1 Generating Heavy Neutral Lepton events via FeynRules and MadGraph5

The model for the event generation was taken from arxiv.org/pdf/1806.07396.pdf. It is a type-I seesaw mechanism, in which the existence of heavy sterile right-handed neutrinos is assumed. Those neutrinos have an $H\nu N$ interaction vertex, which leads to the mass mixing due to nonzero Higgs vacuum expectation value. The lagrangian (after symmetry breaking) has the form:

$$\mathcal{L}_{int} = -\frac{g}{\sqrt{2}}\bar{N}_{Ri}\theta_{ij}\gamma^{\mu}e_{Lj}W^{+}_{\mu} - \frac{g}{2\cos\theta_W}\bar{N}_{Ri}\theta_{ij}\gamma^{\mu}\nu_{Lj}Z_{\mu} - \frac{gM_{ij}}{\sqrt{2}m_W}\bar{N}_{Ri}\theta_{jk}\gamma^{\mu}\nu_{Lk}H + h.c. \tag{1}$$

where θ_{ij} is a mixing matrix, M_{ij} is the sterile neutrino mass matrix, and N_{Ri} is a sterile neutrino multiplet in the mass basis. For the simulation, the number of sterile neutrinos $N = 3$ was chosen, since it is the minimal number of generations required to give masses to all the three neutrino flavors. The model is implemented in FeynRules, a Mathematica™ package used to convert lagrangian to the set of Feynman rules. A same theory was implemented before (https://feynrules.irmp.ucl.ac.be/wiki/HeavyN), so the mixing and masses were chosen to be the same in order to test the model. Namely, θ_{ij} is an indentity matrix, neutrino masses are $300, 500$ and 1000 GeV with the widths $0.303, 1.5$ and 12.3 GeV respectively. A default standard model file http://feynrules.irmp.ucl.ac.be/attachment/wiki/StandardModel/SM.fr was used. The model was exported in the UFO format.

The model was imported to the MadGraph and a tes process with n1 (the lightest sterile neutrino in the model) was generated:

```
p p > w+ > n1 e+ , n1 > e+ mu- vm~
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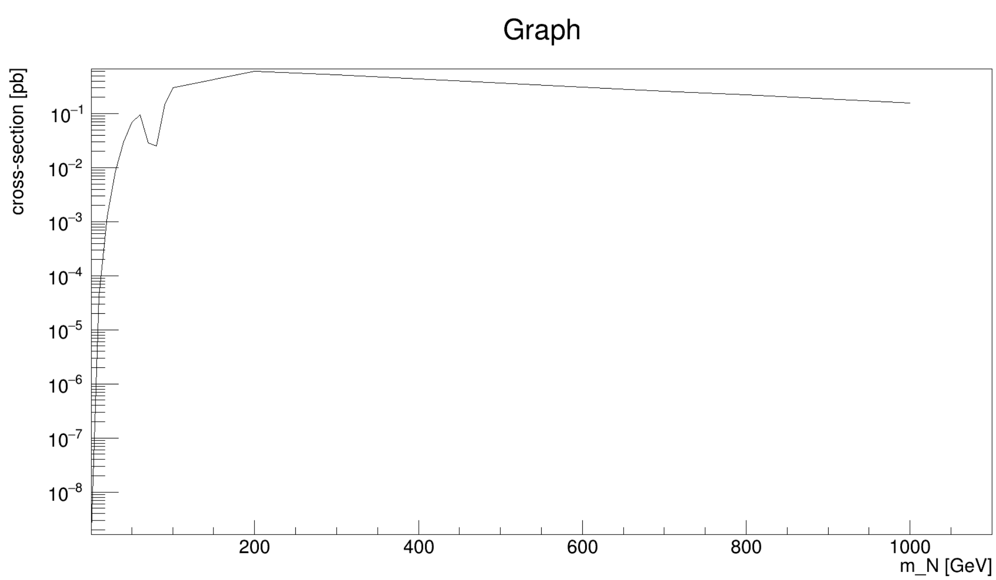
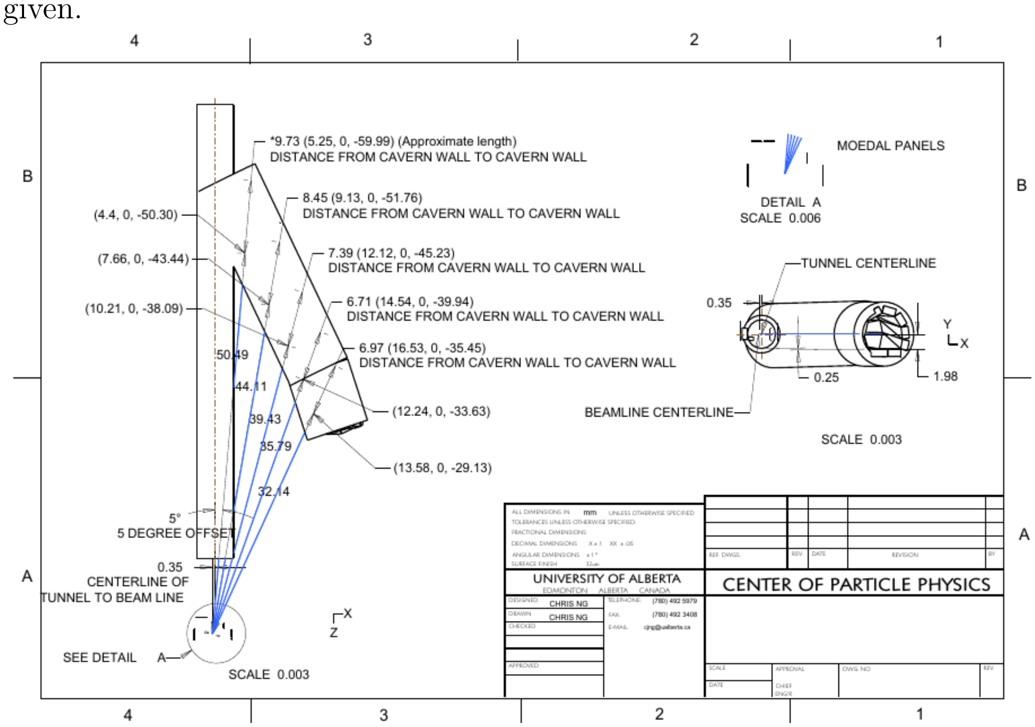
