The Radiative SUSY Seesaw Mechanism

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Based on P. Candia, A. Pilaftsis, Phys. Rev. D 102, 095013 (2020)

Seesaw mechanism and neutrino masses

- Neutrino masses and mixings require physics beyond the SM
- Majorana neutrino masses are appealing
- The lowest order effective operator

$$\mathcal{L}^{d=5} = \frac{c_{ij}}{\Lambda} \left(\overline{L}_i^c \tilde{\Phi}^*\right) \left(\tilde{\Phi}^\dagger L_j\right) + \mathrm{H.\,c.}$$

- Type I, II and III seesaws and hybrid proposals

Seesaw mechanism and neutrino masses

- Type I seesaw

Minkowski ‘77; Yanagida ‘79; Gell-Mann, Ramond, Slansky ‘79; Mohapatra, Senjanovic ‘80

$$\mathbf{m}_\nu = -\mathbf{m}_D \mathbf{m}_M^{-1} \mathbf{m}_D^{\mathsf{T}}$$

- In principle, requires small Yukawa couplings or very massive neutrinos
- **More optimistic:** Inverse seesaw scenarios. Lepton number is an approximate symmetry, Yukawas can be big and RHN masses lower

General inverse seesaw

Mohapatra, Valle '86; Dev, PIlaftsis '12

- Lagrangian:

$$-\mathcal{L}_Y = \overline{L}^C Y_\nu \tilde{\Phi} \nu_R^C + \overline{S}_L^C M_N \nu_R^C + \frac{1}{2}\overline{\nu}_R \mu_R \nu_R^C + \frac{1}{2}\overline{S}_L^C \mu_S S_L + \mathrm{H.c.}$$

- The particle content of the SM is extended with the fields $\nu_R,\ S_L^C$
- The former has LN +1, while the second -1
- LNV occurs softly via the matrices $\mu_{R,S}$

General inverse seesaw

- Mass matrix:

$$-\mathcal{L}^{\nu}_{\text{mass}} = \frac{1}{2}\left(\overline{\nu}_L^C, \overline{\nu}_R, \overline{S}_L^C\right) \begin{pmatrix} \mathbf{0}_3 & \mathbf{M}_D & \mathbf{0}_{3\times n} \\ \mathbf{M}_D^\mathsf{T} & \boldsymbol{\mu}_R & \mathbf{M}_N^\mathsf{T} \\ \mathbf{0}_{n\times 3} & \mathbf{M}_N & \boldsymbol{\mu}_S \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^C \\ S_L \end{pmatrix} + \text{H.c.}$$

General inverse seesaw

- Mass matrix:

$$-\mathcal{L}^{\nu}_{\mathrm{mass}} = \frac{1}{2}\left(\overline{\nu}_L^C, \overline{\nu}_R, \overline{S}_L^C\right)\begin{pmatrix} \mathbf{0}_3 & \mathbf{M}_D & \mathbf{0}_{3\times n} \\ \mathbf{M}_D^{\mathsf{T}} & \boxed{\boldsymbol{\mu}_R} & \mathbf{M}_N^{\mathsf{T}} \\ \mathbf{0}_{n\times 3} & \mathbf{M}_N & \boxed{\boldsymbol{\mu}_S} \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^C \\ S_L \end{pmatrix} + \mathrm{H.c.}$$

Dev, Pilaftsis ‘12

Tree-level mass (for μ_S = 0)
Vanishes

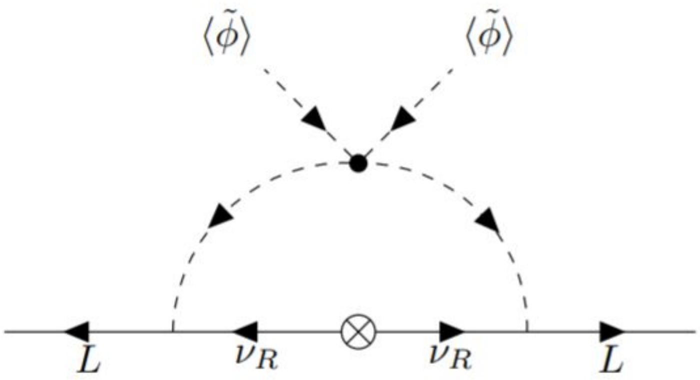
Mohapatra, Valle ‘86

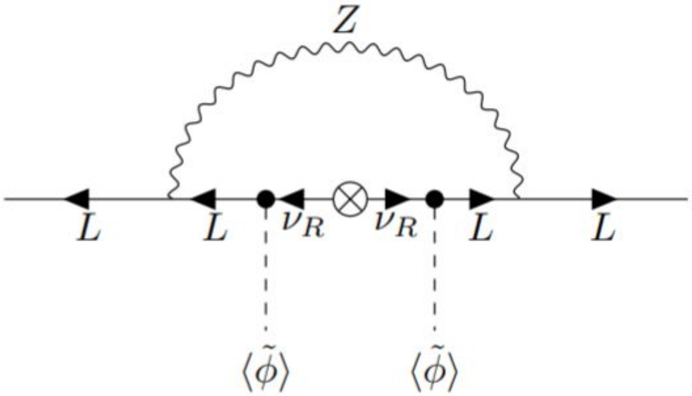
Tree-level mass (for μ_R = 0) is

$$\mathbf{m}_\nu = -M_D M_N^{-1}\mu_S M_N^{-1\mathsf{T}} M_D^{\mathsf{T}} + \mathcal{O}(\mu_S^3)$$

One-loop neutrino masses

Pilaftsis ‘92
Grimus ‘02
Ma ‘06
Dev, Pilaftsis ‘12
...





