Using Feynrules, Calchep and Madgraph for BSM at LHC studies

Radomir Sevillano
Katowice, Poland

Durham, 19 March 2012

Introduction: Left-Right Model

The model has been constructed in 1973-1974,

Pati, Salam, Senjanovic, Mohapatra

- Phenomenology of Left-Right symmetric models at LHC.

- Model Parametrization in Feynrules based on the paper **Quantization and Renormalization of the Manifest Left-Right Symmetric Model of Electroweak Interactions** - P. Duka, J. Gluza and M. Zralek. Annals of Physics **280**, 336-408 (2000).

- Using of Feynrules.

- Calculation of branching ratios, total widths and processes for heavy non-standard particles with Calchep & Madgraph.

Left-Right Symmetric Model

- Left-Right symmetric model is based on local gauge symmetry which extend Standard Model Gauge Group $SU(2)_L \otimes U(1)_Y$ to $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

- Left-Right model is able to solve some unanswered SM's problems:

❖ Small masses of light neutrinos.

❖ Physical interpretation of the standard U(1) generator as the B-L quantum number:

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}.$$

❖ Charge quantization.

❖ Understanding of the smallness of CP violation in the quark sector.

❖ Solution of the strong CP problem.

Fermion and Gauge Fields

$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge group restores lepton-quark symmetry to the weak interactions:

$$L_{iL} = \begin{pmatrix} \nu_i' \\ l_i' \end{pmatrix}_L , L_{iR} = \begin{pmatrix} \nu_i' \\ l_i' \end{pmatrix}_R ,$$

$$Q_{iL} = \begin{pmatrix} u_i' \\ d_i' \end{pmatrix}_L , Q_{iR} = \begin{pmatrix} u_i' \\ d_i' \end{pmatrix}_R ,$$

Higgs multiplets: Bidoublet & Triplet

The minimal Higgs sector consists of one bidoublet

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

and two triplets

$$\Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix}$$

$$M_{W_{1,2}}^2 = \frac{g^2}{4}[\kappa_+^2 + v_R^2 \mp \sqrt{v_R^4 + 4\kappa_1^2\kappa_2^2}], \kappa_+ = \sqrt{\kappa_1^2 + \kappa_2^2}$$

with VEV allowed for the neutral particles

$$< \phi >= \begin{pmatrix} \kappa_1/\sqrt{2} & 0 \\ 0 & \kappa_2/\sqrt{2} \end{pmatrix}, < \Delta_{L,R} >= \begin{pmatrix} 0 & 0 \\ v_{L,R}/\sqrt{2} & 0 \end{pmatrix},$$

Unphysical $->$ physical fields

• Minimalization of the scalar potential gives 20 real scalar fields, of which 14 are physical
(the rest are Goldstone bosons):

- 4 neutral scalars: H_0^0 ,H_1^0, H_2^0, H_3^0,
  (the first can be considered to be the light Higgs of the SM at tree level),

- 2 neutral pseudo-scalars: A_1^0, A_2^0,

- 2 charged scalars: $H_1^{\pm}, H_2^{\pm}$,

- 2 doubly-charged scalars: $H_1^{\pm\pm}, H_2^{\pm\pm}$.

• see-saw mechanism for the generation of light neutrino masses, with specific SB sectors. The neutrino mass matrix

$$M_\nu = \begin{pmatrix} M_L(v_L) & M_D(\kappa_{1,2}) \\ M_D^T & M_R(v_R) \end{pmatrix}$$

with $M_L \ll M_D \ll M_R$.

