Constraints on Seesaw Models and Signatures at the LHC

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Outline

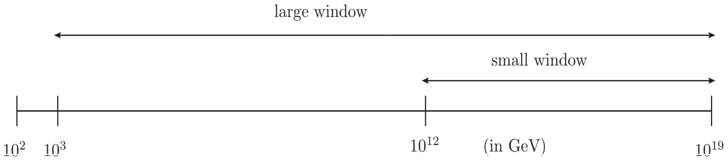
- Introduction
- Metastability within Standard Model (SM)
- The seesaw models
- Metastability in seesaw models
- Constraints from Lepton Flavor Violation (LFV)
- $0\nu\beta\beta$ decay
- Collider Signatures
  - Production crossection and branching ratio of heavy neutrinos
  - Simulation and Results
  - Discovery potential
- Summary

Introduction

- Popular mechanism to incorporate a light neutrino mass term is known as the seesaw mechanism which includes the addition of heavy fields.
- Typical mass scale of such heavy fields is near GUT scale $\left(M_R \sim 10^{12} - 10^{14} \text{ GeV}\right)$.
- However testability at colliders motivates people to study TeV scale seesaw models.
- Mass scale of the seesaw models can be brought down to few hundred GeV assuming hierarchical Yukawa couplings.
- As a result, important collider signatures can be predicted as well as other signatures such as lepton flavor violation.

Introduction

- Another important consequence of such model is significant modification towards the condition of metastability of the electroweak vacuum upto Planck scale.
- The presence of new Yukawa couplings in seesaw models modifies the β function of Higgs self-coupling.
- In the conventional type-I seesaw model, generation of small neutrino mass requires the mass scale of the singlet to be of the order of 10^{12} GeV. However for TeV scale seesaw models, as the neutrino Yukawa runs from TeV to Planck scale, the effect can be large.



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Metastability within SM

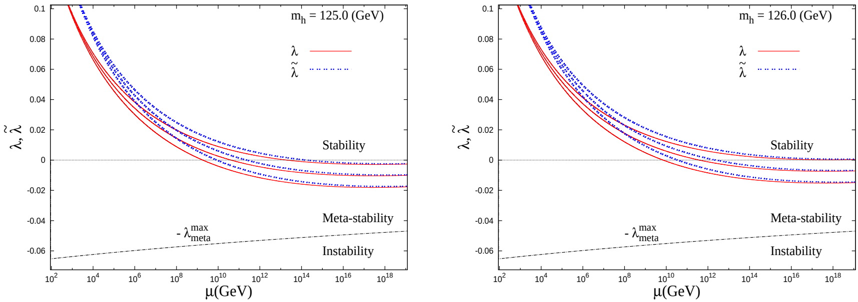

Figure: Variation of λ and $\tilde{\lambda}^2$ with the renormalization scale for fixed values of the parameters $(m_h\,, m_t\,, \alpha_s)$. The upper, middle and lower curves are drawn with the set of parameters (m_t, α_s)=$\{(172.3\,\mathrm{GeV}\,, 0.1191)$, $(173.2\,\mathrm{GeV}\,, 0.1184)$, $(174.1\,\mathrm{GeV}\,, 0.1177)\}$ respectively.

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[1] J. A. Casas *et al.*, Phys. Lett. B **342**, 171 (1995); J. A. Casas, J. R. Espinosa and M. Quiros, Phys. Lett. B 382, 374 (1996); G. Degrassi *et al.*, JHEP 1208, 098 (2012)

[2] J. A. Casas *et al.*, Phys. Lett. B **342**, 171 (1995); J. A. Casas, J. R. Espinosa and M. Quiros, Phys. Lett. B 382, 374 (1996); G. Degrassi *et al.*, JHEP 1208, 098 (2012)

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The seesaw models

- We shall consider two variant of Type I seesaw model with (i) two heavy neutrinos and (ii) three heavy neutrinos leading to hierarchical and quasi-degenerate light neutrino mass spectrum respectively.
- In addition to this we shall also consider minimal number of free parameters to enhance the predictivity of the model.
- In the minimal scenario the Yukawa matrix is fully determined in terms of oscillation parameters apart from a constant.
- We shall also consider degenerate heavy neutrino mass spectrum leading to overall two unknown in each of the two cases mentioned above, namely (1) heavy neutrino mass scale and (2) an unknown constant in the Yukawa matrix.

