Neutrino masses from SUSY breaking in radiative seesaw models

(based on arXiv:1406.0557)

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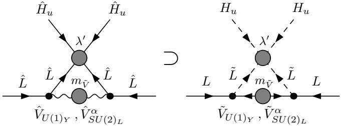
Introduction

$$\langle \hat{X} \rangle \sim \theta^2 F_X$$

- Hard-$\cancel{\text{SUSY}}$ terms and only MSSM visible fields: [Frere *et al* '99]
  - $\tilde{L}$-number breaking provided by hard-$\cancel{\text{SUSY}}$ terms that respect R-parity

$$\lambda' \sim \left(\frac{m_{\text{soft}}}{M_X}\right)^{1 \text{ or } 2} \lambda : \quad (\tilde{L}H_u)^2 \subset \frac{1}{M_X^2} \int d^2\theta \hat{X} (\hat{L}\hat{H}_u)^2 \text{ or } \tilde{L}H_d^\dagger \tilde{L}H \subset \frac{1}{M_X^2} \int d^4\theta \hat{X}^\dagger \hat{X} \hat{L} \hat{H}_d^\dagger \hat{L}\hat{H}$$

  - Turned into L-number breaking via gaugino fermion-number violation



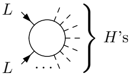
$$\Rightarrow m_\nu \sim \frac{\alpha}{4\pi} \frac{v^2}{M_X}$$

  - But, if $\cancel{\text{SUSY}}$ sector breaks L-number, why wouldn't generate $\frac{1}{M_X} \hat{L}\hat{L}\hat{H}_u\hat{H}_u \subset \mathcal{W}_{\text{eff}}$?
- Suppose $\cancel{\text{SUSY}}$ sector carries visible sector symmetries (e.g. forbid $H_u H_d$ so that $\mu \sim m_{\text{soft}}$). May forbid RH neutrino masses/couplings to visible sector: [Arkani-Hamed *et al* '00]
  - Majorana: $\frac{1}{M_X} \int d^4\theta \hat{X}^\dagger \hat{N}\hat{N} \supset m_{\text{soft}} NN$ and $\frac{1}{M_X} \int d^2\theta \hat{X} \hat{L}\hat{N}\hat{H}_u \supset \sqrt{\frac{m_{\text{soft}}}{M_X}} LNH_u \Rightarrow m_\nu \sim \frac{v^2}{M_X}$
  - Dirac: $\frac{1}{M_X^2} \int d^4\theta \hat{X}^\dagger \hat{L}\hat{N}\hat{H}_u \supset \frac{m_{\text{soft}}}{M_X} LNH_u \Rightarrow m_\nu \sim \frac{v\, m_{\text{soft}}}{M_X}$
- New visible sector symmetry may forbid unsuppressed terms & allow suppressed ones:
  - E.g. $U(1)'$ gauge symmetry may forbid LH_uN and $m_{\text{soft}} \tilde{L} H_u \tilde{N}$ [Demir *et al* '07]
  - and allow $\frac{m_{\text{soft}}}{M_X} LH_d^\dagger N \subset \frac{1}{M_X^2} \int d^4\theta \hat{X}^\dagger \hat{L}\hat{H}_d^\dagger \hat{N}$ and $\frac{m_{\text{soft}}^2}{M_X} \tilde{L}H_d^\dagger \tilde{N} \subset \frac{1}{M_X^3} \int d^4\theta \hat{X}^\dagger \hat{X} \hat{L}\hat{H}_d^\dagger \hat{N}$
  - Tree- and loop-level $LH_d^\dagger N \Rightarrow m_\nu \sim \frac{v\, m_{\text{soft}}}{M_X}$

Radiative m_ν in SUSY

Radiative m_ν $\xrightarrow[\text{(non-renormalisation theorem)}]{\text{SUSY}}$ m_ν from ~~SUSY~~

- Dimensionless suppression
- Maybe Dark Matter



$$\mathrm{OP}_\nu \subset \int d^4\theta\, \widehat{\mathrm{OP}}_\nu$$

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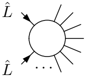
- ~~SUSY~~ sector needs not carry visible symmetries



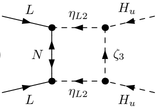
• *L*-number breaking can be independent of ~~SUSY~~ and still $m_\nu \propto$ ~~SUSY~~

- Not entirely obvious in component field calculations
- Examples in the literature:
  - Genuine radiative seesaw