$$\begin{aligned} m_N &\sim M_R = \sqrt{2} h_M v_R \sim v_R \\ m_{\text{light}} &\sim M_D^2 / M_R \sim 1/v_R \end{aligned}$$

$$\phi_2^0 = \frac{1}{\sqrt{2}\kappa_+}[H_0^0(\kappa_2 a_0 + \kappa_1 b_0) + H_1^0(\kappa_2 a_1 + \kappa_1 b_1)$$
$$+ H_2^0(\kappa_2 a_2 + \kappa_1 b_2) - i\kappa_2 \tilde{G}_1^0 - i\kappa_1 A_1^0],$$

$$\begin{pmatrix} \phi_-^{or} \\ \phi_+^{or} \\ \delta_R^{or} \end{pmatrix} = \begin{pmatrix} a_0 & a_1 & a_2 \\ b_0 & b_1 & b_2 \\ c_0 & c_1 & c_2 \end{pmatrix} \begin{pmatrix} H_0^0 \\ H_1^0 \\ H_2^0 \end{pmatrix},$$

$$\begin{pmatrix} G_1^o \\ \\ G_2^o \end{pmatrix} \equiv \begin{pmatrix} \cos\psi_n & \sin\psi_n \\ & \\ \sin\psi_n & -\cos\psi_n \end{pmatrix} \begin{pmatrix} \tilde{G}_1^o \\ \\ \tilde{G}_2^o \end{pmatrix},$$

$$\cos\psi_n = -\frac{g\kappa_+}{2M_{Z_1}\cos\Theta_W}\left(\cos\phi + \sqrt{\cos 2\Theta_W}\sin\phi\right),$$
$$\sin\psi_n = -\frac{1}{M_{Z_1}}\cot\Theta_W v_R g' \sin\phi.$$

Gauge boson mass matrices diagonalized & mixing angles:

$$\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} cos\xi & sin\xi \\ -sin\xi & cos\xi \end{pmatrix} \begin{pmatrix} W_1^{\pm} \\ W_2^{\pm} \end{pmatrix},$$

$$\begin{pmatrix} W_{3L} \\ W_{3R} \\ B \end{pmatrix} = \begin{pmatrix} c_W c & c_W s & s_W \\ -s_W s_M c - c_M s & -s_W s_M s + c_M c & c_W s_M \\ -s_W c_M c + s_M s & -s_W c_M s - s_M c & c_W c_M \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \\ A \end{pmatrix}$$

$$\tan 2\xi = -\frac{2\kappa_1 \kappa_2}{v_R^2}, \quad s \to \sin 2\phi = -\frac{g^2 \kappa_+^2 \sqrt{\cos 2\Theta_W}}{2\cos^2\Theta_W \left(M_{Z_2}^2 - M_{Z_1}^2\right)}.$$

Masses of the physical gauge bosons:

$$M^2_{W_{1,2}} = \frac{g^2}{4}[\kappa_+^2 + v_R^2 \mp \sqrt{v_R^4 + 4\kappa_1^2\kappa_2^2}],$$

$$M^2_{Z_{1,2}} = \frac{1}{4}([g^2\kappa_+^2 + 2v_R^2(g^2 + g'^2)]$$
$$\mp\sqrt{[g^2\kappa_+^2 + 2v_R^2(g^2 + g'^2)]^2 - 4g^2(g^2 + 2g'^2)\kappa_+^2 v_R^2}),$$

Approximations of the masses

$$M^2_{W_1} \simeq \frac{g^2}{4}\kappa_+^2\left(1-\frac{(\kappa_1\kappa_2)^2}{\kappa_+^2 v_R^2}\right), \quad M^2_{W_2} \simeq \frac{g^2 v_R^2}{2},$$

$$M^2_{Z_1} \simeq \frac{g^2\kappa_+^2}{4\cos^2\Theta_W}\left(1-\frac{\cos^2 2\Theta_W \kappa_+^2}{2\cos^4\Theta_W v_R^2}\right),$$

$$M^2_{Z_2} \simeq \frac{v_R^2 g^2\cos^2\Theta_W}{\cos 2\Theta_W},$$

satisfied only if $v_R >> \kappa_+ = \sqrt{\kappa^2+\kappa_2^2}$

Fermion-Gauge interaction

$$L_f = \sum_{\Psi=(Q),(L)} \bar{\Psi}_L \gamma^\mu \left(i\partial_\mu + g_L \frac{\vec{\tau}}{2} \vec{W}_{L\mu} + g' \frac{Y}{2} B_\mu \right) \Psi_L + (L \to R) \,.$$

$$\begin{aligned} D_\mu \Psi_L &= \left(\partial_\mu - i g_L \frac{\vec{\tau}}{2} \vec{W}_{L\mu} - i g' \frac{Y}{2} B_\mu \right) \Psi_L, \\ D_\mu \Psi_R &= \left(\partial_\mu - i g_R \frac{\vec{\tau}}{2} \vec{W}_{R\mu} - i g' \frac{Y}{2} B_\mu \right) \Psi_R, \end{aligned}$$