The calculated cross-section is 0.522 ± 0.002pb, which is in a perfect agreement with the test model. Then, the same process was run for different masses of $mN1$, and the cross-section was calculated. The results are:



mN1, GeV	σ, pb
1	$(1.832 \pm 0.008) \times 10^{-9}$
10	$(4.223 \pm 0.016) \times 10^{-5}$
20	$(1.25 \pm 0.006) \times 10^{-3}$
30	$(8.52 \pm 0.022) \times 10^{-3}$
40	$(3.010 \pm 0.007) \times 10^{-2}$
50	$(6.822 \pm 0.026) \times 10^{-2}$
60	$(9.559 \pm 0.035) \times 10^{-2}$
70	$(2.84 \pm 0.01) \times 10^{-2}$
80	$(2.503 \pm 0.009) \times 10^{-2}$
90	0.1473 ± 0.0005
100	0.2982 ± 0.0009
100	0.2982 ± 0.0009
200	0.6043 ± 0.0014
300	0.522 ± 0.002
400	0.4412 ± 0.0015
500	0.3694 ± 0.0013
600	0.3104 ± 0.0010
700	0.2608 ± 0.0009
800	0.2203 ± 0.0009
900	0.1856 ± 0.0005
1000	0.1564 ± 0.0005

2 Geant4 simulations of the MAPP detector

The scheme of the MAPP detector is given on the picture. There is five different places in the cave, where MAPP can be installed; the cave has a 5° downwards slope; and the positions of the edges of the detector are given.



For the simulation, the dimensions of the detector were taken as 1m x 1m x 5m, the long edges point to the origin.

The geometry is implemented using GDML - an XML scheme for Geant4 geometry. Geant 4 must be built with "-DG4LIB_BUILD_GDML=ON" flag to be able to use a GDML parser. For the simulation, air, stainless steel for the tube and rock for cave are used. Their properties were taken from http://pdg.lbl.gov/2017/AtomicNuclearProperties/. A cave is constructed using the CSG technique by subtracting tube and cave solids from the world solid.

A range of events with millicharged particles had been generated in the LHE format. For the simulations, they were converted to the HepMC format using the program located at http://rivet.hepforge.org/svn/contrib/lhef2hepmc/lhef2hepmc.cc. The simulation code is based on stock examples, **//examples/extended/eventgenerator/HepMC/** and **//examples/extended/exotic-physics/monopole/**, in which the HepMC particle generator and a user-defined particle are created.

