The Type I Seesaw Mechanism and Displaced Vertices at the LHC

Alexander Moreno Briceño

Universidad Antonio Nariño

In collaboration with
A. Gago, P. Hernández, J. Jones-Pérez and M. Losada

Laboratoire Charles Coulomb (L2C)
Université de Montpellier

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Introduction

We study the minimal 3+2 neutrino model (minimal in the sense that is the minimal model beyond the Standard Model that explains the neutrino masses) in scenarios where the singlets have masses at the GeV scale. This can lead to Higgs decays into heavy neutrinos, which would be observable at the LHC. What are the implications of this?:

- We would be observing new neutral fermions,
- the Higgs coupling to light and heavy neutrinos would suggest the seesaw mechanis is at work,
- the size of the couplings, along with the "lightness" of the heavy masses would suggest the existence of an approximate lepton-number symmetry
- and this can be further correlated to future measurements of lepton flavor violating processes.

Introduction (cont'd)

The most general Lagrangian, which consists of the addition of $n + n'$ fermion gauge singlets, N_i, to the SM particle content without imposing lepton number conservation, is given by:

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kin} - Y_{\alpha i} \bar{N}_i \hat{\phi}^\dagger L_\alpha - \frac{1}{2} \bar{N}_i M_{ij} N_j^c + h.c.$$

After EWSB, the seesaw mass matrix

$$M = \begin{pmatrix} 0 & m_Y \\ m_Y^T & M_N \end{pmatrix}$$

and

$$m \sim \frac{m_Y^T m_Y}{M}$$

$$m \sim Y^2 \frac{\upsilon^2}{M}$$

and, therefore, for $M \sim GeV$, $Y^2 \sim 10^{-12}$, which is too small to measure.

Introduction (cont'd)

In the minimal 3+2 neutrino model, an approximate $U(1)_L$ symmetry could be assumed and this naive scaling does not work: Y and flavour effects can be large. This requires quasi-degenerate heavy neutrinos.

The structure of the mass matrix is approximately

$$\begin{pmatrix} 0 & Y & \epsilon \\ Y & \epsilon & M \\ \epsilon & M & \epsilon \end{pmatrix}.$$

Neutrino masses are supressed with ϵ but Y can be large.

The degeneracy can be lifted in the so-called extended seesaw

$$\begin{pmatrix} 0 & Y & \epsilon \\ Y & \mu & M \\ \epsilon & M & \epsilon \end{pmatrix},$$

which also leads to $m \sim \epsilon$ for an arbitrary μ (the degeneracy of the heavy states is controlled by μ, which is not small in this case) but only at tree level.

J. Lopez-Pavon, S. Pascoli and Chan-fai Wong, Phys. Rev. D87 (2013) 9, 093007 [arXiv:1209.5342[hep-ph]]

The Minimal 3+2 Neutrino Model: Normal and Inverted Hierarchies

For the normal hierarchy, the 5×5 neutrino mass matrix in diagonal form is defined through:

$$\mathcal{M}_\nu = U^\star diag(0, m_2, m_3, M_1, M_2) U^\dagger .$$

U can be decomposed into four blocks

$$U = \begin{pmatrix} U_{al} & U_{ah} \\ U_{sl} & U_{sh} \end{pmatrix}$$

and each block in the following way:

$$U_{al} = U'_{PMNS} \begin{pmatrix} 1 & 0 \\ 0 & H \end{pmatrix}, \qquad U_{ah} = iU'_{PMNS} \begin{pmatrix} 0 \\ H m_l^{1/2} R^\dagger M_h^{-1/2} \end{pmatrix},$$

$$U_{sl} = i \begin{pmatrix} 0 & \bar{H} M_h^{-1/2} R m_l^{1/2} \end{pmatrix}, \qquad U_{sh} = \begin{pmatrix} \bar{H} \end{pmatrix},$$

A. Donini et al., JHEP 1207 (2012) 161[arXiv:1205.5230[hep-ph]]

where

$$M_h = diag(M_1, M_2),$$

$$m_l = diag(m_2, m_3) = diag(\sqrt{\Delta m^2_{sol}}, \sqrt{\Delta m^2_{atm}}),$$

$$H = (I + m_l^{1/2} R^\dagger M_h^{-1} R m_l^{1/2})^{-1/2},$$

$$\bar{H} = (I + M_h^{1/2} R m_l R^\dagger M_h^{1/2})^{-1/2}$$

and

$$R = \begin{pmatrix} \cos(\theta_{45} + i\gamma_{45}) & \sin(\theta_{45} + i\gamma_{45}) \\ -\sin(\theta_{45} + i\gamma_{45}) & \cos(\theta_{45} + i\gamma_{45}) \end{pmatrix}.$$