Feynman rule calculation

```
LLR= LYukawa+LHiggs+LFermions+LGauge

FeynmanRules[LLR, FlavorExpand -> True]

Starting Feynman rule calculation.

Collecting the different structures that enter the vertex...

Found 2083 possible non zero vertices.

Start calculating vertices...
```

2083 vertices obtained.

```
CheckMassSpectrum[LLR]

Neglecting all terms with more than 2 particles.
All mass terms are diagonal.

CheckKineticTermNormalisation[LLR, FlavorExpand -> True]

Expanding flavors...
All kinetic terms are diagonal.
Expanding flavors...
All kinetic terms are correctly normalized.
True
```

W_1 & W_2 vertices with leptons and heavy neutrinos

```
Particle 1 : Dirac , e
Particle 2 : Majorana , RN1
Particle 3 : Vector , W1
Vertex:
```

$$\frac{i * \mathsf{Cxi} * \mathsf{Stn}_1 * g_L * \gamma^{\mu_3}.P_{-\mathsf{s}_2,\mathsf{s}_1}}{\sqrt{2}} - \frac{i * \mathsf{Ctn}_1 * \mathsf{Sxi} * g_R * \gamma^{\mu_3}.P_{+\mathsf{s}_2,\mathsf{s}_1}}{\sqrt{2}}$$

```
Particle 1 : Dirac , e
Particle 2 : Majorana , RN1
Particle 3 : Vector , W2
Vertex:
```

$$\frac{i * \mathsf{Stn}_1 * \mathsf{Sxi} * g_L * \gamma^{\mu_3}.P_{-\mathsf{s}_2,\mathsf{s}_1}}{\sqrt{2}} + \frac{i * \mathsf{Ctn}_1 * \mathsf{Cxi} * g_R * \gamma^{\mu_3}.P_{+\mathsf{s}_2,\mathsf{s}_1}}{\sqrt{2}}$$

Neutrino mixing angles

$$M_\nu = \begin{pmatrix} 0 & M_D(\kappa_{1,2}) \\ M_D^T & M_R(v_R) \end{pmatrix}$$

$$M_D = \begin{pmatrix} M_D[1] & 0 & 0 \\ 0 & M_D[2] & 0 \\ 0 & 0 & M_D[3] \end{pmatrix} M_R = \begin{pmatrix} M_R[1] & 0 & 0 \\ 0 & M_R[2] & 0 \\ 0 & 0 & M_R[3] \end{pmatrix}$$

$$tn1 \equiv \theta_1 = \arctan[\frac{(2\frac{M_D[1]}{M_R[1]})}{(1+\sqrt{1+4(\frac{M_D[1]}{M_R[1]})^2})}]$$

Z_2 - RN1 - RN1 vertex in Feynrules

```
Particle 1 : Vector , Z2
Particle 2 : Majorana , RN1
Particle 3 : Majorana , RN1
Vertex:
```

$$\gamma^{\mu_1}.\gamma^5{}_{\mathrm{s}_2,\mathrm{s}_3}\Big(-\frac{1}{2}i\mathsf{SphiStn}_1^2 c_w g_L + \frac{1}{2}i\mathsf{cmCphiCtn}_1^2 g_R + \frac{1}{2}i\mathsf{cmCtn}_1^2\mathsf{Sphi}g_p s_w$$
$$-\frac{1}{2}i\mathsf{cmSphiStn}_1^2 g_p s_w + \frac{1}{2}i\mathsf{CphiCtn}_1^2\mathsf{sm}g_p - \frac{1}{2}i\mathsf{CphismStn}_1^2 g_p - \frac{1}{2}i\mathsf{Ctn}_1^2\mathsf{smSphi}g_R s_w\Big)$$

$$cm = \frac{\sqrt{\cos 2\Theta_W}}{\cos\Theta_W}, \quad sm = tg\Theta_W, \quad Ctn1 = \cos\theta_1, Stn1 = \sin\theta_1$$