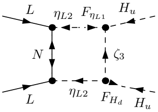
[Ma *et al* '14]

$$\frac{M_N}{2}\hat N\hat N + \mu \hat H_u \hat H_d + \mu_{L2}\hat\eta_{L1}\hat\eta_{L2} + \frac{\mu_{s3}}{2}\hat\zeta_3\hat\zeta_3 + f_9 \hat H_d\hat\eta_{L2}\hat\zeta_3 + f_{10}\hat H_u\hat\eta_{L1}\hat\zeta_3 + f_{16}\hat L\hat N\hat\eta_{L2} \subset \mathcal{W}$$

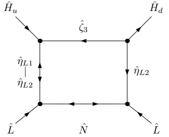
(e.g.)



$\Leftrightarrow$



$\subset$



  - *R*-parity violation

$$\frac{1}{M^2} L L H_u F^\dagger_{H_d} \quad \subset \quad \frac{1}{M^2}\int d^4\theta\, \hat L \hat L \hat H_u \hat H_d^\dagger$$

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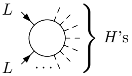

$$\mathrm{OP}_\nu \subset \int d^4\theta\, \widehat{\mathrm{OP}}_\nu$$

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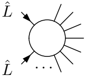

- L-number breaking can be independent of $\cancel{\text{SUSY}}$ and still $m_\nu \propto \cancel{\text{SUSY}}$

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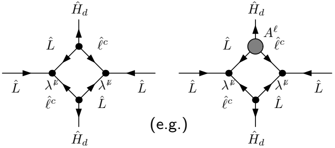

$$\Rightarrow \left.\begin{array}{l} \hat{L}\hat{L}\hat{H}_d^\dagger\hat{H}_d^\dagger \\ \hat{X}^\dagger\hat{L}\hat{L}\hat{H}_d^\dagger\hat{H}_d^\dagger \end{array}\right\} \subset \mathcal{K}_{\text{eff}} \rightarrow m^\nu \sim \frac{A^{\ell,d} - \mu\, c_\xi\, t_\beta}{16\pi^2}\left(\frac{m^{\ell,d}}{m^{\tilde{\ell},\tilde{d}}}\right)^2$$

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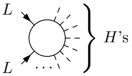

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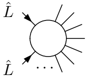
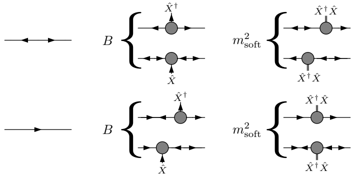


- L-number breaking can be independent of $\cancel{\text{SUSY}}$ and still $m_\nu \propto \cancel{\text{SUSY}}$

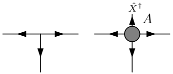
- Can classify the $\cancel{\text{SUSY}}$ contributions as:
  - Related to EWSB

$$\langle F^\dagger \rangle = \sum_H \mu_H \langle H \rangle + \sum_H \lambda_H \langle HH' \rangle \neq 0 \text{ or } \langle D \rangle = g \sum_H \langle H^\dagger \otimes_H H \rangle \neq 0$$

  - Otherwise: insertions of $\cancel{\text{SUSY}}$ spurions into internal lines or vertices



(e.g. soft-$\cancel{\text{SUSY}}$)



Radiative seesaws in SUSY

- Assume
  - L-number broken by 2 units at SUSY level with a radiative seesaw at scale M
  - Low energy Higgs sector of the MSSM

$$\langle F^{\dagger}_{H_{u,d}} \rangle = \mu \langle H_{d,u} \rangle \,,$$

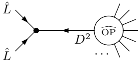
$$\langle D_{U(1)_Y} \rangle = \frac{g'}{2} \left(|\langle H_u \rangle|^2 - |\langle H_d \rangle|^2 \right) \,, \qquad \langle D^3_{SU(2)_L} \rangle = \frac{g}{2} \left(-|\langle H_u \rangle|^2 + |\langle H_d \rangle|^2 \right)$$

- Expectations

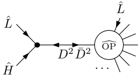
$$\frac{m_\nu}{v^2} \propto \frac{\mu}{M^2} \oplus \frac{g^2 v^2}{M^3} \oplus \frac{m_{\text{soft}}}{M^2}$$

- If $\frac{m_{\text{soft}}}{M}$ is small, supergraphs very convenient calculation tool
  - Automatic component field cancellations
  - Non-renormalisation theorem becomes manifest
  - Simpler Lorentz structure
  - Fewer diagrams