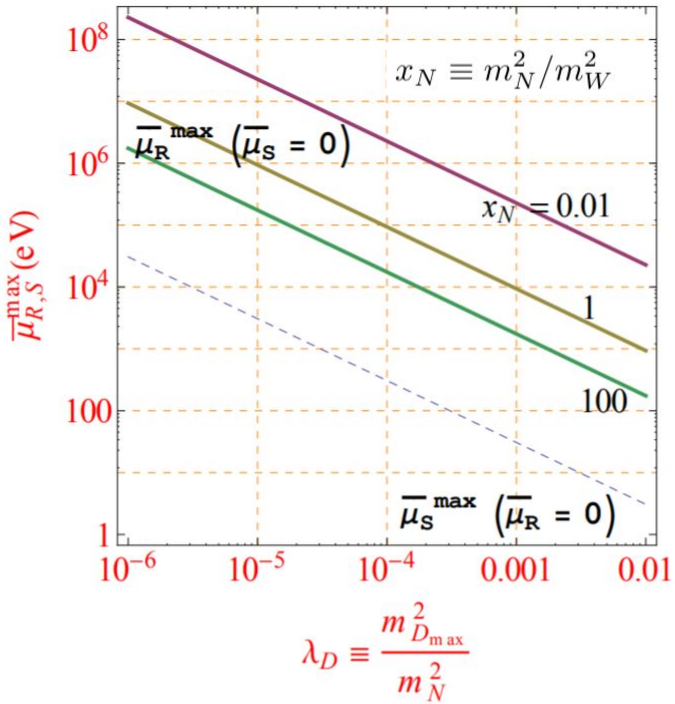
Flavour space calculation leads to the formula:

$$\Delta \mathbf{m}^\nu = \frac{\alpha_W}{16 M_W^2} \mathcal{M}_D \mathcal{M}_S \left[\frac{m_H^2}{\mathcal{M}_S^2 - m_H^2 \mathbf{1}_n} \ln \frac{\mathcal{M}_S^2}{m_H^2} + \frac{3 M_Z^2}{\mathcal{M}_S^2 - M_Z^2 \mathbf{1}_n} \ln \frac{\mathcal{M}_S^2}{M_Z^2} \right] \mathcal{M}_D^T$$

$$\mathcal{M}_S = \begin{pmatrix} \mu_R & M_N^T \\ M_N & 0 \end{pmatrix}$$

$$\mathcal{M}_D = (M_D, \mathbf{0})$$

One-loop neutrino masses



Dev, Pilaftsis 1209.4051

- The results show that LNV is less constrained by neutrino masses in the radiative scenario relative to the standard inverse seesaw
- For the same mixing, bigger values for the LNV parameter can be obtained for the case μ_S = 0, μ_R non zero due to loop suppression

Supersymmetric seesaw

- Superpotential

$$W = W_{\mathrm{MSSM}} + \widehat{L} i\sigma_2 \widehat{H}_u \mathbf{Y}_\nu \widehat{N}^C + \frac{1}{2}\widehat{N}^C \mathbf{m}_M \widehat{N}^C$$

- The new superfield has RH neutrinos ν_R and RH sneutrinos $\tilde{\nu}_R$
- Extra parameters from soft SUSY breaking

$$-\mathcal{L}_{\mathrm{soft}} = -\mathcal{L}_{\mathrm{soft}}^{\mathrm{MSSM}} + \tilde{\nu}_R^* \mathbf{m}_{\tilde{\nu}}^2 \tilde{\nu}_R + \left(\tilde{\nu}_R^* \boxed{\mathbf{b}_\nu \mathbf{m}_M} \tilde{\nu}_R^* + \tilde{L}^{\mathsf{T}} i\sigma_2 H_u \mathbf{Y}_\nu \mathbf{A}_\nu \tilde{\nu}_R^* + \mathrm{H.c.}\right)$$

- We assume: $\mathbf{m}_{\tilde{\nu}}^2 = m_{\tilde{\nu}}^2 \mathbf{1}_{n_R}\,,\qquad \mathbf{A}_\nu = A_\nu \mathbf{1}_{n_R}\,,\qquad \mathbf{b}_\nu = b_\nu \mathbf{1}_{n_R}$