Z_1 - light - heavy neutrino vertex

Particle 1 : Majorana , RN1

Particle 2 : Majorana , ve

Particle 3 : Vector , Z1

Vertex:

$$\gamma^{\mu_3}.\gamma^5{}_{\mathsf{s}_1,\mathsf{s}_2}(-\frac{1}{2}i\mathsf{CphiCtn}_1\mathsf{Stn}_1 c_w g_L - i\mathsf{cmCphiCtn}_1\mathsf{Stn}_1 g_p s_w$$
$$-\frac{1}{2}i\mathsf{cmCtn}_1\mathsf{SphiStn}_1 g_R - \frac{1}{2}i\mathsf{CphiCtn}_1\mathsf{smStn}_1 g_R s_w + i\mathsf{Ctn}_1\mathsf{smSphiStn}_1 g_p)$$

C-symmetry, example

```
Particle 1 : Scalar , a10
Particle 2 : Vector , W1
Particle 3 : Vector , W2
Vertex:
```

$$-\frac{\mathrm{Cxi}^2\kappa_1^2 g_L g_R \eta_{\mu_2,\mu_3}}{2\kappa_+}-\frac{\mathrm{Cxi}^2\kappa_2^2 g_L g_R \eta_{\mu_2,\mu_3}}{2\kappa_+}-\frac{\kappa_1^2\mathrm{Sxi}^2 g_L g_R \eta_{\mu_2,\mu_3}}{2\kappa_+}-\frac{\kappa_2^2\mathrm{Sxi}^2 g_L g_R \eta_{\mu_2,\mu_3}}{2\kappa_+}$$

present couplings:

$$i * A_1^0 * (W_1^+ W_2^- - W_1^- W_2^+)$$

but no vertices:

$$i * A_1^0 * W_1^+ W_1^-$$

and

$$i * A_1^0 * W_2^+ W_2^-$$

Results: Calchep & Madgraph

Calchep

```
WriteCHOutput[LFermions + LGauge + LScalar + LYukawa,
MaxExpressionLength -> 1654, MaxParticles -> 3]
```

```
Calculating Feynman rules for L1
Starting Feynman rule calculation for L1.
Neglecting all terms with more than 4 particles.
Expanding indices...
Expanding flavors...
Collecting the different structures that enter the vertex...
Found 1309 possible non zero vertices.
Start calculating vertices...
ProgressIndicatorBox[Dynamic[PRIVATE‘progress$11474]]\)
```

```
1309 vertices obtained.
```

Madgraph

```
WriteUFO[LFermions + LGauge + LScalar + LYukawa, FlavorExpand
-> True]

 --- Universal FeynRules Output (UFO) v 0.1 ---

Starting Feynman rule calculation.

Collecting the different structures that enter the vertex...

Found 1309 possible non zero vertices.

Start calculating vertices...



1309 vertices obtained.
```

Tools used

- Calchep: only with the Feynrules version 1.4.9 (issues with 1.6 version)

- Madgraph 5: with Feynrules version 1.6

- Scripts for generation (blind in calchep) and processing of data (Bash)