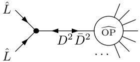
Radiative seesaws in SUSY: Understanding ~~SUSY~~ contributions



$\int d^4\theta D^2(\hat{L}\hat{L})\widehat{\text{OP}}$



$\int d^4\theta \hat{L}\hat{H}\,\widehat{\text{OP}}[\hat{L}]$



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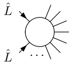


- In general $\text{OP}_\nu = LL \otimes \text{Higgses} \subset \int d^4\theta\, \widehat{\text{OP}}_\nu$:

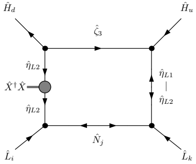
$$\widehat{\text{OP}}_\nu \in \left[\hat{A}\, D^2(\hat{L}\hat{L}\hat{H}^k) \text{ or } \hat{B}^\dagger\, \hat{L}\hat{L}\right] \otimes \left\{\hat{H}, \hat{H}^\dagger, D^2 Z, \bar{D}^2\hat{Z}^\dagger, D\bar{D}^2 D\hat{V}\right\}^n$$

$$D\bar{D}^2 D\hat{V}| = D \supset g\hat{H}^\dagger \otimes H\,, \quad \bar{D}^2\hat{Z}^\dagger| = F_Z^\dagger \supset \mu H \text{ or } \lambda H \otimes H'$$

$$\int d^4\theta \hat{A} \;\text{ and }\; \int d^2\bar{\theta}\hat{B}^\dagger \sim \text{Constants and/or Higgses}$$

- Pure-~~SUSY~~$_{\text{EWSB}}$ contributions $\hat{A} \sim \hat{V}$ or $\hat{B}^\dagger\hat{B}$ and $\hat{B}^\dagger \sim \hat{Z}^\dagger$ or $D^2\hat{V}$
- ~~SUSY~~$_{\text{EWS}}$ contributions
  - Insertions of spurionic constants $D^2\hat{X}$ and $\bar{D}^2\hat{X}^\dagger$

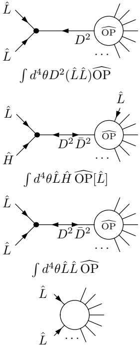
(e.g.)



$$\frac{1}{M^4}\int d^4\theta\, \bar{D}^2 D^2 \left(\frac{\hat{X}^\dagger\hat{X}}{M_X^2}\right)_{m^2_{\text{soft}}} \hat{L}\hat{L}\hat{H}_u\hat{H}_d^\dagger \supset \frac{\mu m^2_{\text{soft}}}{M^4} LLH_uH_u$$

  - Insertions of ~~SUSY~~ spurions $\hat{X}$ and $\hat{X}^\dagger$

Radiative seesaws in SUSY: Understanding ~~SUSY~~ contributions



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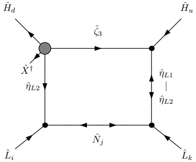
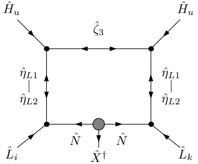


$$\frac{1}{M^2}\int d^4\theta \left(\frac{\hat{X}^\dagger}{M_X}\right)_A \hat{L}\hat{L}\hat{H}_u\hat{H}_d^\dagger \supset \frac{A^*}{M^2} LLH_uH_d^\dagger$$

Radiative seesaws in SUSY: $\not{\text{SUSY}}_{\text{EWS}}$ superoperators

- Identically zero topologies in SUSY limit can contribute through internal $\not{\text{SUSY}}$ effects

(e.g.)



$$\frac{1}{M^3}\int d^4\theta\,(\hat{X}^\dagger)_B \hat{L}\hat{L}\hat{H}_u\hat{H}_u \supset \frac{B^*}{M^3} LLH_uH_u$$

- Ask in general: which superoperators only contribute to OP_ν by insertions of $\not{\text{SUSY}}$ spurions?