The information about the particles is stored using the ROOT TTree class. The incoming particles are either MCPs (pdg code ±9000005) or delta-electrons (pdg code 11). All the particles of the single event are contained in separate vectors. After the run, the acceptance (i.e. ratio of events where at least one MCP entered the given detector to the total number) for each detector. The results of the calculations are given in the table:

Mass, GeV	Detector 1	Detector 2	Detector 3	Detector 4	Detector 5
0.1	0.004 %	0.006 %	0.013 %	0.016 %	0.046%
0.2	0.0061 %	0.0051 %	0.0061 %	0.0142 %	0.0456%
0.3	0.003 %	0.0061 %	0.004 %	0.0081 %	0.0383%
0.4	0.0072 %	0.0083 %	0.0083 %	0.0217 %	0.0465%
0.5	0.009 %	0.004 %	0.007 %	0.014 %	0.042%
0.6	0.004 %	0.004 %	0.0081 %	0.0121 %	0.0424%
0.7	0.0 %	0.0051 %	0.0081 %	0.0152 %	0.0515%
0.8	0.004 %	0.008 %	0.008 %	0.0131 %	0.0522%
0.9	0.004 %	0.003 %	0.0091 %	0.0211 %	0.0523%
1.0	0.003 %	0.0051 %	0.0101 %	0.0203 %	0.0436%
2.0	0.006 %	0.01 %	0.013 %	0.03 %	0.0931%
3.0	0.012 %	0.0211 %	0.0191 %	0.0451 %	0.1143%
4.0	0.0131 %	0.0221 %	0.0171 %	0.0412 %	0.1326%
5.0	0.006 %	0.019 %	0.024 %	0.05 %	0.116%
6.0	0.015 %	0.0171 %	0.0311 %	0.0331 %	0.1344%
7.0	0.013 %	0.027 %	0.025 %	0.043 %	0.1381%
8.0	0.008 %	0.024 %	0.032 %	0.0521 %	0.1512%
9.0	0.015 %	0.0291 %	0.0391 %	0.0482 %	0.1214%
10	0.0191 %	0.0232 %	0.0302 %	0.0473 %	0.145%
20	0.017 %	0.017 %	0.038 %	0.061 %	0.168%
30	0.019 %	0.021 %	0.04 %	0.064 %	0.1681%
40	0.0111 %	0.0202 %	0.0353 %	0.0677 %	0.2019%
50	0.014 %	0.018 %	0.032 %	0.0811 %	0.1661%
60	0.017 %	0.03 %	0.023 %	0.0671 %	0.1982%
70	0.026 %	0.028 %	0.035 %	0.061 %	0.1861%
80	0.013 %	0.03 %	0.037 %	0.063 %	0.178%
90	0.0261 %	0.0271 %	0.0311 %	0.0862 %	0.1733%
100	0.018 %	0.029 %	0.0451 %	0.0821 %	0.1852%

The results were compared with the previously obtained acceptances:

Mass, GeV	Detector 1	Detector 2	Detector 3	Detector 4	Detector 5
0.1	0.004 %	0.006 %	0.013 %	0.016 %	0.046%
0.2	0.0061 %	0.0051 %	0.0061 %	0.0142 %	0.0456%
0.3	0.003 %	0.0061 %	0.004 %	0.0081 %	0.0383%
0.4	0.0072 %	0.0083 %	0.0083 %	0.0217 %	0.0465%
0.5	0.009 %	0.004 %	0.007 %	0.014 %	0.042%
0.6	0.004 %	0.004 %	0.0081 %	0.0121 %	0.0424%
0.7	0.0 %	0.0051 %	0.0081 %	0.0152 %	0.0515%
0.8	0.004 %	0.008 %	0.008 %	0.0131 %	0.0522%
0.9	0.004 %	0.003 %	0.0091 %	0.0211 %	0.0523%
1.0	0.003 %	0.0051 %	0.0101 %	0.0203 %	0.0436%
2.0	0.006 %	0.01 %	0.013 %	0.03 %	0.0931%
3.0	0.012 %	0.0211 %	0.0191 %	0.0451 %	0.1143%
4.0	0.0131 %	0.0221 %	0.0171 %	0.0412 %	0.1326%
5.0	0.006 %	0.019 %	0.024 %	0.05 %	0.116%
6.0	0.015 %	0.0171 %	0.0311 %	0.0331 %	0.1344%
7.0	0.013 %	0.027 %	0.025 %	0.043 %	0.1381%
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60	0.017 %	0.03 %	0.023 %	0.0671 %	0.1982%
70	0.026 %	0.028 %	0.035 %	0.061 %	0.1861%
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90	0.0261 %	0.0271 %	0.0311 %	0.0862 %	0.1733%
100	0.018 %	0.029 %	0.0451 %	0.0821 %	0.1852%

Their ratio is:

Mass, GeV	Detector 1	Detector 2	Detector 3	Detector 4	Detector 5
0.1	2.000	6.000	2.167	1.778	0.780
0.2	2.033	2.550	1.017	0.747	0.786
0.3	0.375	0.610	2.000	0.810	0.912
0.4	1.200	1.186	1.660	1.447	1.224
0.5	1.500	0.333	0.875	0.583	0.737
0.6	0.800	0.500	1.620	0.807	0.848
0.7	0.000	1.020	0.675	0.800	0.954
0.8	1.333	1.000	0.667	1.008	1.214
0.9	0.667	0.600	0.910	1.241	0.918
1.0	0.750	0.850	1.443	2.256	0.890
2.0	0.750	1.000	0.684	0.811	1.012
3.0	1.500	2.110	1.124	1.074	0.853
4.0	1.191	1.842	0.814	1.114	0.921
5.0	0.273	1.000	0.960	1.000	0.730
6.0	1.071	0.552	1.196	0.704	0.960
7.0	0.650	1.286	0.806	1.075	1.031
8.0	0.381	0.857	0.889	0.840	1.088
9.0	0.833	1.164	1.348	0.679	0.820
10	1.124	1.221	1.079	0.910	0.890
20	0.944	0.708	0.927	0.824	0.949
30	1.267	0.724	1.000	0.955	0.761
40	0.793	0.918	1.261	1.167	1.057
50	0.933	0.947	1.000	1.142	0.810
60	1.000	1.071	0.575	1.017	0.972
70	1.368	1.167	0.854	0.859	0.846
80	0.684	1.304	0.974	0.724	0.932
90	1.631	0.934	0.622	1.181	1.070
100	0.947	1.160	0.980	1.039	1.077