Results: Calchep & Madgraph

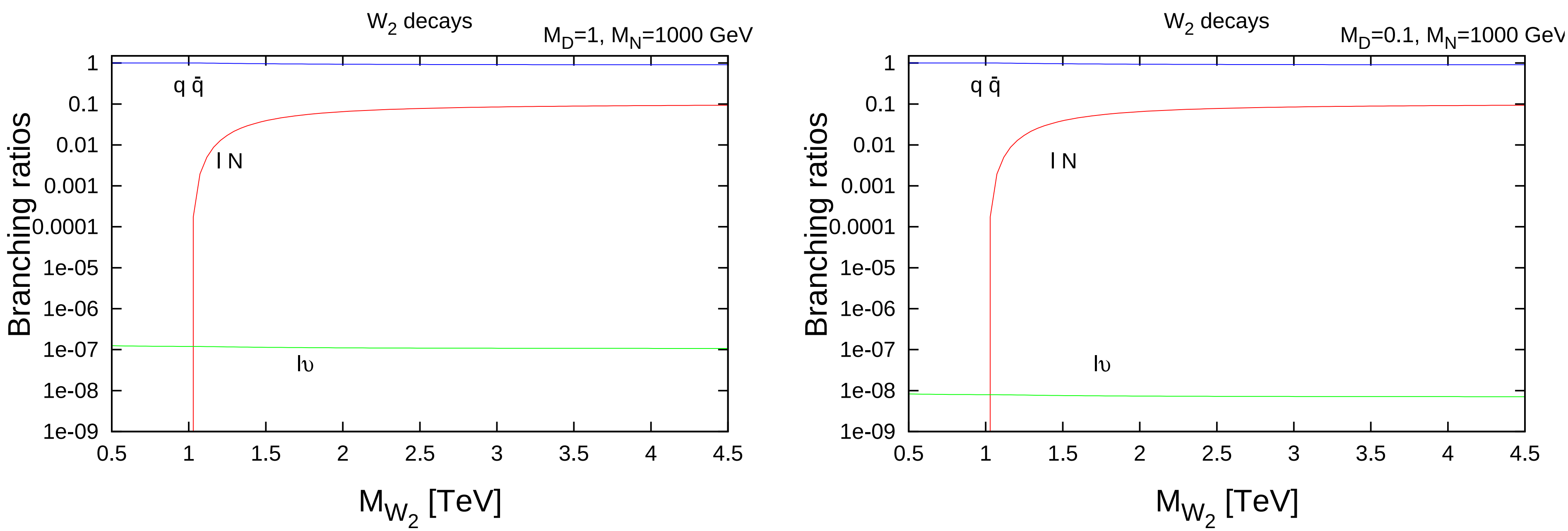

Figure 1: Branching ratios of W_2^+ to the sum of quarks, leptons, Higgs and heavy bosons for $M_D = 1 \& M_D = 0.1$