The model is then described by 11 parameters: 3 mixing angles and 2 CPV phases from the UPMNS matrix, 2 non-zero light neutrino masses, 2 heavy neutrino masses and a complex angle participating in active-heavy neutrino mixing.

A. Donini et al., JHEP 1207 (2012) 161[arXiv:1205.5230[hep-ph]]

For the inverted hierarchy, the 5×5 neutrino mixing is defined through:

$$\mathcal{M}_\nu = V^\star diag(m_2, m_3, 0, M_1, M_2) V^\dagger .$$

V can be decomposed into four blocks

$$V = \begin{pmatrix} V_{al} & V_{ah} \\ V_{sl} & V_{sh} \end{pmatrix}$$

and each block in the following way:

$$V_{al} = U'_{PMNS} \begin{pmatrix} H & 0 \\ 0 & 1 \end{pmatrix}, \qquad V_{ah} = iU'_{PMNS} \begin{pmatrix} Hm_l^{1/2} R^\dagger M_h^{-1/2} \\ 0 \end{pmatrix},$$

$$V_{sl} = i \begin{pmatrix} \bar{H} M_h^{-1/2} R m_l^{1/2} & 0 \end{pmatrix}, \qquad V_{sh} = \begin{pmatrix} \bar{H} \end{pmatrix},$$

The inverse hierarchy just implies a rearrangement of the rows and columns of the mixing matrix.

Neutrino Couplings

Now we need to write the Dirac and Majorana mass terms, m_Y and M_N, in terms of the parameters shown before (i.e. H, R, M_h, m_l). These terms enter the neutrino Majorana mass matrix:

$$M_\nu = \begin{pmatrix} 0 & m_Y \\ m_Y^T & M_N \end{pmatrix},$$

after projecting out the zero eigenvalue of the neutrino mass matrix, we get for the normal hierarchy

$$m_Y^{n.h.} = U'^{\star}_{PMNS} \begin{pmatrix} 0 \\ -iH^\star m_l^{1/2}(m_l R^\dagger + R^T M_h) M_h^{-1/2} \bar{H} \end{pmatrix},$$

and for the inverted hierarchy

$$m_Y^{i.h.} = U''^{\star}_{PMNS} \begin{pmatrix} -iH^\star m_l^{1/2}(m_l R^\dagger + R^T M_h) M_h^{-1/2} \bar{H} \\ 0 \end{pmatrix}.$$

For M_N we obtain

$$M_N = \bar{H}^\star (M_h - M_h^{-1/2} R^\star m_l^2 R^\dagger M_h^{-1/2}) \bar{H}.$$

Now we can apply the perturbativity bounds on the Yukawa coupling, $\sqrt{2}M_Y/\upsilon$. For definiteness we follow the condition

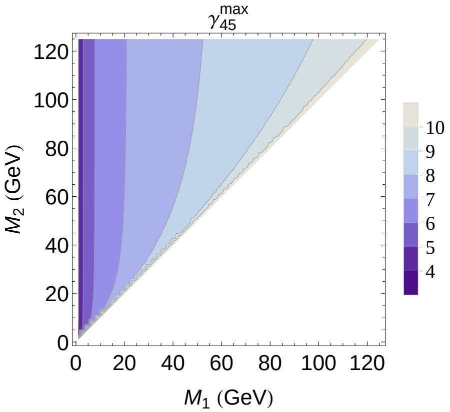
$$Tr\left[\frac{2}{\upsilon^2}m_Y m_Y^\dagger\right] \leq 3$$

J. A. Casas et al., JHEP 1103 (2011) 034[arXiv:1010.5751[hep-ph]]

When both heavy masses are of $\mathcal{O}(GeV)$, then $\gamma_{45} \leq 40 - 50$ for perturbativity to hold. For larger masses, the bound drops to $\gamma_{45} \leq 10 - 20$ when $M_1 M_2 \geq \mathcal{O}(10^5 GeV^2)$.