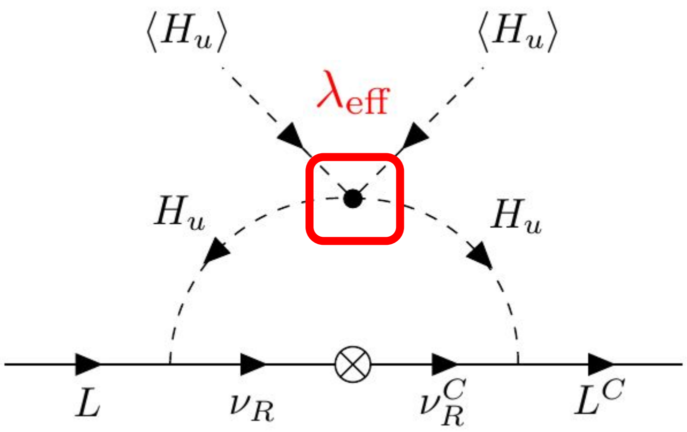
Supersymmetric seesaw

- The tree-level seesaw neutrino mass matrix is not modified by SUSY
- Radiative corrections **must vanish in the supersymmetric limit** $\tan\beta = 1,\ \mu = 0 \text{ and } M_{\mathrm{SUSY}} \to 0$ M. Grisaru, W. Siegel, M. Rocek '79
- This is due to the non-renormalisation of the superpotential
- Radiative neutrino mass scenarios are of particular interest since **LNV observables could be less constrained by neutrino masses**

Supersymmetric seesaw

- The SM-like diagrams now involve the *Z* and the up-type Higgs H_u
- Its quartic coupling receives sizeable corrections from stop loops to raise the predicted Higgs mass from $m_h \leq M_Z$ to $m_h \simeq 125 \text{ GeV}$

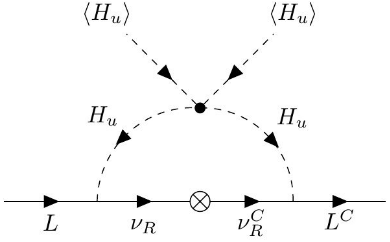
Ellis, Ridolfi, Zwirner '91
Haber, Hempfling '91
Okada, Yamaguchi, Yanagida '91

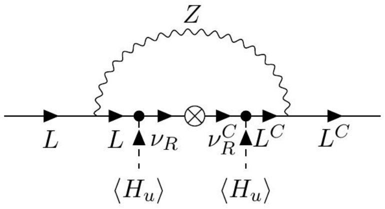


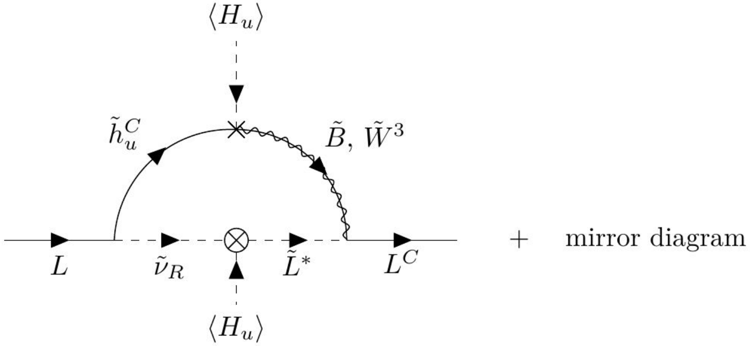
- We assume a simplified approach where we promote the tree-level quartic coupling to an effective one