Seesaw model

- The Lagrangian is given by

$$-\mathcal{L} = \overline{N}_R Y'_\nu \tilde{\phi}^\dagger l_L + \frac{1}{2}\overline{N_R} M'_R N_R^{\mathcal{C}}$$

- The neutrino mass matrix, in the (ν_L, N_R^c) basis, given by

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & {m'_D}^T \\ m'_D & M'_R \end{pmatrix}$$

where $m'_D = Y'_\nu v/\sqrt{2}$

- For n generation heavy neutrinos

$$m'_D \equiv \left(m'_D\right)_{n\times 3}$$
$$M'_R \equiv \left(M'_R\right)_{n\times n}$$

Two right handed neutrino

$$(m'_D)_{2\times 3} = \begin{pmatrix} m_D \\ m_S \end{pmatrix}_{2\times 3} \qquad \equiv \qquad (Y'_\nu)_{2\times 3} = \begin{pmatrix} Y_\nu \\ Y_S \end{pmatrix}_{2\times 3}$$

- where $m_D\,, m_S\,, Y_\nu\,, Y_S$ are three dimensional row vectors

$$(M'_R)_{2\times 2} = \begin{pmatrix} M_N & M_R \\ M_R & \mu' \end{pmatrix}$$

- In the minimal scenario, M_N and μ' are taken to be zero. Hence the light neutrino mass matrix given by

$$m_\nu = m_D^T {M_R}^{-1} m_S + m_S^T {M_R}^{-1} m_D$$

- $m_\nu \sim \mathcal{O}(0.1 \text{ eV})$, $Y_\nu \sim \mathcal{O}(1)$, $M_R \sim \text{TeV}$
  $\Rightarrow\; Y_S \sim \mathcal{O}\left(10^{-10}\right)$.
- If one assumes the two heavy neutrino are with different lepton number then the smallness of Y_S is explained as tiny lepton number violation in theory. This is minimal linear seesaw model (MLSM).

Minimal Linear Seesaw Model(MLSM)

- Strictly speaking Type I seesaw and linear/inverse seesaw arise in different GUT model.
- Type I seesaw arises in the fundamental representation of $SO(10)$ GUT whereas linear/inverse seesaw arises in the 27 dimensional represetation of E_6 GUT.
- However here we treated them in the smilar way to bring the mass matrix into equal footing.

Minimal Linear Seesaw Model(MLSM): Reconstruction

- The Yukawa couplings are reconstructed as[3]

$$\begin{aligned}(Y_\nu)_{\mathrm{NH,IH}} &= \frac{y_\nu}{\sqrt{2}}\left(\sqrt{1+\rho_{\mathrm{NH,IH}}}\,U^\dagger_{3,2} + e^{i\frac{\pi}{2}}\sqrt{1-\rho_{\mathrm{NH,IH}}}\,U^\dagger_{2,1}\right)\\ (Y_S)_{\mathrm{NH,IH}} &= \frac{y_s}{\sqrt{2}}\left(\sqrt{1+\rho_{\mathrm{NH,IH}}}\,U^\dagger_{3,2} - e^{i\frac{\pi}{2}}\sqrt{1-\rho_{\mathrm{NH,IH}}}\,U^\dagger_{2,1}\right)\end{aligned}$$

with

$$\rho_{\mathrm{NH}} = \frac{\sqrt{1+r}-\sqrt{r}}{\sqrt{1+r}+\sqrt{r}} \qquad \rho_{\mathrm{IH}} = \frac{\sqrt{1+r}-1}{\sqrt{1+r}+1} \qquad r = \frac{\Delta m^2_\odot}{\Delta m^2_A}$$

- U_i's are the columns of the unitary matrix U_{PMNS}.
- Using the parameterization of Y_ν and Y_S, we have

$$\begin{aligned}\mathrm{Tr}\left[Y'^\dagger_\nu Y'_\nu\right] &= y_\nu^2 + y_s^2 \simeq y_\nu^2\\ \mathrm{Tr}\left[Y'^\dagger_\nu Y'_\nu Y'^\dagger_\nu Y'_\nu\right] &= y_\nu^4 + 2y_\nu^2 y_s^2 \rho^2 + y_s^4 \simeq y_\nu^4\end{aligned}$$

since $y_s << y_\nu$.

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[3] M. B. Gavela *et al.*, JHEP **0909**, 038 (2009).

Numerical values of the low energy parameters

- U_{PMNS} is parameterized as

$$\begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -c_{23}\, s_{12} - s_{23}\, s_{13}\, c_{12}\, e^{i\delta} & c_{23}\, c_{12} - s_{23}\, s_{13}\, s_{12}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{23}\, s_{12} - c_{23}\, s_{13}\, c_{12}\, e^{i\delta} & -s_{23}\, c_{12} - c_{23}\, s_{13}\, s_{12}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix} P$$

  where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, δ is the Dirac CP phase.
- Majorana phase matrix P is given by $P = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$.
- If one light neutrino mass is zero then $\alpha_1 = -\alpha_2 = -\alpha$
- Recent results on neutrino oscillation parameters[4]

Parameters	$3\ \sigma$ range: NH (IH)	Best fit
$\Delta m^2_{21}\ [10^{-5}\ \mathrm{eV}^2]$	7.12-8.20	7.62
$\Delta m^2_{31}\ [10^{-3}\ \mathrm{eV}^2]$	2.31-2.74 (2.21-2.64)	2.55
$\sin^2\theta_{12}$	0.27-0.37	0.32
$\sin^2\theta_{23}$	0.36-0.68 (0.37-0.67)	0.62
$\sin^2\theta_{13}$	0.017-0.033	0.024
δ	0–2π	$1.37\,\pi$

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[4] D. V. Forero *et al.*, Phys. Rev. D **86**, 073012 (2012).