Constraints

- $0\nu\beta\beta$ in the minimal 3+2 seesaw

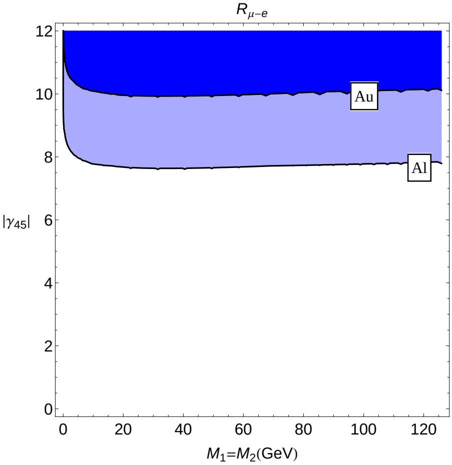


$0\nu\beta\beta$ strongly constraints active-heavy mixing, ruled by γ_{45}. This bound can be avoided by having degenerate heavy neutrinos, which brings a cancellation. Such degeneracy can be justified by introducing an approximate lepton-number symmetry.

M. Blennow, E. Fernandez-Martinez, J. Lopez Pavon and J. Menendez, JHEP 1007 (2010) 096[arXiv:1005.3240[hep-ph]]

Constraints (cont'd)

- Lepton Flavor Violation

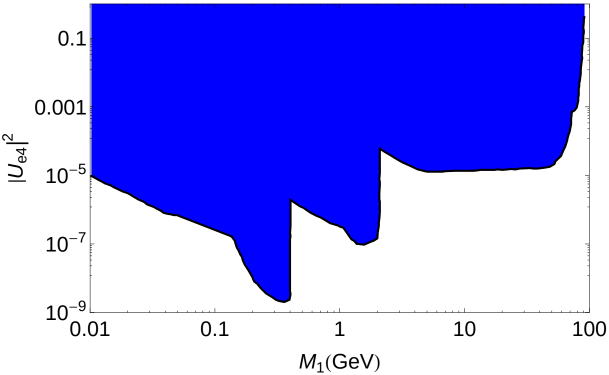


LFV involves the $\mu \to e\gamma$ decay and the $\mu \to e$ conversion in nuclei. This gives an upper bound on γ_{45}, even on the degenerate case.

R. Alonso, M. Dhen, M. B. Gavela and T. Hambye, JHEP 1301 (2013) 118[arXiv:1209.2679[hep-ph]]

Constraints (cont'd)

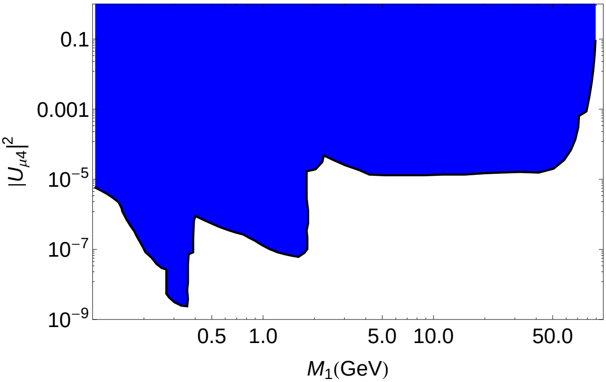
- Direct Search Bounds



A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 0905 (2009) 030[arXiv:0901.3589[hep-ph]]

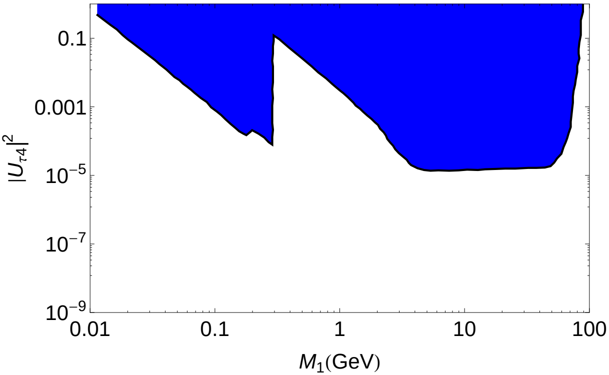
Constraints (cont'd)

- Direct Search Bounds



A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 0905 (2009) 030[arXiv:0901.3589[hep-ph]]