One-loop corrections in SUSY

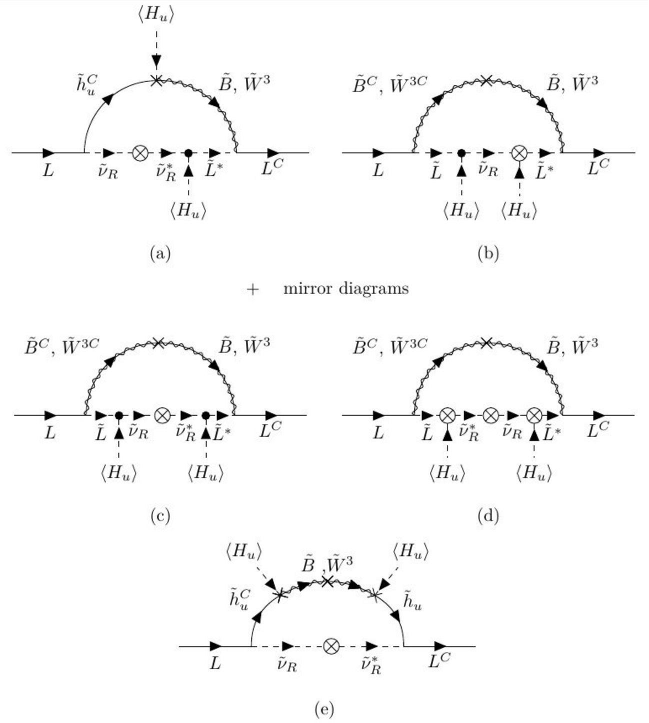
SUSY diagrams





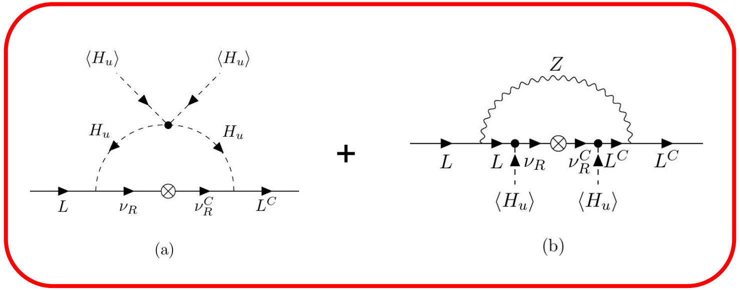


SUSY breaking diagrams



Candia da Silva, Pilaftsis 2008.05450

Cancellation scenarios: bilinear case



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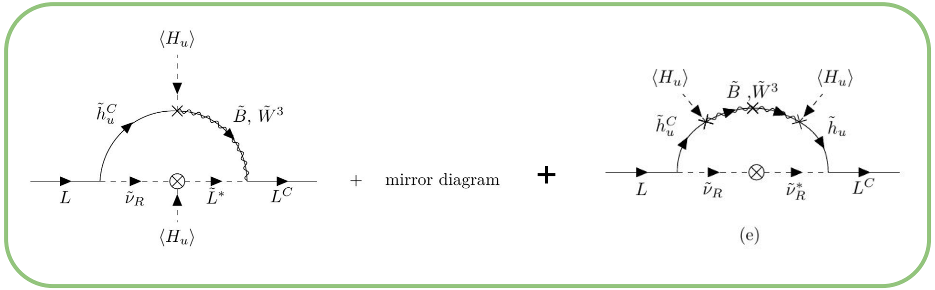
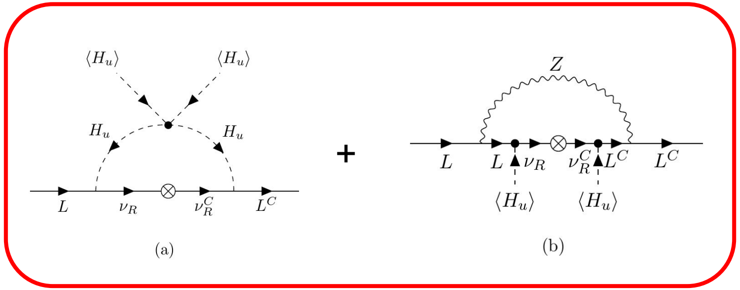


These corrections dominate when the singlet sector is nearly supersymmetric.
Assuming $b_\nu \neq 0$,

$$\Sigma = \mathbf{m}_D \mathbf{m}_M^\dagger f_1(\mathbf{m}_M \mathbf{m}_M^\dagger)\mathbf{m}_D^T + b_\nu^* \mathbf{m}_D \mathbf{m}_M^\dagger f_2(\mathbf{m}_M \mathbf{m}_M^\dagger)\mathbf{m}_D^T$$

Some values of the Majorana sneutrino mass screen the corrections to the neutrino mass!

Cancellation scenarios: trilinear case



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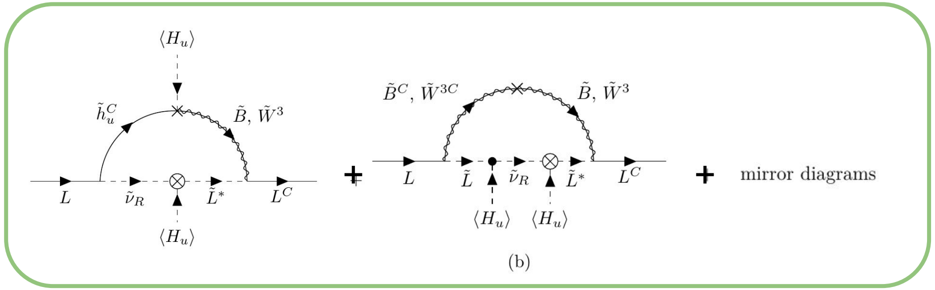


Another interesting scenario is found when Assuming $b_\nu = 0, \ \mathbf{A}_\nu \neq 0$

$$\Sigma = \mathbf{m}_D \mathbf{m}_M^\dagger f_1(\mathbf{m}_M \mathbf{m}_M^\dagger) \mathbf{m}_D^T + \mathbf{m}_D \left[(\mathbf{A}_\nu - \mu^* \cot\beta \mathbf{1}_{n_R}) \mathbf{m}_M^\dagger f_3(\mathbf{m}_M \mathbf{m}_M^\dagger) + \text{transpose} \right] \mathbf{m}_D^T$$