Three right handed neutrino

- The Yukawa matrix is parameterized as[5]

$$(Y'_\nu)_{3\times 3} = \frac{\sqrt{2}}{v}\sqrt{{M'_R}^d}\,R\sqrt{m_\nu^d}\,U^\dagger_{PMNS}$$

- Superscript ^{d} stands for diagonal. We choose ${M'_R}^d = M'_R$.
- R is a 3×3 complex orthogonal matrix, given by

$$R = e^{iA}\,O$$

- A is real anti symmetric and O is real orthogonal matrix. A is given by

$$A = \begin{pmatrix} 0 & a & b \\ -a & 0 & c \\ -b & -c & 0 \end{pmatrix}$$

- $a, b, c \in \mathbb{R}^1$.

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[5] J. Casas and A. Ibarra, Nucl.Phys. B**618**, 171 (2001).

Three right handed neutrino

- For nearly degenerate light neutrinos O can be absorbed in the U_{PMNS}[6]
- R can be rewritten in terms of a new parameter $\omega = \sqrt{a^2 + b^2 + c^2}$ as

$$e^{iA} = \mathbb{1} - \frac{\cosh\omega - 1}{\omega^2} A^2 + i \frac{\sinh\omega}{\omega} A$$

- In the minimal scenario, we choose $a = b = c = \omega/\sqrt{3}$.
- With this parameterization, we have

$$\begin{aligned} \mathrm{Tr}\left[Y_\nu'^\dagger Y_\nu'\right] &\simeq \frac{2\,M_R}{v^2}\, m_0\,(1 + 2\cosh(\,2\,\omega)) \\ \mathrm{Tr}\left[Y_\nu'^\dagger Y_\nu' Y_\nu'^\dagger Y_\nu'\right] &\simeq \frac{4\,M_R^2}{v^4}\, m_0^2\,(1 + 2\cosh(\,4\,\omega)) \end{aligned}$$

- m_0 is the common light neutrino mass scale and M_R is the degenerate eigenvalues of ${M_R'}^d$.

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[6] S. Pascoli, S. Petcov, and C. Yaguna, Phys.Lett. B564, 241 (2003).

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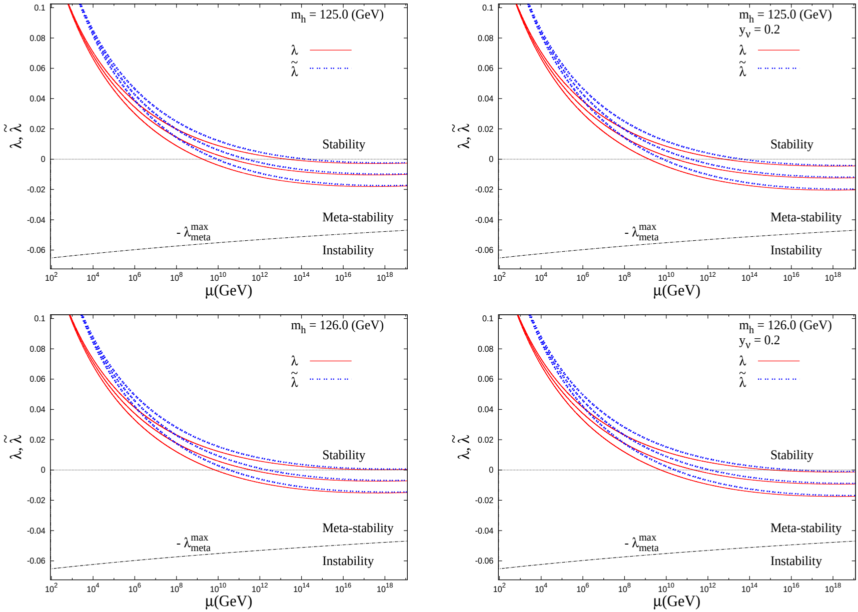
Metastability in seesaw model



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$\mu \to e\,\gamma$

- Experimental upper limits on LFV processes[7] ⇒ constraints can be btained on the the parameter y_ν/M_R. The experimental bound is given by

$$\mathrm{Br}\,(\mu \to e\,\gamma) \leq 5.7 \times 10^{-13}$$

- Branching ratio for the process, $\mu \to e\gamma$ is given by[8]

$$\mathrm{Br}\,(\mu \to e\,\gamma) = \frac{3\alpha}{8\pi}\left|V_{ei}V^{\dagger}_{i\mu}f(x)\right|^2$$

where, $x = \left(\frac{M_i^2}{m_W^2}\right)$ and $f(x) = \frac{x\left(1-6x+3x^2+2x^3-6x^2\ln x\right)}{2(1-x)^4}$.