- Direct Search Bounds



A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 0905 (2009) 030[arXiv:0901.3589[hep-ph]]

Higgs Decays into Neutrinos

The decay rate of a Higgs decaying into two fermions of different mass is given by

$$\Gamma = \frac{\omega}{8\pi} m_h \left(1 - 2\frac{m_1^2 + m_2^2}{m_h^2} + \frac{(m_1^2 - m_2^2)^2}{m_h^4}\right)^{1/2} \left[(S+P)\left(1 - \frac{(m_1 + m_2)^2}{m_h^2} + 4P\left(\frac{m_1 m_2}{m_h^2}\right)\right)\right]$$

where S and P indicate the scalar and pseudoscalar coupling of the Higgs to the two fermions. The factor ω is a statistical factor, equal to 1/2 if the particles in the final states are identical and equal to unity otherwise.

Higgs Decay in the 3+2 Seesaw

The Yukawa coupling of the Higgs to two neutrinos is $Y_\nu = \sqrt{2} m_Y / \upsilon$. For $h \to \nu_i \nu_j$ we have

$$S = \frac{g^2}{4m_W^2}((m_{\nu_i} + m_{\nu_j}) Re[C_{ij}])^2,$$

$$P = \frac{g^2}{4m_W^2}((m_{\nu_j} - m_{\nu_i}) Im[C_{ij}])^2,$$

with

$$C_{ij} = \sum_{k=1}^{3} U^\star_{ki} U_{kj}.$$

Thus, we have

$$\Gamma(h \to \nu_i \nu_j) = \omega \frac{g^2}{32\pi} \frac{(m_{\nu_i}^2 + m_{\nu_j}^2)}{m_W^2} m_h \left(1 - 2\frac{m_{\nu_i}^2 + m_{\nu_j}^2}{m_h^2} + \frac{(m_{\nu_i}^2 - m_{\nu_j}^2)^2}{m_h^4}\right)^{1/2} \times$$
$$\left[\left([C_{ij}]^2 + \frac{2m_{\nu_i} m_{\nu_j}}{m_{\nu_i}^2 + m_{\nu_j}^2}(Re[C_{ij}]^2 - Im[C_{ij}]^2)\right)\left(1 - \frac{(m_{\nu_i} + m_{\nu_j})^2}{m_h^2}\right) + \right.$$
$$\left. \frac{(m_{\nu_j} - m_{\nu_i})^2}{m_{\nu_i}^2 + m_{\nu_j}^2} Im[C_{ij}]^2 \left(\frac{m_{\nu_i} m_{\nu_j}}{m_h^2}\right)\right]$$

Higgs Decay in the 3+2 Seesaw (cont'd)

- Higgs decay into two light neutrinos, $n_k(m_{\nu_k} \to 0)$

$$\Gamma(h \to n_i n_j) = \omega \frac{g^2}{32\pi} \frac{(m_{\nu_i}^2 + m_{\nu_j}^2)}{m_W^2} m_h \left([C_{ij}]^2 + \frac{2 m_{\nu_i} m_{\nu_j}}{m_{\nu_i}^2 + m_{\nu_j}^2} (Re[C_{ij}]^2 - Im[C_{ij}]^2) \right),$$

where

$$C_{ll'} = \begin{pmatrix} 1 & 0 \\ 0 & H^2 \end{pmatrix}$$

- Higgs decay into one light neutrino (m_{ν_i}), and one heavy neutrino N_j with mass M_j

$$\Gamma(h \to n_i N_j) = \frac{g^2}{32\pi} \frac{(M_j^2)}{m_W^2} m_h \left(1 - \frac{M_j^2}{m_h^2}\right)^2 [C_{ij}]^2,$$

where

$$C_{lh} = i \begin{pmatrix} 0 \\ H^2 m_l^2 R^\dagger M_h^{-1/2} \end{pmatrix}$$

Higgs Decay in the 3+2 Seesaw (cont'd)