Z_2 decays

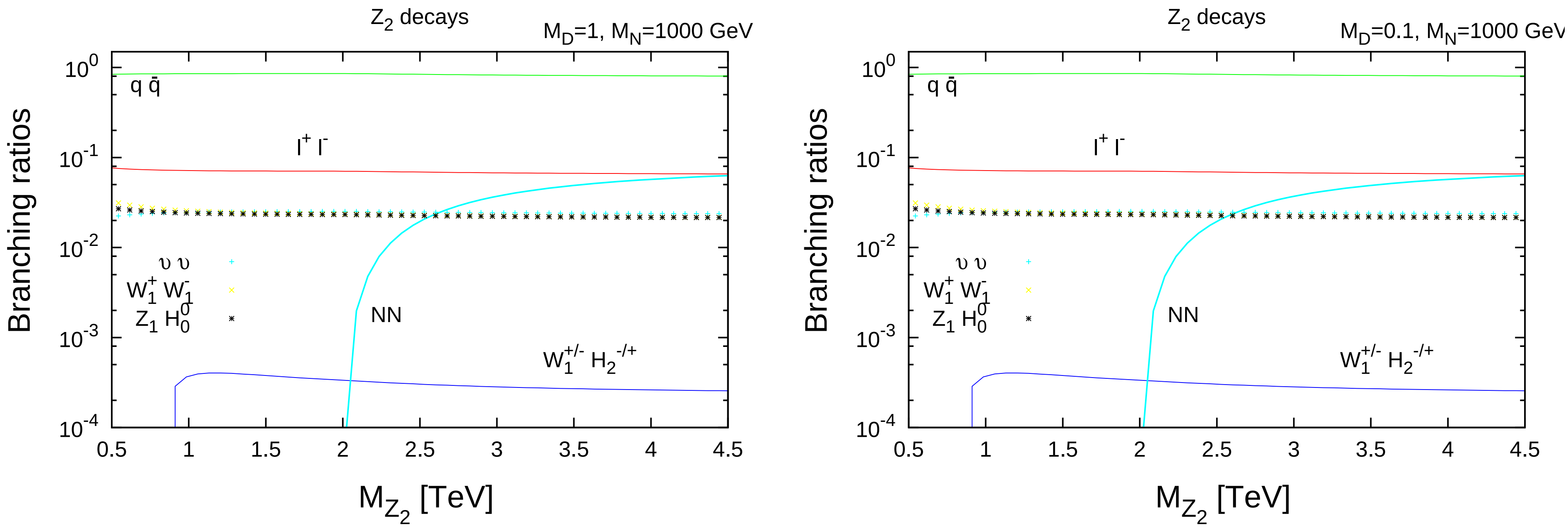

Figure 2: Branching ratios of Z_2 to the sum of quarks, leptons, Higgs and heavy bosons for $M_D = 1 \& M_D = 0.1$

N_1 decays

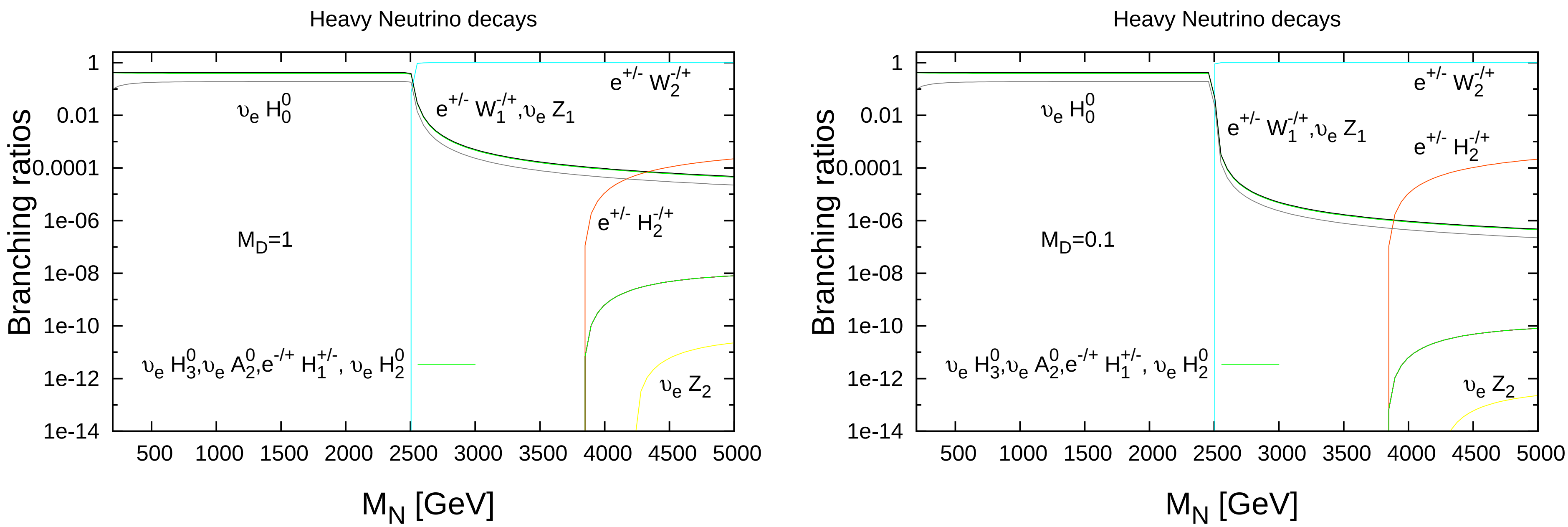

Figure 3: Branching ratios of N_1 to the sum of leptons, Higgs and heavy bosons for $M_D = 1 \& M_D = 0.1$