- $f(x)$ is a slowly varying function of x ranging from 0 to 1 for x between 0 to infinity.
- V is given by

$$V = {m'_D}^{\dagger}\left({M'_R}^{-1}\right)^{*}U_R \qquad U_R \text{ diagonalizes } M'_R$$

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[7] J. Adam *et al.* [MEG Collaboration], Phys. Rev. Lett. **107** (2011) 171801; 1303.0754

[8] D. Tommasini *et al.*, Nucl. Phys. B **444**, 451 (1995).

Upper bound on y_ν/M_R

- For NH, the branching ratio can be expressed as

$$\begin{aligned}\mathrm{Br}\,(\mu\to e\gamma) \;&=\; \frac{3\alpha}{8\pi}\frac{y_\nu^4 v^4}{4M_R^4} f^2(x)\left(\sqrt{r}\, s_{12}^2 + 2\, r^{(1/4)}\, s_{13}\, s_{12}\, s_{(\alpha+\delta)}\right.\\ &+\; \left. r^{(3/4)}\, c_{23}\, s_{12}\, s2_{12}\, s_\alpha/s_{23}\right) s_{23}^2 + \mathcal{O}\left(y_s, (\sqrt{r}, s_{13})^2\right)\end{aligned}$$

- The above equation can be inverted to put an upper bound on y_ν/M_R, using the experimental bound, as given

$$y_\nu/M_R \leq \left[\frac{5.7\times 10^{-11}}{3\alpha v^4 f^2(x) G^{NH}(r,\theta_{ij},\alpha,\delta)}\right]^{1/4}$$

- Similarly for IH and QD.

Combined constraints from metastability and LFV

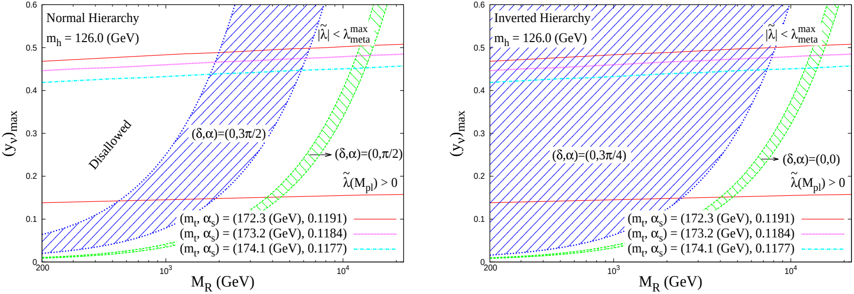

Figure: The allowed regions of y_ν^{max} as a function of M_R from the combined constraints of $Br(\mu \to e\gamma)$ and vacuum (meta)stability. The area to the right of the curved lines are allowed from experimental bound on $Br(\mu \to e\gamma)$ while the area below the slanting lines are allowed from the constraint on vacuum (meta)stability.

Combined constraints from metastability and LFV

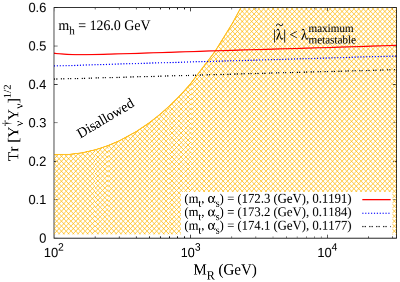

Figure: Allowed region of the Yukawa norm $\mathrm{Tr}[Y_\nu^\dagger Y_\nu]$ as a function of the heavy neutrino mass M_R by imposing combined constraints coming from metastability of the electroweak vacuum as well as lepton flavor violating decay ($\mu \to e\,\gamma$). Choice of Higgs mass fixed at $m_h = 126$ GeV. The horizontal slanting lines represent the upper bound on $\mathrm{Tr}[Y_\nu^\dagger Y_\nu]$ consistent with the metastability bound. Three lines are due to three different set of values for top mass and strong coupling. The shaded area below the curved line is allowed from the lepton flavor violating constraint. This is after putting global best-fit values of oscillation parameters together with the particular values of unknown phases within their full range. The yellow line corresponds to $\omega = 11.9$ and gives us the best choice for study within the bound of LFV. Hence, the region marked "Disallowed" is ruled out from LFV for such choice of ω.