- Higgs decay into two identical heavy neutrinos

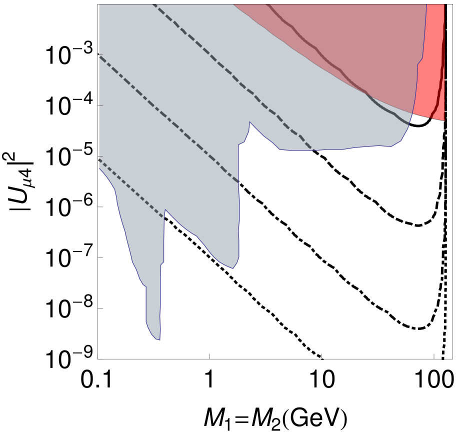
$$\Gamma(h \to N_i N_j) = \omega \frac{g^2}{16\pi} \frac{(M_i^2)}{m_W^2} m_h \left(1 - 4\frac{M_i^2}{m_h^2}\right)^{3/2} Re|C_{ij}|^2,$$

where

$$C_{hh'} = M_h^{-1/2} R m_l^{1/2} H^2 m_l^{1/2} R^\dagger M_h^{-1/2}.$$

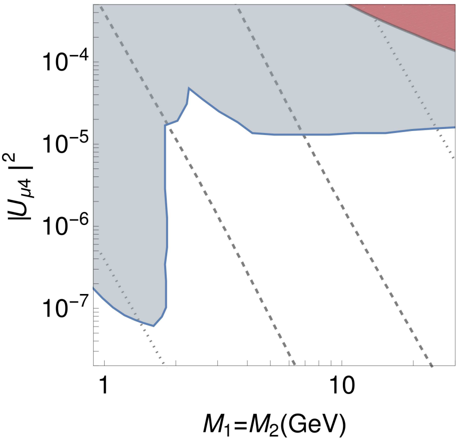
Higgs Decay in the 3+2 Seesaw (cont'd)

Branching ratio for $h \to nN$. Branching ratios of 10^{-2}, 10^{-4}, 10^{-6} and 10^{-8}.



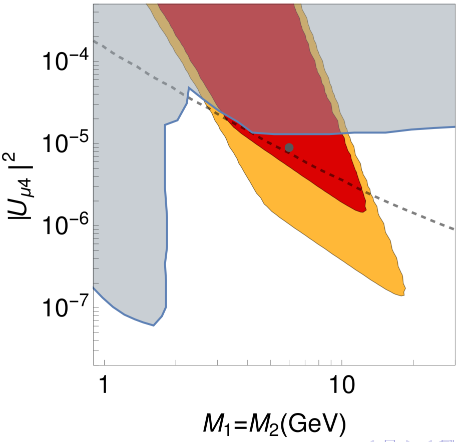
Displaced Vertices from Higgs Decays at the LHC

Decay length, $\tau_N c$. Region between dashed lines has $1mm \leq \tau_N c \leq 10^3 mm$ (If the neutrino transverse decay length lies in this region, a displaced vertex could be recorded at ATLAS and CMS) and dotted lines between $10^{-3} mm \leq \tau_N c \leq 10^6 mm$.



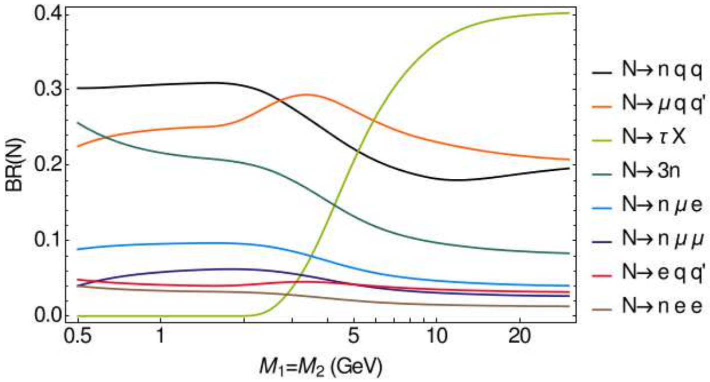
Displaced Vertices from Higgs Decays at the LHC (cont'd)

Region sensitive to events with a displaced vertex for an integrated luminosity of 300 fb^{-1} at 13 TeV. Region in red would have more than 250 events with a displaced vertex. Region in orange would have more than 50 events.



