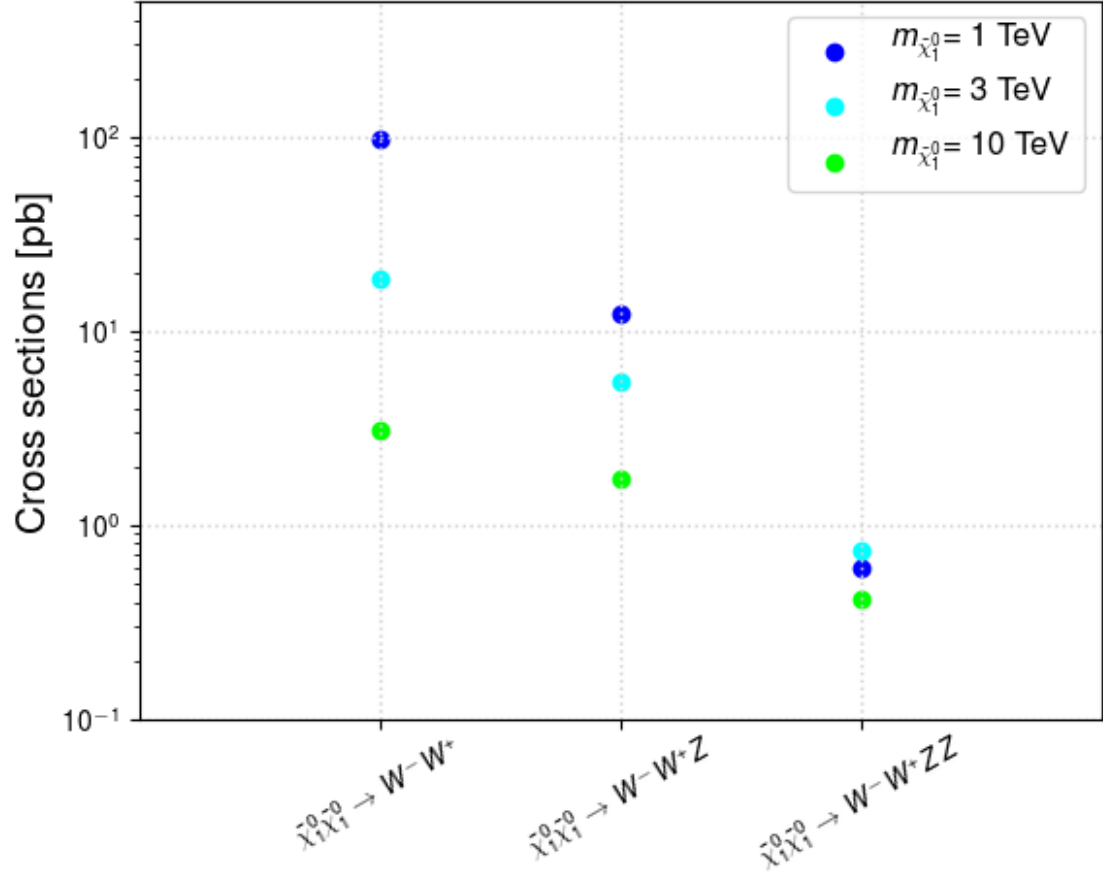


Figure 26. Cross sections for the tree-level annihilation and the emission of one and two extra Z bosons.

11 Validation Luca's plot from MadDM 3.0 paper

This is just to check that everything works fine with Luca's model and his validation.