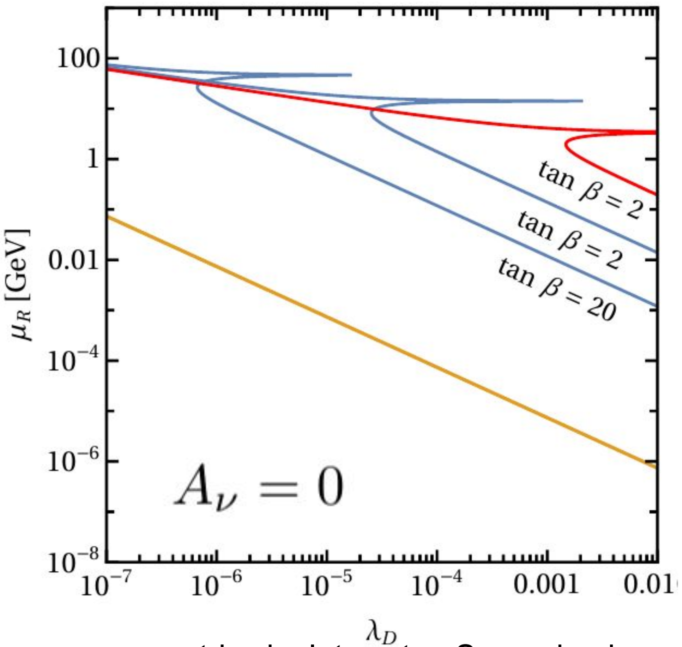
In this case, some values of the soft trilinear parameter could screen the neutrino masses

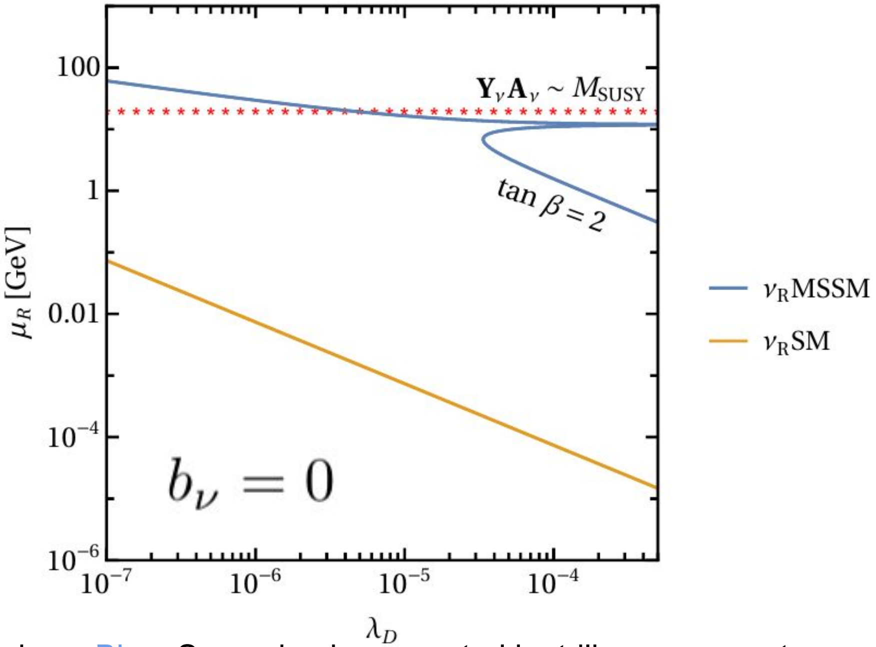
Numerical results

- We evaluate the loop corrections for the n = 2 radiative inverse seesaw
- The free parameters are adjusted to enforce agreement with low energy neutrino data
- The quartic Higgs coupling is adjusted to agree with the observed value of the Higgs mass

Parameter	Numerical value/interval
$\tan\beta$	2, 20
μ	1200 GeV
M_1	1500 GeV
M_2	1500 GeV
m_h	125.38±0.14 GeV
m_A	5000 GeV
m_H	5002.8 GeV
m_N	500 GeV
$m^2_{\tilde{\ell}}$	$(3500\ \text{GeV})^2$
μ_R	$[10^{-6}, 10^2]$ GeV