Total Width of N_1

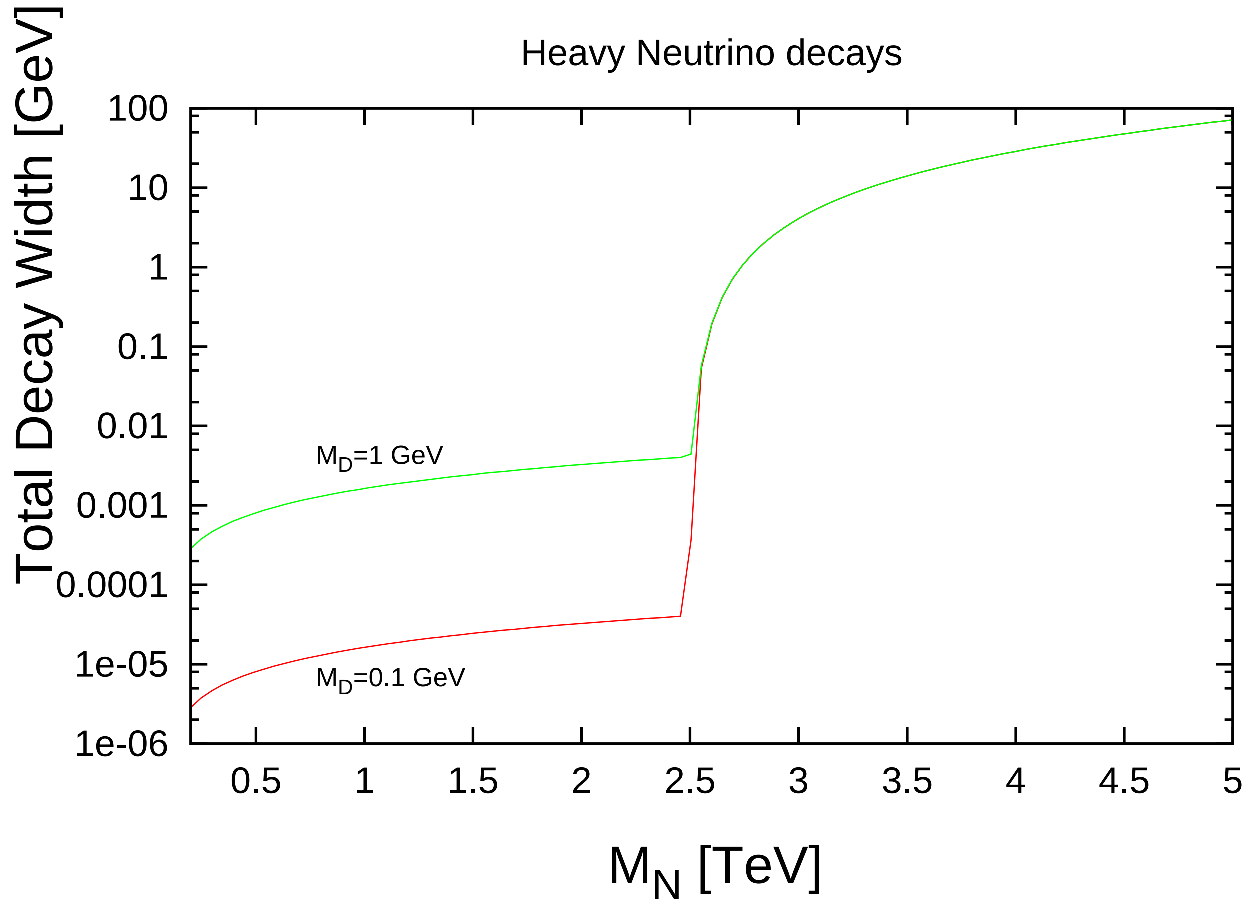

Figure 4: Total width of N_1

Conclusions:

- Our model has been tested and is complete, including Higgs sector, so can be used in one-loop calculations for LHC phenomenology using for example Madgraph or GoSam.

- Physical phenomenology of L-R model at LHC will be given in a talk by Robert Szafron.