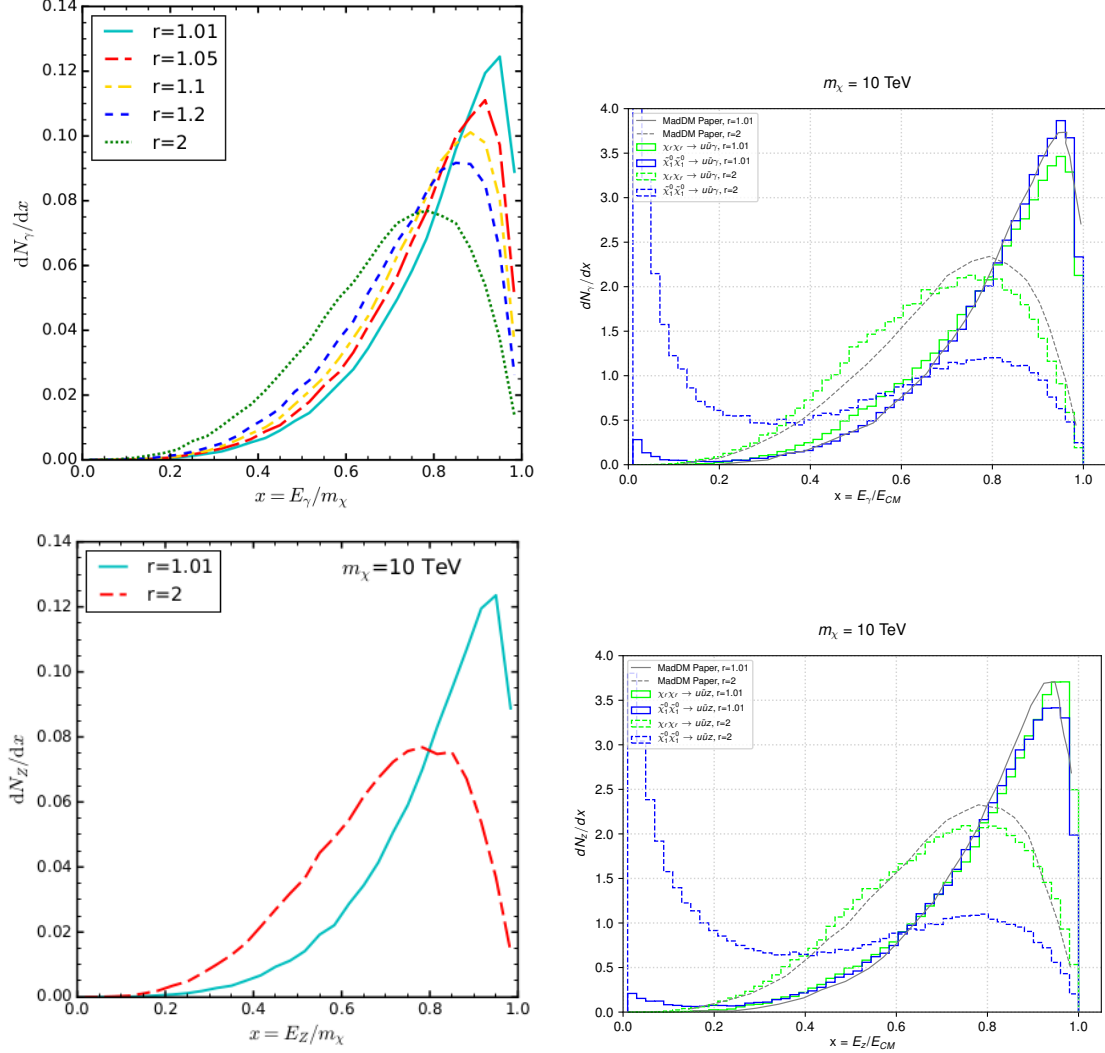


Figure 27. Validation of Luca's plots from MadDM 3.0

12 Analysis of the ElectroWeak Corrections

In this section we break down the contribution of each EW emission of bosons to the total CR spectra. We consider the emission of a single $X = z, \gamma, h$ boson. the CR spectra are presented in Fig. 28-???. Samples are generated with `MadGraph5_aMC@NL0` in the form $n1\ n1 > w^- w^+ X$ (colored dashed lines), except for the inclusive sample (solid blue line) for which the processes $n1\ n1 > w^- w^+ + n1\ n1 > w^- w^+ X$ are considered. The results are compatible with the magenta line, obtained by summing the contribution of each EW process to the tree level and rescaled by the proper cross section.