Numerical results

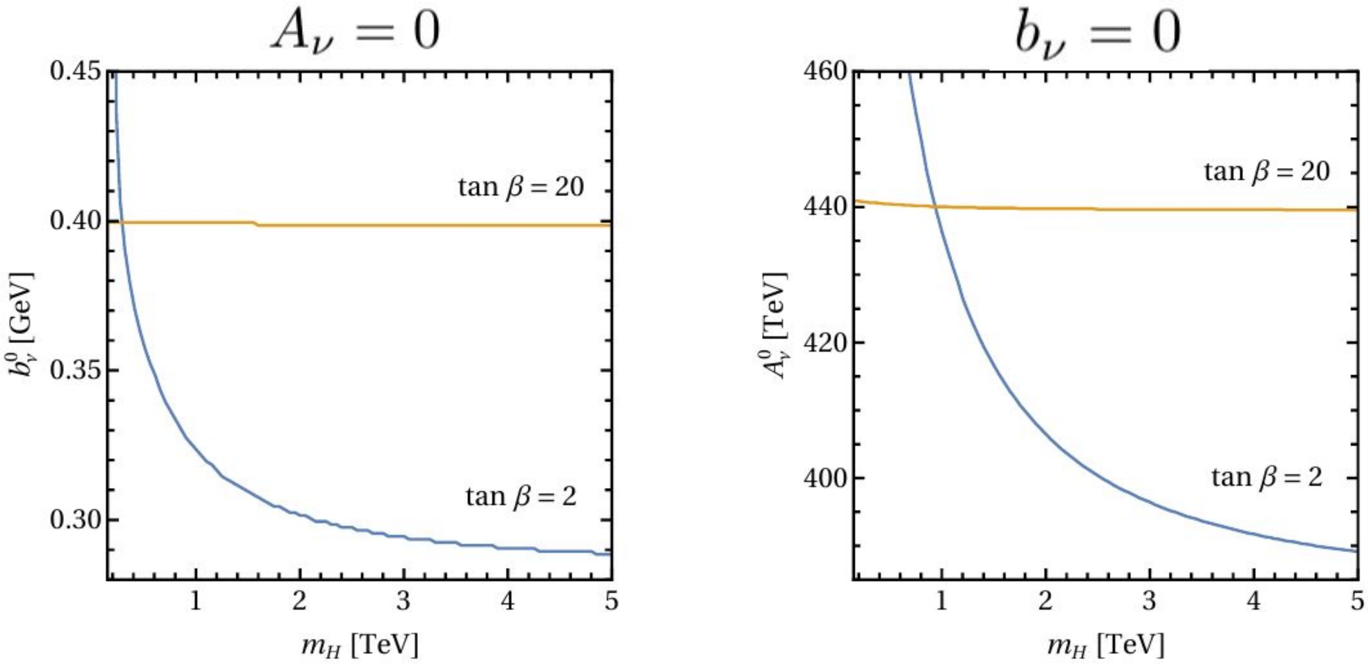




Red: Fully supersymmetric singlet sector. Screening is generated by mu parameter
Blue: Screening is generated by sneutrino Majorana mass term

Blue: Screening is generated by trilinear parameter

Numerical results



As tan beta increases, the heavy Higgs loop is less significant, allowing smaller b_ν

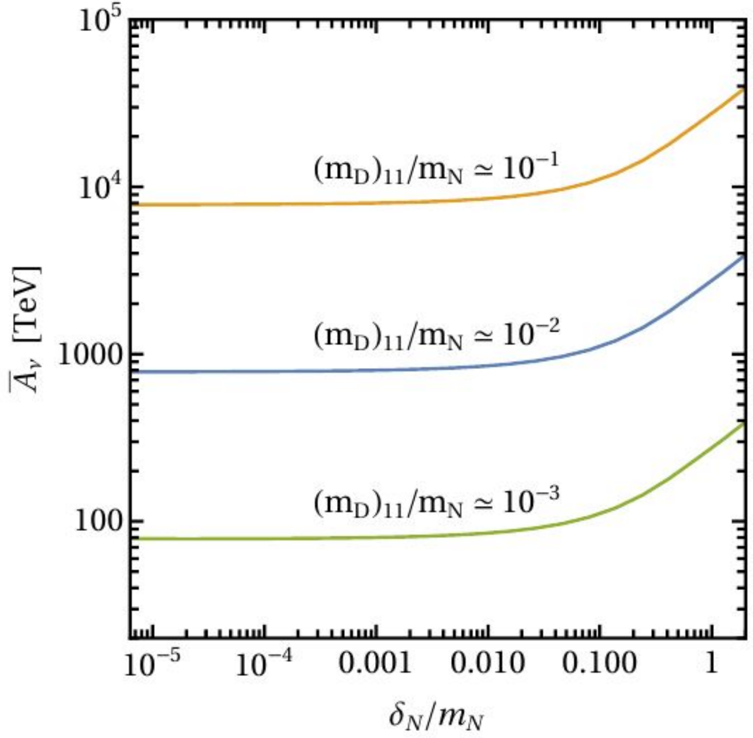
Other radiative neutrino models

$$\mathbf{m}_D = \frac{v_u}{\sqrt{2}} \begin{pmatrix} a & b\, e^{2i\pi/3} & c\, e^{-2i\pi/3} \\ a & b\, e^{2i\pi/3} & c\, e^{-2i\pi/3} \\ a & b\, e^{2i\pi/3} & c\, e^{-2i\pi/3} \end{pmatrix}$$

$$\mathbf{m}_M = \mathrm{diag}\left(m_N\,,\, m_N + \delta_N\,,\, m_N + 2\delta_N\right)$$

$$b = a\sqrt{1 + \frac{\delta_N}{m_N}}\,, \qquad c = a\sqrt{1 + \frac{2\delta_N}{m_N}}\,,$$

- This scenario leads to large corrections in the non-SUSY case (Pilaftsis ‘92) unless $\delta_N/m_N \lesssim 10^{-5}$, but these can be compensated by soft SUSY cancellations



Conclusions

- We performed a **complete flavour space calculation of one-loop corrections** to neutrino masses in the ν_RMSSM
- In the radiative SUSY seesaw, thanks to screening effects from sneutrino loops, **LNV is significantly less constrained by low energy neutrino data**
- In the $\nu_R\mathrm{MSSM}$ **both the visible and DM sectors of the theory contribute to the generation of neutrino masses**
- The RH sneutrinos can be the DM when R parity is preserved