Close look on the constraints from LFV

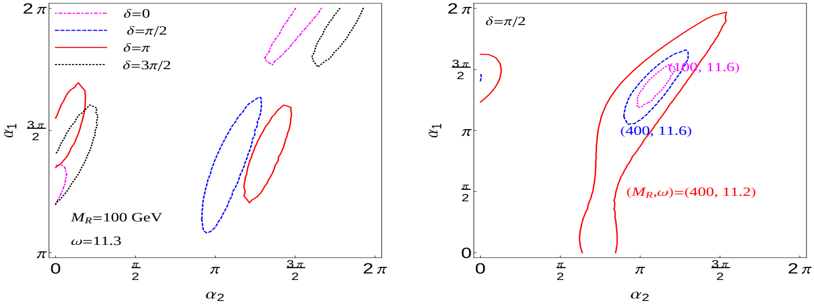

Figure: (Left panel) Contours of allowed lepton flavor violating regions with $\mathrm{Br}\,(\mu \to e\gamma) = 5.7 \times 10^{-13}$ in the parameter plane of Majorana phases α_1 and α_2 with different values of Dirac CP phase δ. Considering all the neutrino oscillation parameters and mass differences in the global best-fit values, the area within each contours are consistent with the experimental LFV upper bound from the decay rate of $\mu \to e\,\gamma$. (Right panel) demonstrates the variation of these LFV equality contours for different choices of the heavy neutrino mass M_R and parameter ω considering one example ($\delta = \pi/2$) contour from the left panel. As expected, decreasing the M_R or increasing the ω would make the contour narrower, retaining a smaller window for choices of these unknown parameters.

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$0\nu\beta\beta$ decay

- The half life for neutrino-less double beta decay in presence of heavy singlets is given by[9]

$$T_{\frac{1}{2}}^{-1} = G\,\frac{|\mathcal{M}_\nu|^2}{m_e^2}\left|\sum_i (U_{PMNS})^2_{e\,i}\,\left(m_\nu^d\right)_i + \sum_j \langle p^2\rangle \frac{V_{e\,j}^2}{M_{R_j}}\right|^2$$

- $G = 7.93 \times 10^{-15}$ yr^{-1}.
- The contribution from the heavy part, in MLSM, is $2\langle p^2\rangle m_{s1} m_{d1}/M_R^3 \sim 10^{-8} m_i$.
- Therefore, $0\nu\beta\beta$ is only due to the light neutrinos only.
- In the case of three heavy neutrinos, the second term of the above expression can be rewriten as

$$\frac{\langle p^2\rangle}{M_R^2}\left(U_{PMNS}\sqrt{m_\nu^d}\,R^\dagger R^*\sqrt{m_\nu^d}\,U_{PMNS}^T\right)_{e\,e} = \frac{\langle p^2\rangle}{M_R^2}\,(U_{PMNS})^2_{e\,i}\,\left(m_\nu^d\right)_i$$

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[9] M. Mitra *et al.*, Nucl. Phys. B **856**, 26 (2012); J. Chakrabortty *et al.*, JHEP **1208**, 008 (2012).

$0\nu\beta\beta$ decay

- With this the half life becomes

$$T_{\frac{1}{2}}^{-1} = G \frac{|\mathcal{M}_\nu|^2}{m_e^2} \left(1 + \frac{\langle p^2 \rangle}{M_R^2}\right)^2 \left| (U_{PMNS})^2_{e\,i} \left(m_\nu^d\right)_i \right|^2$$

- heavy neutrino contribution towards $0\nu\beta\beta$ is $\sim 0.001\%$ of the light neutrino contribution even for a heavy neutrino mass of 100 GeV.
- From these observation we conclude that for both of these models, the same sign dilepton (SSDL) signal in the collider will be suppressed.
- So trilepton plus missing transverse energy is good channel for the discovery of heavy neutrino as this has low SM background.

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Collider signatures

- Since SSDL is highly suppressed, we look for trilepton plus missing energy final state in the search for heavy neutrinos at the 14 TeV LHC.
- The dominant production channel is s-channel in which heavy neutrinos are produced along with a charged lepton.
- The heavy neutrino further decays to a second lepton (of sign opposite to the first lepton as SSDL is suppressed) together with a W-boson.
- The W-boson can further decay leptonically to produce a lepton and a neutrino, thus giving trilepton plus missing energy final state.
- This channel is expected to have tiny contamination from standard model backgrounds.

Collider signatures

- Another class of channel is the production of heavy neutrinos through vector boson fusion (VBF) leading to the signal under consideration (tri-leptons) along with two highly forward jets.
- The VBF channel becomes important in the context of hadron colliders since the tagging of forward jets allows us to reduce the background considerably.
- The lack of color exchange between these jets makes the central region free from the color activities and this is exploited by vetoing central jets[10].

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[10] D. L. Rainwater(1999), arXiv:hep-ph/9908378.