1. $\widehat{\text{OP}} = D^2(\hat{L}\hat{L}\hat{H}^n) \otimes \Big($a superoperator whose D-term is zero at $p_{\text{ext}} = 0\Big)$
2. $\widehat{\text{OP}} = \hat{L}\hat{L} \otimes \Big($a superoperator whose $F^\dagger$-term is zero at $p_{\text{ext}} = 0\Big)$

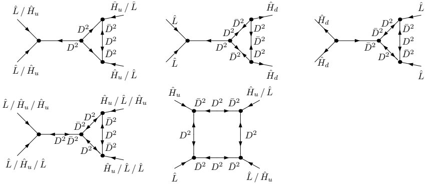
- If in a radiative seesaw model all leading superoperators are of this type:

$$m_\nu^{\text{leading}} \propto \text{soft-}\not{\text{SUSY}} \text{ effects in seesaw mediators}$$

- $m_\nu^{\text{leading}} \propto \frac{m_{\text{soft}}}{M}$ without resorting to non-standard $\not{\text{SUSY}}$ terms

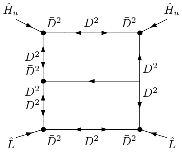
Radiative seesaws in SUSY: ~~SUSY~~$_{\text{EWS}}$ one-loop topologies for $LLHH$

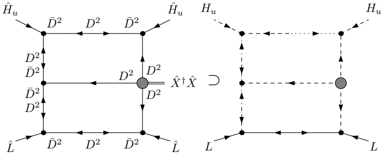
- 1 1PI + 4 based on radiative vertices:
  - $D^2(\hat{L}\hat{L})\hat{H}_u\hat{H}_u$, $\hat{L}\hat{L}D^2(\hat{H}_u\hat{H}_u)$, $D^2(\hat{L}\hat{L})\hat{H}_d^\dagger\hat{H}_d^\dagger$ and $\hat{L}\hat{L}\bar{D}^2(\hat{H}_d^\dagger\hat{H}_d^\dagger)$
    – type-II without a chirality flip
  - $\hat{L}\hat{L}\hat{H}_u\hat{H}_u$ (1PR)
    – type-II with a chirality flip, type-I and -III
  - $\hat{L}\hat{L}\hat{H}_u\hat{H}_u$ (1PI)



- 14 based on self-energies
- Dimensional suppressions:
  - $\mu m_{\text{soft}}/M^3$ or m_{soft}^2/M^3 to $\mu^2 m_{\text{soft}}/M^4$, $\mu m_{\text{soft}}^2/M^4$ or m_{soft}^3/M^4
  - Non-minimal least suppressions consequence of holomorphy: higher loops contain m_{soft}/M^2 contributions:

(e.g.)





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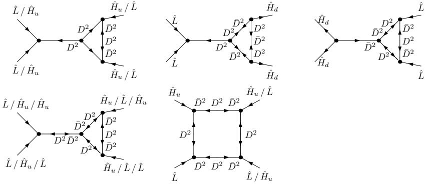

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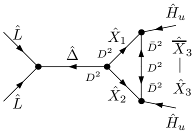
Construction of models

- Pick a symmetry that forbids undesired leading topologies and allow desired
- General criterion: radiative seesaw either couples to $\hat{H}_u$ or to $\hat{H}_d^\dagger$, but not both
- However, this structure is not respected by
  - Higher-loop contributions to operators of leading dimension
  - Operators of higher dimension

A Model Example

- Base topology



$$\hat{\rho}^\dagger \hat{\Delta}^\dagger \hat{H}_u \hat{H}_u \to \langle \rho^\dagger \rangle \hat{\Delta}^\dagger \hat{H}_u \hat{H}_u + \hat{\rho}^\dagger \hat{\Delta}^\dagger \hat{H}_u \hat{H}_u$$

- Charges

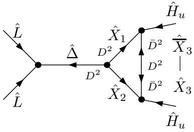
	$SU(2)_L \otimes U(1)_Y$	$U(1)_X$	$U(1)_L$
$\hat{\Delta}$	$(\mathbf{3}, 1)$	0	-2
$\hat{\rho}$	$(\mathbf{1}, 0)$	0	2
$\hat{X}_1$	$(\mathbf{2}, -1/2)$	1	1
$\hat{X}_2$	$(\mathbf{2}, -1/2)$	-1	1
$\hat{X}_3$	$(\mathbf{1}, 0)$	1	-1
$\hat{\overline{X}}_3$	$(\mathbf{1}, 0)$	-1	-1

- Superpotential

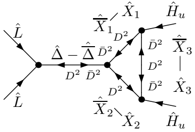
$$\begin{aligned} \mathcal{W} &= \mathcal{W}_{\text{MSSM}} + M_\Delta \hat{\Delta} \hat{\overline{\Delta}} + \sum_{i=1}^{2} M_{X_i} \hat{X}_i \hat{\overline{X}}_i + \lambda \hat{\rho} \hat{X}_3 \hat{\overline{X}}_3 \\ &\quad + \hat{H}_u \left(\lambda_1 \hat{X}_1 \hat{\overline{X}}_3 + \lambda_2 \hat{X}_2 \hat{X}_3 \right) + \hat{\Delta} \left(\lambda_L \hat{L} \hat{L} + \lambda_X \hat{X}_1 \hat{X}_2 \right) + \bar{\lambda}_X \hat{\overline{\Delta}} \hat{\overline{X}}_1 \hat{\overline{X}}_2 \end{aligned}$$