BACK-UP SLIDES

SUSY limit, effective coupling and Higgs mass

- Minimization conditions:

$$m_{H_d}^2 + |\mu|^2 = -B\mu\frac{v_u}{v_d} + \frac{1}{8}(g^2 + g'^2)(v_u^2 - v_d^2)$$

$$m_{H_u}^2 + |\mu|^2 = -B\mu\frac{v_u}{v_d} + \frac{1}{8}(g^2 + g'^2)(v_d^2 - v_u^2)$$

<u>SUSY limit:</u>

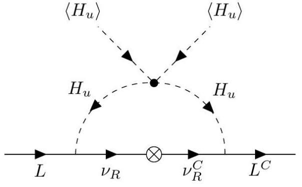
$\tan\beta = 1,\ \mu = 0$ and $M_{\rm SUSY} \to 0$

- We promote the tree-level quartic coupling of H_u from $\lambda_{\rm tree} = (g^2 + g'^2)/8$ to an effective coupling that renders the lightest mass eigenstate of the mass matrix

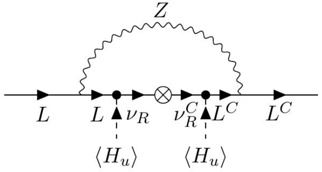
$$\mathcal{L}^{\rm mass}_{\text{CP-even}} = -\frac{1}{2}\begin{pmatrix}\phi_u & \phi_d\end{pmatrix}\begin{pmatrix} B\mu\cot\beta + \widetilde{M}_Z^2\sin^2\beta & -B\mu - M_Z^2\cos\beta\sin\beta \\ -B\mu - M_Z^2\cos\beta\sin\beta & B\mu\tan\beta + M_Z^2\cos^2\beta\end{pmatrix}\begin{pmatrix}\phi_u \\ \phi_d\end{pmatrix}$$

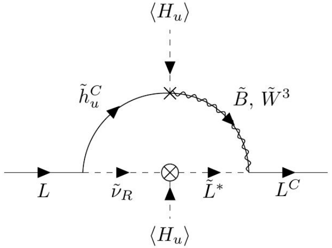
equal to 125 GeV. Above, we defined $\widetilde{M}_Z^2 \equiv 2\lambda_{\rm eff}(v_u^2 + v_d^2)$.

Analytical expressions



(a)





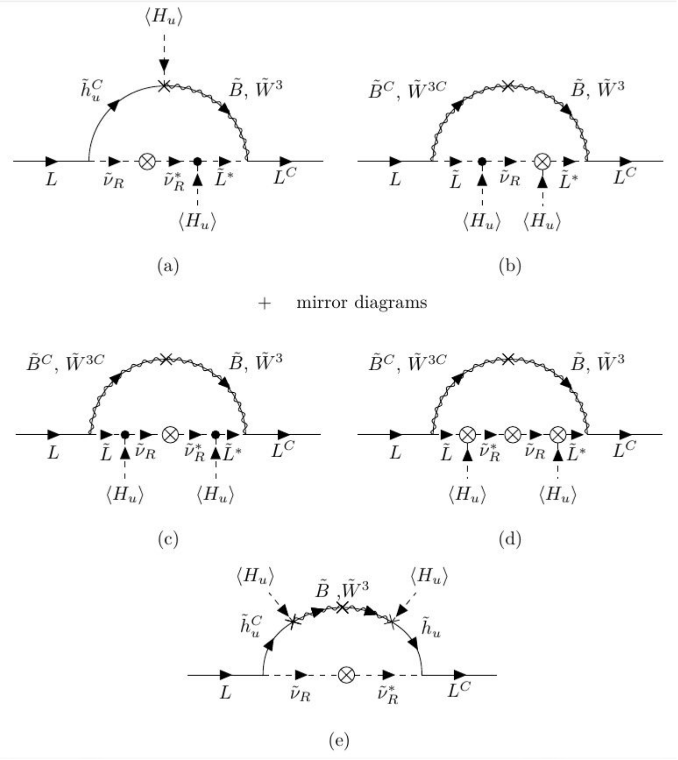
$$
\begin{aligned}
i\Sigma_M^{[1(\mathrm{a})]} = 2\lambda_{\mathrm{eff}}\, \mathbf{m}_D \mathbf{m}_M^\dagger \Big[& I_3(m_h^2, m_H^2, \mathbf{m}_M \mathbf{m}_M^\dagger) \\
& + m_A^2 (1 + 2\cos 2\beta) I_4(m_A^2, m_h^2, m_H^2, \mathbf{m}_M \mathbf{m}_M^\dagger) \\
& + m_A^4 \cos^2 2\beta\, I_5(0, m_A^2, m_h^2, m_H^2, \mathbf{m}_M \mathbf{m}_M^\dagger) \Big] \mathbf{m}_D^\mathsf{T}
\end{aligned}
$$