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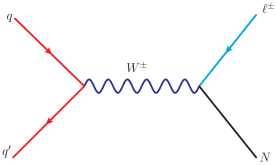
Production crossection

- Dominant s-channel production of heavy neutrino at the leading order the parton level process is given as $q\bar{q}' \to W^{\pm} \to \ell^{\pm} N$



Production crossection

- The VBF production of heavy neutrino

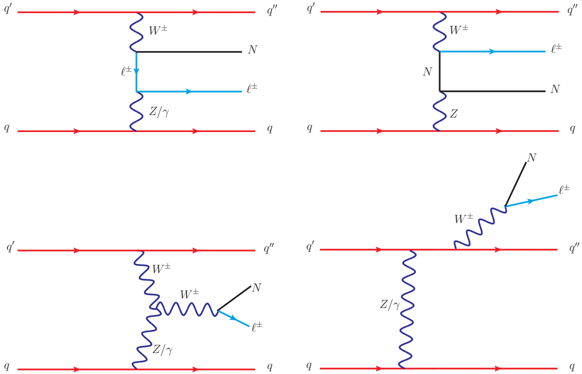


Figure: Mirror diagrams are not shown here and also the last diagram is one of the four diagrams with $W^\pm$ emitting from each of the quark legs.

Production crossection

- Parton distribution function (PDF): CTEQ6L1[11]
- Basic cuts: $p_{T\ell} > 20$ GeV, $|\eta_\ell| < 2.5$
- Factorization scale set at heavy neutrino mass M_R

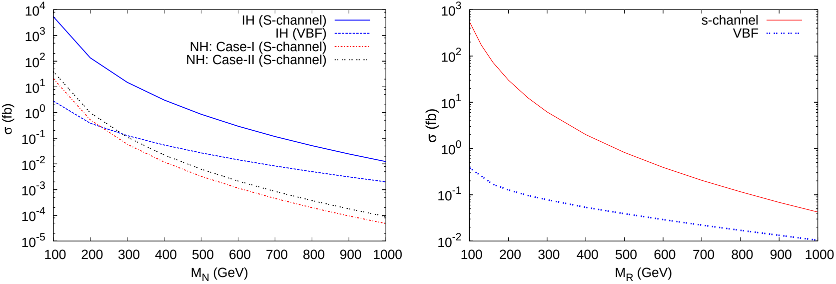


Figure: The total production cross section (generated with `MadGraph`), as a function of heavy neutrino mass, is shown.

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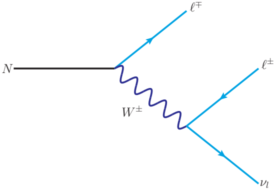
[11] J. Pumplin, D. Stump, J. Huston, H. Lai, P. M. Nadolsky, et al., JHEP 0207, 012 (2002).

Branching ratio

- Heavy neutrino decay modes are given by

$$N \to W^{\pm} l^{\mp} / Z \nu_l / H \nu_l, \quad \text{where} \quad l \equiv e, \mu, \tau$$

- Representative diagram for decay channels used in the analysis



Branching ratio

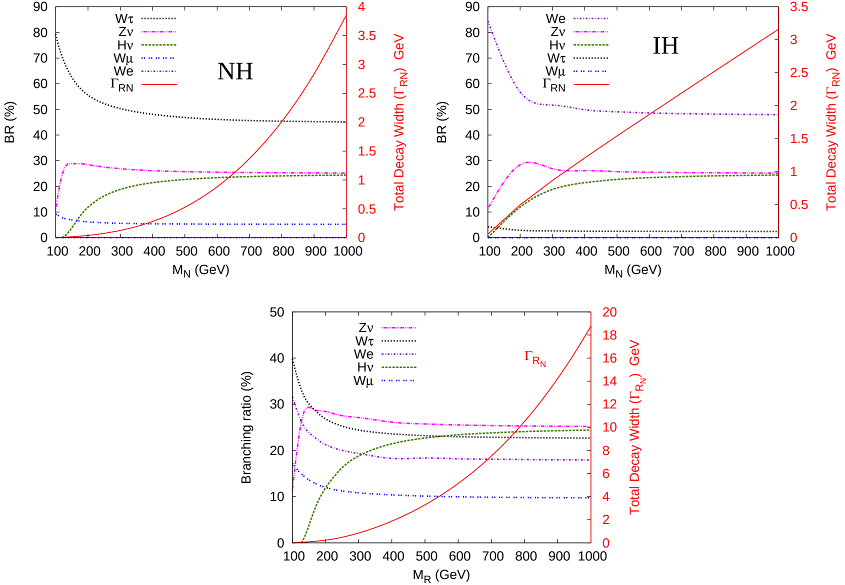


Figure: The decay branching ratios of the heavy neutrino (N) (generated with `MadGraph`), as a function of heavy neutrino mass.