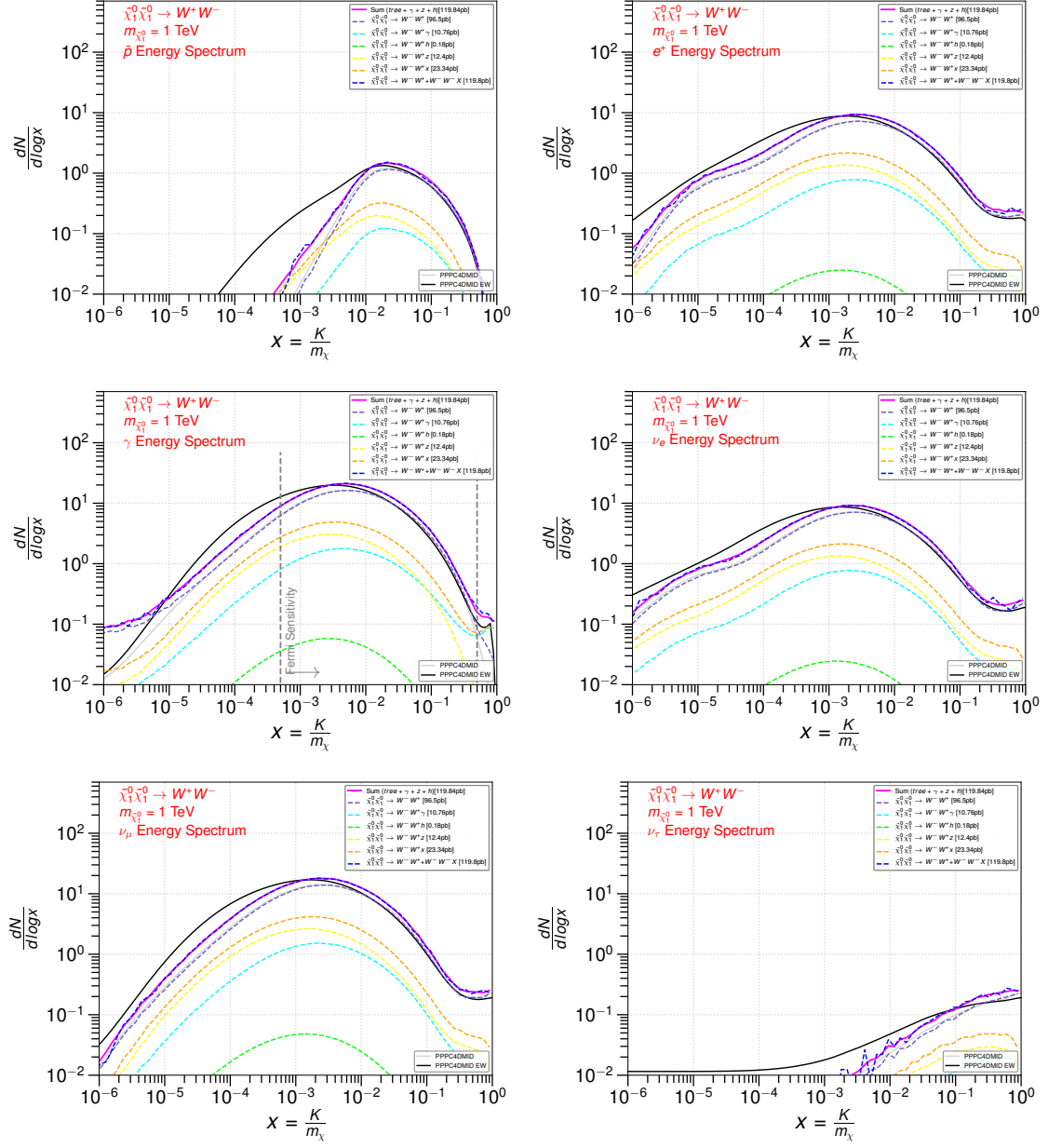


Figure 28. Contribution of the different EW processes to the CR spectra, up to the emission of one extra boson, for $m_{\tilde{\chi}_1^0} = 1$ TeV . The magenta line was obtained summing the various contribution of the extra boson to the tree level process, while for the blue dashed line the tree level and extra radiation were already generated together in MG5. In the legend, the cross section for each process is reported.