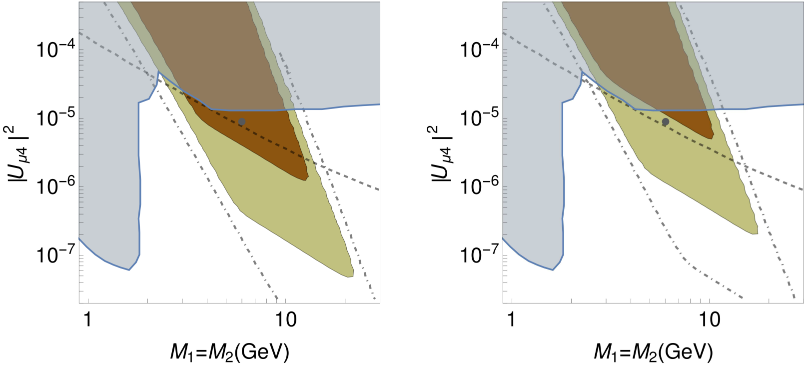
Signatures from Heavy Neutrinos

Branching ratios for relevant heavy neutrino decay channels.



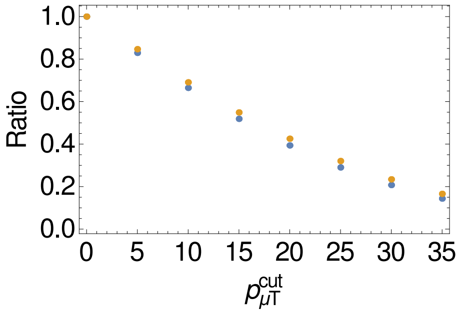
Signatures from heavy Neutrinos (cont'd)

Region sensitive to events with a displaced vertex in the $h \to nN \to n\mu qq'$ channel for an integrated luminosity of 300 fb^{-1} at 13 TeV. Region in brown would have more than 100 events with a displaced vertex. Region in green would have more than 10 events.



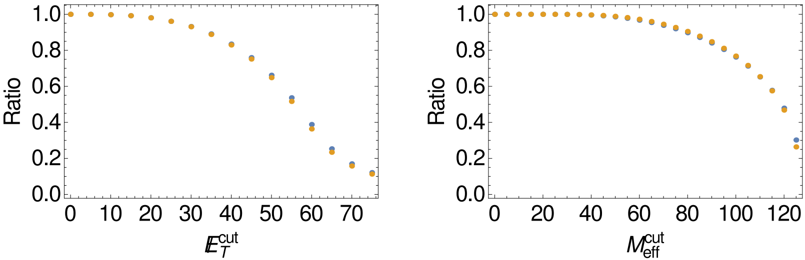
Kinematical Cuts

Ratio between the number of events with and without a cut on the muon transverse momentum for the $h \to n_i N_j \to n_i \mu q q'$ channel. The blue(orange) points represent $M_i = 3\ GeV$ ($15\ GeV$)



Kinematical Cuts (cont'd)

Ratio between the number of events with and without a cut on the missing transverse energy (left) and on the M_{eff} for the $h \to n_i N_j \to n_i \mu q q'$ channel. The blue(orange) points represent $M_i = 3\ GeV$ ($15\ GeV$)



Conclusions and Outlook

- We study the possible observation of Higgs decays involving heavy neutrinos, by means of a search for displaced vertices, and it is done in the context of the minimal $3+2$ neutrino model, which is based on a Type I seesaw with two heavy sterile neutrinos.
- After imposing all constraints on the parameter space, we find that the model can be described in terms of two additional parameters (a degenerate mass for the two heavy neutrinos and γ_{45}), apart from the light neutrino masses and mixing.
- We calculate the partial width for Higgs decay into any two neutrinos. We find that the $h \to n_i N_j$ channel has the largest branching ratio, and concentrate on the description of a displaced vertex signal. This signal is particularly relevant for degenerate heavy neutrino masses of the order of a few Gev. This prediction depends on the neutrino masses and on γ_{45}, with no dependence on the neutrino mixing angles nor phases of the PMNS matrix.

Conclusions and Outlook

- For the LHC Run 2, there exist allowed regions of parameter space where the number oh Higgs decays with a displaced vertex could be as large as $\mathcal{O}(100)$, before any other kinematical cut.
- The observation of a displaced vertex relies strongly on the decay channel of the heavy neutrinos and on the detection efficiency. As an example, we have included the branghing ratio due to $N \to \mu q q'$ decay, and imposed pseudorapidity cuts on the final states. Both considerations reduce the number of events down to $\mathcal{O}(20\%)$ from the original number, still leaving a large amount to be observed.