A Model Example

- L-number recovered if any in $\{\lambda_1, \lambda_2, \lambda_L\}$, or both λ_X and any in $\{\bar{\lambda}_X, M_\Delta, M_{X_1}, M_{X_2}\}$ goes to zero
  - Contribution to neutrino masses proportional to either $\lambda_1 \lambda_2 \boldsymbol{\lambda}_L \lambda_X^*$ or $\lambda_1 \lambda_2 \boldsymbol{\lambda}_L \bar{\lambda}_X M_\Delta M_{X_1} M_{X_2}$
  - Leading perturbation theory contributions:



$\frac{1}{M^2} D^2(\hat{L}\hat{L})\hat{H}_u\hat{H}_u$



$\frac{1}{M} \hat{L}\hat{L}\hat{H}_u\hat{H}_u$

- Leading $LLHH$ in the absence of ~~SUSY~~ spurions:

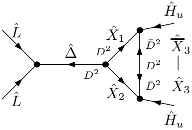
$$\int d^4\theta\, D^2(\hat{L}\hat{L})\hat{H}_u\hat{H}_u \;=\; -\Box(\tilde{L}\tilde{L})\left[\tilde{H}_u\tilde{H}_u + 2F_{H_u}H_u\right] - \Box(H_u H_u)\left[LL + 2F_L\tilde{L}\right] + 4\,(p_L + p_{\tilde{L}})^2\, L\tilde{H}_u\tilde{L}H_u$$

$$\int d^4\theta\, \hat{L}\hat{L}\hat{H}_u\hat{H}_u \;=\; 0 \quad \left(\text{or} \quad \int d^4\theta\, \hat{\bar{\Delta}}\hat{H}_u\hat{H}_u = 0\right)$$

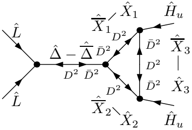
$m_\nu^{\text{leading}} = 0$ in the absence of ~~SUSY~~ spurions

A Model Example

- L-number recovered if any in $\{\lambda_1, \lambda_2, \lambda_L\}$, or both λ_X and any in $\{\bar{\lambda}_X, M_\Delta, M_{X_1}, M_{X_2}\}$ goes to zero
  - Contribution to neutrino masses proportional to either $\lambda_1 \lambda_2 \boldsymbol{\lambda}_L \lambda_X^*$ or $\lambda_1 \lambda_2 \boldsymbol{\lambda}_L \bar{\lambda}_X M_\Delta M_{X_1} M_{X_2}$
  - Leading perturbation theory contributions:

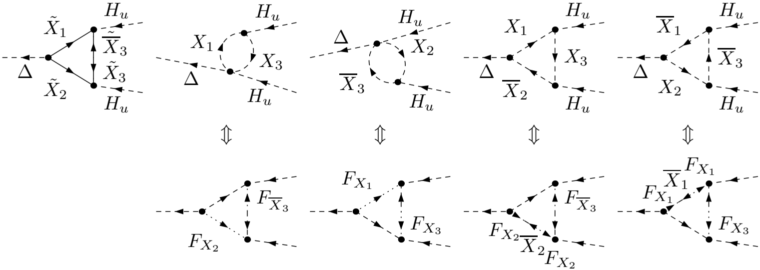


$\frac{1}{M^2} D^2(\hat{L}\hat{L})\hat{H}_u\hat{H}_u$



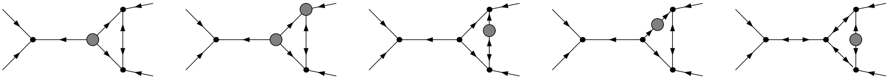
$\frac{1}{M} \hat{L}\hat{L}\hat{H}_u\hat{H}_u$

- Leading $LLHH$ in the absence of ~~SUSY~~ spurions:



A Model Example

- Leading soft-~~SUSY~~ effects

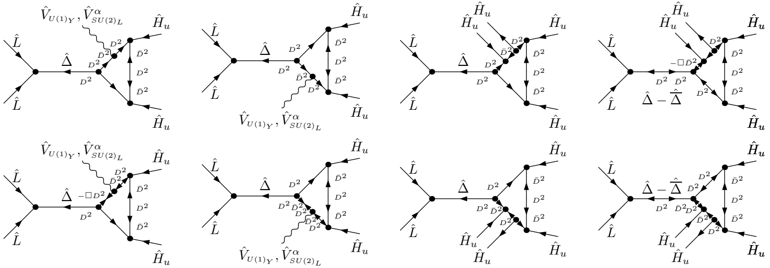


$$\frac{\mu^* A^*}{M^3} LLH_uH_d^\dagger \oplus \frac{A^* A \oplus m_{\text{soft}}^2 \oplus B^*}{M^3} LLH_uH_u$$

- Or up to order 3

$$\frac{1}{64\pi^2 M_\Delta^2}\left(\mathbf{a}\left[\frac{2m_{\text{soft}}^2}{M_X} + \frac{2A}{M_X}\left(A_X^* - \frac{B_\Delta}{M_\Delta}\right) - \frac{A_X^* B_X}{M_X^2}\right] + \mathbf{b} M_\Delta \frac{B_X}{M_X^2}\right) LLH_uH_u$$
$$-\frac{\mathbf{a}}{32\pi^2 M_\Delta^2}\left(\frac{\mu^*}{M_X}\right)\left[A_X^*\left(1 - \frac{m_{\text{soft}}^2}{M_X^2} - \frac{(m_{\text{soft}}^2)_\Delta}{M_\Delta^2}\right) - \frac{B_\Delta}{M_\Delta}\right] LLH_uH_d^\dagger$$
$$-\frac{\mathbf{a}}{192\pi^2 M_\Delta^2}\left(\frac{\mu^*}{M_X}\right)^2 \frac{A_X^* B_X}{M_X^2} LLH_d^\dagger H_d^\dagger$$

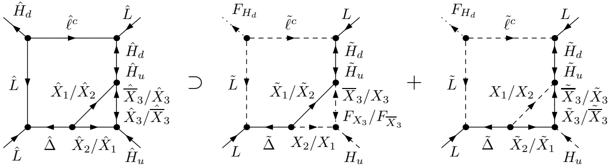
A Model Example



$$\frac{1}{M^3} D^2(\hat{L}\hat{L})\hat{H}_u\hat{H}_u\hat{V}_{U(1)_Y,SU(2)_L}\,, \quad \frac{1}{M^5} D^2(\hat{L}\hat{L})\hat{H}_u\hat{H}_u\hat{H}_u^\dagger\hat{H}_u\,, \quad \frac{1}{M^4}\hat{L}\hat{L}\hat{H}_u\hat{H}_u\hat{H}_u^\dagger\hat{H}_u$$

- At one-loop order $\not{\text{SUSY}}_{\text{EWSB}}$ contributions have dimension-7: $\frac{g'^2 \oplus g^2}{M^3}$, $\frac{|\mu|^2}{M^5}$, $\frac{\mu}{M^4}$
- At higher-loops there are contributions to dimension-5 operators that are not proportional to $\not{\text{SUSY}}$ effects involving the seesaw mediators

(e.g.)



Conclusions

- L-number breaking can take place at SUSY level and still $m_\nu \propto \not{SUSY}$
- There are models in which m_ν^{leading} is proportional to soft-$\not{SUSY}$ involving the seesaw mediators, say m. Schematically

$$\frac{m_\nu^{\text{leading}}}{v^2} \propto \frac{\mu\, m \oplus m^2}{M^3}$$

- In these models the smallness m can be partially responsible for the smallness of m_ν
- Ballpark figure

$$M \sim 10\ \text{TeV}\,,\ \lambda \sim 0.1\,,\ \mu \sim 2\ \text{TeV}\ : \quad m \lesssim 100\ \text{GeV}\,,\ m_\nu \lesssim 1\ \text{eV}$$

- Explicative power of small m is limited by the size of next-to-leading order contributions that are independent of m
- Caveat: how small can m be does depend on the amount of hierarchy in soft-$\not{SUSY}$ terms, i.e. on how small is $m/m_{\text{SM-sparticles}}$. Complete understanding would of course require an actual model of $\not{SUSY}$
- Phenomenological virtues:
  - Small m_ν generated by new physics near the TeV scale
  - No need for small superpotential couplings
  - No need for large hierarchies in superpotential mass scales