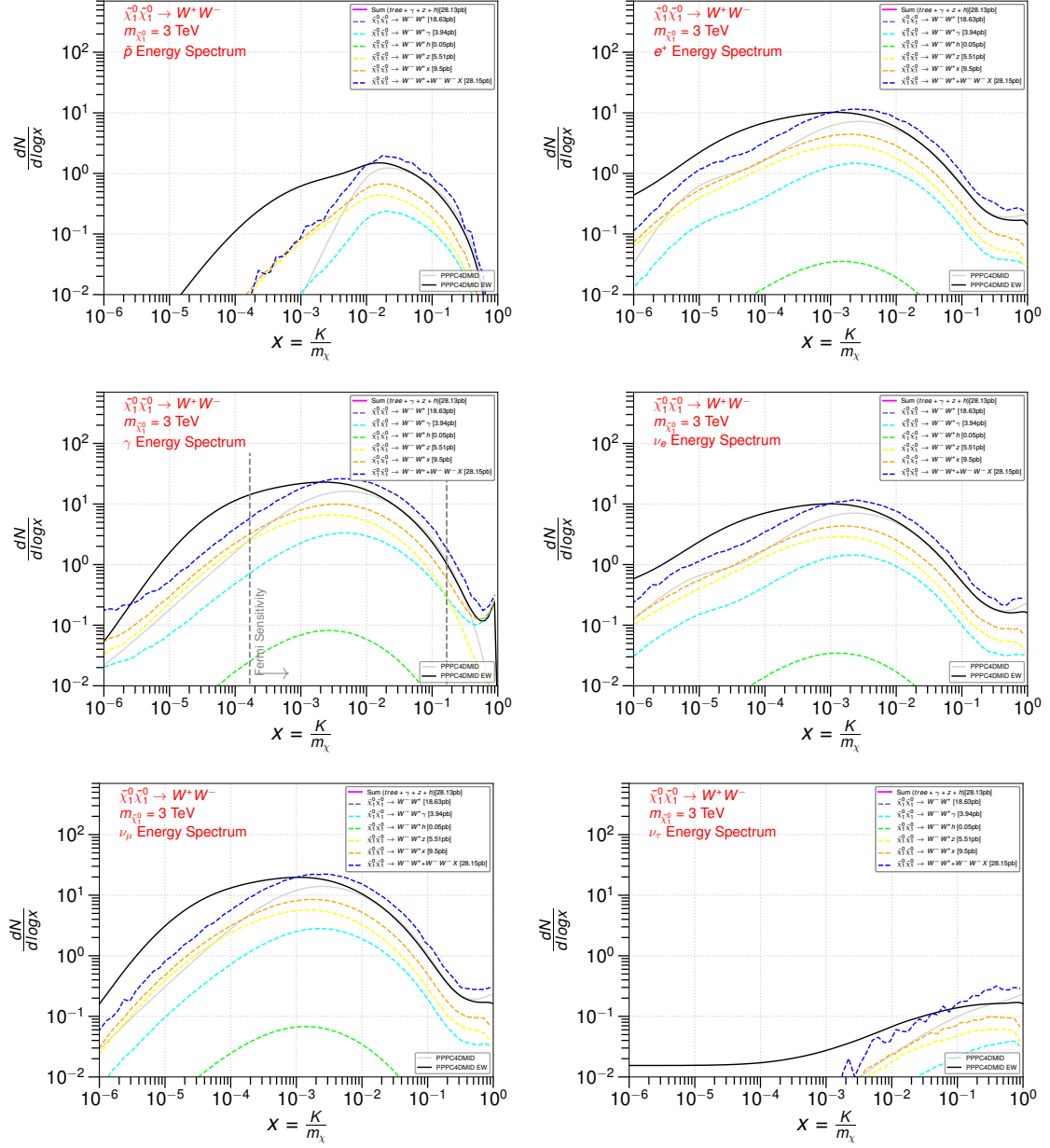


Figure 29. Contribution of the different EW processes to the CR spectra, up to the emission of one extra boson, for $m_{\tilde{\chi}_1^0} = 3$ TeV. The magenta line was obtained summing the various contribution of the extra boson to the tree level process, while for the blue dashed line the tree level and extra radiation were already generated together in MG5. In the legend, the cross section for each process is reported.