$$
i\Sigma_M^{[1(\mathrm{b})]} = \frac{3}{4}(g^2 + g'^2)\, \mathbf{m}_D \mathbf{m}_M^\dagger I_3(0, M_Z^2, \mathbf{m}_M \mathbf{m}_M^\dagger)\, \mathbf{m}_D^\mathsf{T}
$$

$$
\begin{aligned}
i\Sigma_M^{[2]} = \mathbf{m}_D \mathbf{m}_M^\dagger \Big[& A\, I_3\left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m_{\chi_4^0}^2\right) + \mathcal{B}_{A,B} I_4\left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m_{\chi_3^0}^2, m_{\chi_4^0}^2\right) \\
& + \mathcal{C}_{A,B,C} I_5\left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m_{\chi_2^0}^2, m_{\chi_3^0}^2, m_{\chi_4^0}^2\right) + \mathcal{D}_{A,B,C,D} I_6\left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m_{\chi_1^0}^2, m_{\chi_2^0}^2, m_{\chi_3^0}^2, m_{\chi_4^0}^2\right) \Big] \mathbf{m}_D^\mathsf{T}
\end{aligned}
$$

with $I_n(m_1^2, m_2^2, \ldots, m_n^2) \equiv \int \frac{d^d k}{(2\pi)^d} \prod_{j=1}^{n} \frac{1}{k^2 - m_j^2}$

Analytical expressions 2



$$
\begin{aligned}
i\Sigma_M^{[3(\mathrm{a})]} = {} & b_\nu^* \,\mathbf{m}_D \left(\mathbf{A}_\nu - \mu^* \cot\beta \mathbf{1}_{n_R}\right) \mathbf{m}_M^\dagger \Big[A\, I_4 \left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_4^0}\right) \\
& + \mathcal{B}_{A,B}\, I_5 \left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) + \mathcal{C}_{A,B,C}\, I_6 \left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_2^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \\
& + \mathcal{D}_{A,B,C,D}\, I_7 \left(\tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_1^0}, m^2_{\chi_2^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \Big] \mathbf{m}_D^\intercal \\
i\Sigma_M^{[3(\mathrm{b})]} = {} & \mathbf{m}_D \left(\mathbf{A}_\nu - \mu^* \cot\beta \mathbf{1}_{n_R}\right) \mathbf{m}_M^\dagger \Big[A' I_4 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_4^0}\right) \\
& + \mathcal{B}_{A',B'}\, I_5 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) + \mathcal{C}_{A',B',C'}\, I_6 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_1^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \\
& + \mathcal{D}_{A',B',C',D'}\, I_7 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_1^0}, m^2_{\chi_2^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \Big] \mathbf{m}_D^\intercal \\
i\Sigma_M^{[3(\mathrm{c})]} = {} & b_\nu^* \mathbf{m}_D \left(\mathbf{A}_\nu - \mu^* \cot\beta \mathbf{1}_{n_R}\right) \mathbf{m}_M^\dagger \Big[A' I_5 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_4^0}\right) \\
& + \mathcal{B}_{A',B'}\, I_6 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) + \mathcal{C}_{A',B',C'}\, I_7 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2} m^2_{\chi_1^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \\
& + \mathcal{D}_{A',B',C',D'}\, I_8 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_1^0}, m^2_{\chi_2^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \Big] \left(\mathbf{A}_\nu^\intercal - \mu^* \cot\beta \mathbf{1}_{n_R}\right) \mathbf{m}_D^\intercal, \\
i\Sigma_M^{[3(\mathrm{d})]} = {} & b_\nu \,\mathbf{m}_D \mathbf{m}_M^\dagger \mathbf{m}_M \Big[A' I_5 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, m^2_{\chi_4^0}\right) \\
& + \mathcal{B}_{A',B'}\, I_6 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) + \mathcal{C}_{A',B',C'}\, I_7 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, m^2_{\chi_1^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \\
& + \mathcal{D}_{A',B',C',D'}\, I_8 \left(\tilde{H}_1, \tilde{H}_1^*, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, \tilde{\mathbf{H}}_\mathbf{2}^\intercal, m^2_{\chi_1^0}, m^2_{\chi_2^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \Big] \mathbf{m}_M^\dagger \mathbf{m}_D^\intercal\,, \\
i\Sigma_M^{[3(\mathrm{e})]} = {} & b_\nu^* \,\mathbf{m}_D \mathbf{m}_M^\dagger \Big[A'' I_3 \left(\tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_4^0}\right) + \mathcal{B}_{A'',B''}\, I_4 \left(\tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \\
& + \mathcal{C}_{A'',B'',C''}\, I_5 \left(\tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_1^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \\
& + \mathcal{D}_{A'',B'',C'',D''}\, I_6 \left(\tilde{\mathbf{H}}_\mathbf{2}, \tilde{\mathbf{H}}_\mathbf{2}, m^2_{\chi_1^0}, m^2_{\chi_2^0}, m^2_{\chi_3^0}, m^2_{\chi_4^0}\right) \Big] \mathbf{m}_D^\intercal\,.
\end{aligned}
$$