Branching ratio

- Subtantial branching ratio goes to $N \to /Z\nu_l/H\nu_l$ for higher values of M_R ($\sim 25\%$ each).
- $Z\nu_l$ decay mode will be suppressed after applying Z-veto to suppress SM background.
- $H\nu_l$ decay mode will be suppressed in the leptonic decay of Higgs as lepton Yukawa is suppressed by lepton mass.
- Since we shall only consider e and μ in the detector, the $W^\pm\tau^\mp$ decay mode is also not going to contribute in the final event selection.
- Dominant contribution will come from e and μ decay modes associated with W.
- Hadronic decay mode of W: $W^\pm \to jj$, (BR $\sim 70\%$) and leptonic decay mode $W^\pm \to \tau^\pm\nu$ (BR $\sim 10\%$), $W^\pm \to (e^\pm/\mu^\pm)\,\nu$ (BR $\sim 20\%$).
- The tri-lepton signal $pp \to l^\pm l^\mp l^\pm \nu$ ($l = e\,,\mu$) comes from the final decay mode.

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Selection Criteria

- Lepton identification criteria: $|\eta_\ell| < 2.5$ and $p_{T\ell} > 20$ GeV.
- Detector efficiency for leptons: Electron efficiency (for e^- & e^+) - 0.7 (70%), Muon efficiency (for μ^- & μ^+) - 0.9 (90%)
- Smearing: Gaussian smearing of electron energy and muon p_T.
- Jet reconstruction: `PYCELL` cone algorithm in `PYTHIA`.
- Lepton-jet separation: $\Delta R_{lj} \geq 0.4$ (for all jets)[12].
- Lepton-lepton separation: $\Delta R_{ll} \geq 0.2$.
- Lepton-photon separation: $\Delta R_{l\gamma} \geq 0.2$ for all $p_{T\gamma} > 10$ GeV.

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[12] Here $\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 - (\phi_i - \phi_j)^2}$ quantifies the separation between particles i and j in the pseudorapidity(η)-azimuth(ϕ) plane.

Selection Criteria

- Hadronic activity for each lepton (To consider leptons with very less hadronic activity around them): $\frac{\sum p_{T_{hadron}}}{p_{T_l}} \leq 0.2$ ($\equiv$ radius of the cone around the lepton)
- Final p_T cuts for leptons: $p_{T l_1} > 30$ GeV, $p_{T l_2} > 30$ GeV and $p_{T l_3} > 20$ GeV.
- Missing p_T cut: $\not{p}_T > 30$ GeV.
- Z-veto [13]: $|m_{\ell_1 \ell_2} - M_Z| \geq 6\Gamma_Z$.

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[13] Invariant mass for the same flavored and opposite sign lepton pair, $m_{\ell_1 \ell_2}$, must be sufficiently away from Z pole.

Selection Criteria

VBF Cuts

- Central jet veto (to suppress the QCD background substantially): Any additional jet with $p_{T3} > 20$ GeV and $|\eta_0| < 2$ events are discarded, where $|\eta_0| < 2$ is defined as pseudorapidity difference between the average of the two forward jets and the third jet ($\eta_0 = \eta_3 - (\eta_1 + \eta_2)/2$).
- Pseudorapidity of charged leptons: $\eta_{j,min} < \eta_\ell < \eta_{j,max}$ (Charged leptons need to fall in between the rapidities of two forward tagging jets).
- Cut applied to jets: $p_{T\,j_1,j_2} > 20$ GeV, $M_{j_1 j_2} > 600$ GeV, $\eta_{j_1} \cdot \eta_{j_2} < 0$ and $|\eta_{j_1} - \eta_{j_2}| > 4$ (Both the tagged jets to be in the opposite hemisphere and a large rapidity separation among them significantly reduces the BG for VBF.).

Background

- s-channel

Process	Cross section (fb)				
	$\ell\ell\ell$	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$t\bar{t}$	18.972	1.1383	7.0831	8.2214	2.5297
$W^{\pm}(Z/\gamma^{*})$	10.832	0.0677	0.1311	5.9891	4.6440
$(Z/\gamma^{*})(Z/\gamma^{*})$	1.175	0.0734	0.0525	0.6400	0.4090
$t\bar{t}(Z/\gamma^{*})$	1.103	0.0429	0.1329	0.4997	0.4275
$t\bar{t}W^{\pm}$	0.639	0.0328	0.2655	0.2424	0.0983
TOTAL	**32.721**	**1.3551**	**7.6651**	**15.5926**	**8.1085**

- VBF

Process	Cross section (fb)				
	$\ell\ell\ell$	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$W^{+}Zjj$	0.04068	0.00073	0.00105	0.02157	0.01734
$W^{-}Zjj$	0.01923	0.00038	0.00055	0.00994	0.00836
$ZZjj$	0.00094	0.00002	0.00002	0.00066	0.00024
TOTAL	**0.06085**	**0.00113**	**0.00162**	**0.03216**	**0.02594**