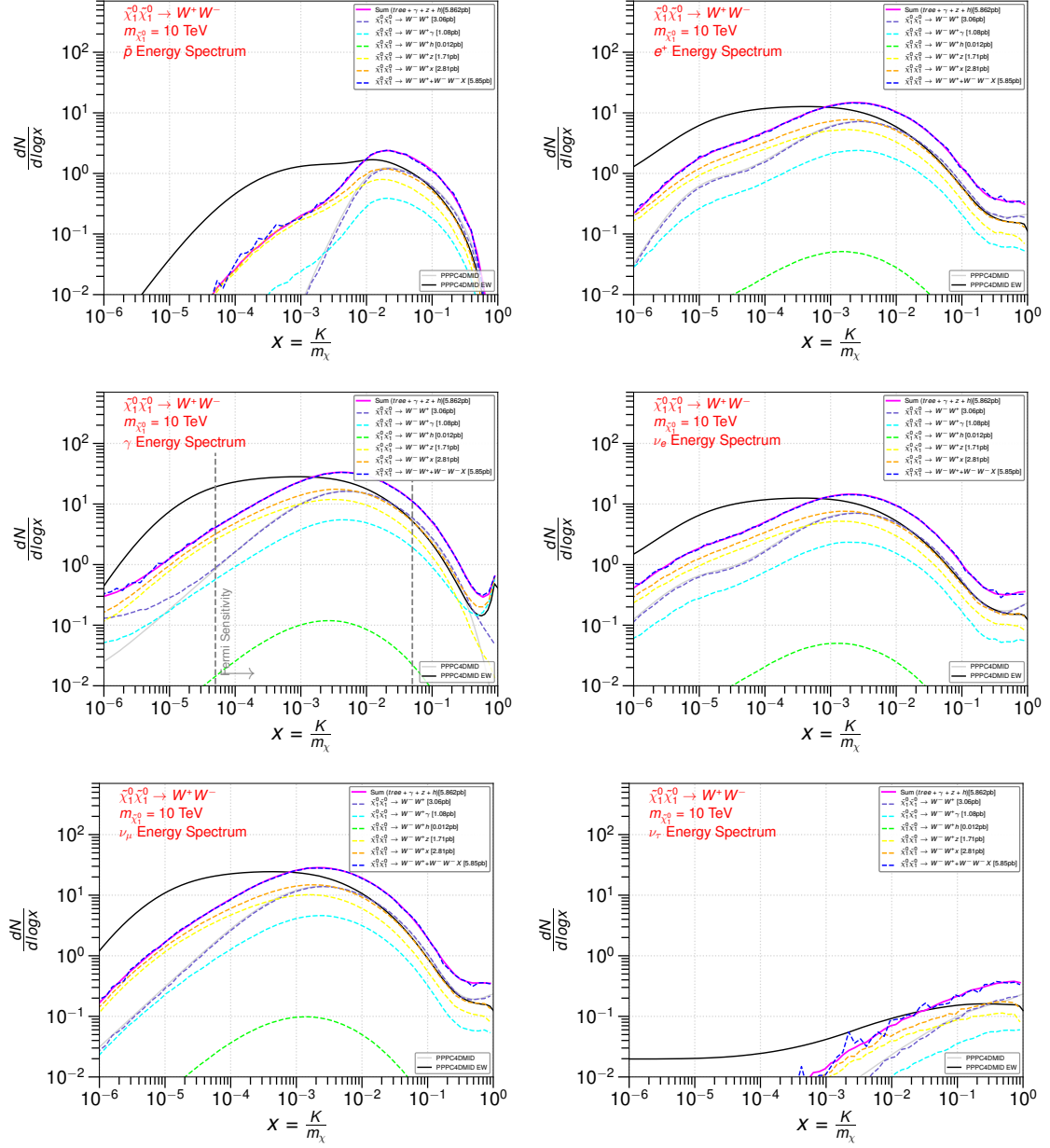


Figure 30. Contribution of the different EW processes to the CR spectra, up to the emission of one extra boson, for $m_{\tilde{\chi}_1^0} = 10$ TeV . The magenta line was obtained summing the various contribution of the extra boson to the tree level process, while for the blue dashed line the tree level and extra radiation were already generated together in MG5. In the legend, the cross section for each process is reported.

Acknowledgments

Thanks

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](#)].
- [2] P. Ciafaloni, D. Comelli, A. Riotto, F. Sala, A. Strumia, and A. Urbano, *Weak Corrections are Relevant for Dark Matter Indirect Detection*, *JCAP* **1103** (2011) 019, [[arXiv:1009.0224](#)].