Signal for s-channel

- The signal coming from decay of heavy neutrinos

$$pp \rightarrow \ell^{\pm} N \rightarrow \ell^{\pm}(\ell^{\mp} W^{\pm}) \rightarrow \ell^{\pm}\ell^{\mp}\ell^{\pm} + \not{E}_T, \qquad \text{where } \ell \equiv e\,,\mu.$$

Hierarchy	Cross section (fb)				
	$\ell\ell\ell$	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
IH(s-channel)	27.07	10.297	16.314	0.459	0.0
IH(VBF)	0.018068	$7.09 \cdot 10^{-3}$,	$1.06 \cdot 10^{-2}$,	$4.06 \cdot 10^{-4}$,	0.00
QD(s-channel)	2.732	0.318	1.144	1.030	0.2

Table: Final tri-lepton signal cross section through s-channel heavy neutrino production at the 14 TeV LHC for the benchmark point $M_R = 100$ GeV including all event selection cuts except VBF cuts. For each hierarchy the tri-lepton signals are classified into four different flavor combinations and the cross section in each case has been presented along with the total light lepton contribution.

Outline

- Introduction
- Metastability within Standard Model (SM)
- The seesaw models
- Metastability in seesaw models
- Constraints from Lepton Flavor Violation (LFV)
- $0\nu\beta\beta$ decay
- Collider Signatures
  - Production crossection and branching ratio of heavy neutrinos
  - Simulation and Results
  - **Discovery potential**
- Summary

Discovery potential

- Significance is express as $S/\sqrt{S+B}$, where $S\,(B) = \mathcal{L}\,\sigma_{S\,(B)}$.
- $\mathcal{L}$ is the integrated luminosity of available data from the experiment.
- $\sigma_{S(B)}$ is the final cross section of the signal (background) after all event selection cut.

Discovery potential

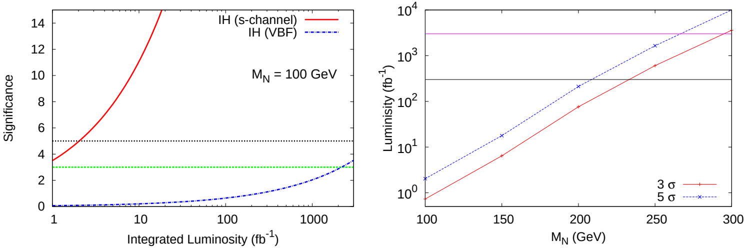

Figure: (Left) The variation of significance $S/\sqrt{S+B}$ for the s-channel production signal for benchmark point $M_N = 100$ GeV with the integrated luminosity available for the low luminosity option at 14 TeV LHC. Black-dotted (green-dashed) line represents 5σ (3σ) significance. (Right) The lines for the 3σ(red) and 5σ (blue) significance in terms of heavy neutrino mass and integrated luminosity. With $300 fb^{-1}$ luminosity at LHC14, the heavy neutrino mass in this model can be probed up to $\sim 210(230)$ GeV with $\sim 5\sigma(3\sigma)$. For a very high luminosity of $3000 fb^{-1}$ this can reach up to $\sim 270(295)$ GeV.

Discovery potential

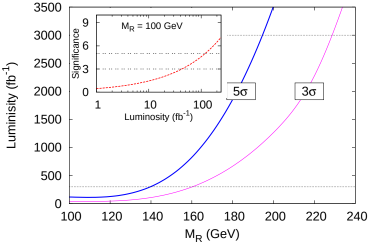

Figure: Contours of constant 3σ and 5σ significance at the 14 TeV LHC in terms of heavy neutrino mass M_R and integrated luminosity. With $300 fb^{-1}$ data tri-lepton signal can probe upto $M_R = 160(140)$ GeV with $3\sigma(5\sigma)$ significance, whereas with $3000 fb^{-1}$ luminosity LHC can reach up to 230(190) GeV. Inset shows variation of significance for the s-channel tri-lepton production signal and backgrounds with heavy neutrino mass $M_N = 100$ GeV.

Summary

- We have considered two variant of TeV scale seesaw model leading to hierarchical and quasi-degenerate light neutrino mass spectrum.
- In the minimal scenario these models are fully reconstructible in terms of the oscillation parameters apart from two unknown constant namely an overall constant to Yukawa coupling and heavy neutrino mass scale.
- We have obtained upper bound on the Yukawa couplings at a fixed M_N from the consideration of metastability of the electroweak vacuum and LFV.

Summary

- Neutrino less double beta decay is highly suppressed in these models and hence SSDL signal in the context of collider is also suppressed.
- We have considered trilepton plus missing transverse energy final to study possible signals of heavy neutrino through *s*-channel as well as VBF characterized by two additional highly forward jets.
- However we find that VBF crossection too exteremly low to probe at 14 TeV LHC.
- We presented the discovery potential of heavy neutrinos for a benchmark value as well as a function of both heavy neutrino mass and integrated lluminosity.

Thank you for your attention !