Neutrino Mass from Higher than $d = 5$ Effective Operators in SUSY, and its Test at the LHC

M. B. Krauss, T. Ota, W. Porod, W. Winter,
Phys. Rev. D (in press), (2011), arXiv:1109.4636

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December 8, 2011

Motivation

- Standard model has been tested very successfully
  BUT it has some limitations
  (Hierarchy problem, unification of gauge couplings, neutrino masses, ...)
  $\rightarrow$ Hints for **physics beyond the SM**
- Observation of neutrino flavor oscillations
  $\rightarrow$ tiny neutrino masses
- (Type I) **See-saw mechanism** generates small m_ν naturally
  BUT requires new physics at GUT scale
  (not testable!)
- **Extensions** of the see-saw
  $\rightarrow$ new physics at **TeV scale**
  (Radiative mass generation, inverse see-saw, higher dimensional effective operators,...)
- New particles with **phenomenology at LHC**

Introduction to Effective Operators

- BSM physics can be parameterized as **tower of effective operators**

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}}^{d=5} + \mathcal{L}_{\mathrm{eff}}^{d=6} + \cdots, \quad \text{with} \quad \mathcal{L}_{\mathrm{eff}}^{d} \propto \frac{1}{\Lambda_{\mathrm{NP}}^{d-4}} \mathcal{O}^{d}$$

  suppressed by powers of the new physics scale $\Lambda_{\mathrm{NP}}^{d-4}$
- Describing **low energy effects** of a fundamental theory at **high energies**
- Obtained by **integrating out** heavy fields
- Good **approximation** below heavy mass scale

Examples

- Fermi theory
- Seesaw mechanism
- ...

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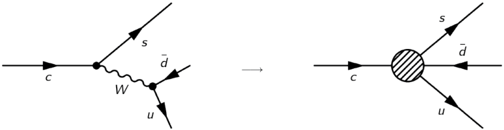
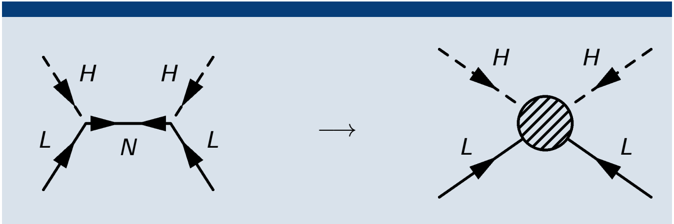


Effective Operators

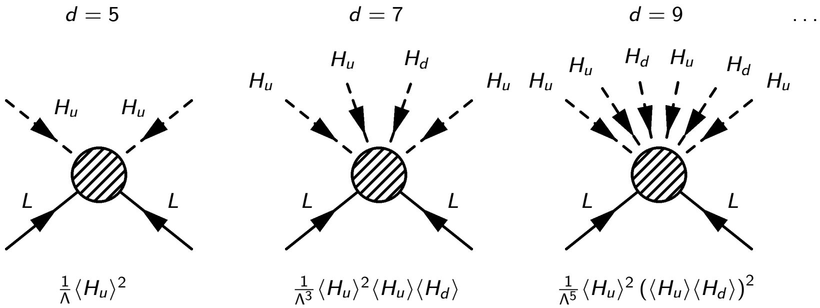
- At d=5 we haven the **Weinberg operator** $\mathcal{O}_W = (\overline{L^c} \mathrm{i}\tau^2 H)\,(H \mathrm{i}\tau^2 L)$
- Obtained from see-saw after integrating out heavy mediators



- After EWSB $\frac{{Y_N}^2}{m_N} \langle H \rangle^2 \bar{\nu}^c \nu$ → generates neutrino mass $m_\nu^{\text{eff}} \propto \frac{v^2}{\Lambda}$, with $\Lambda = m_N$

Higher-Dimensional Effective Operators

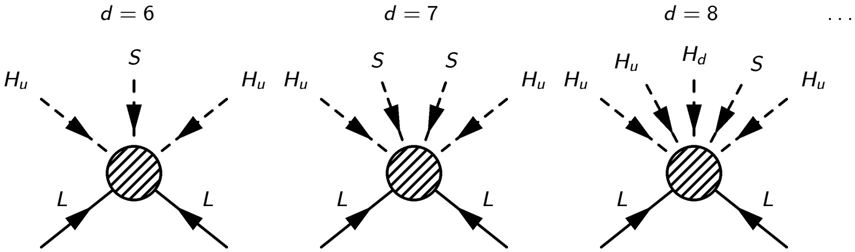
Possible in theories with two Higgs doublets (THDM, MSSM, ...)



- Neutrino mass is generated by **higher dimensional operators**
- New physics scale can be at **lower energy**
- Lower dimensional operators must be forbidden

Higher-Dimensional Effective Operators II

Additional operators are possible with an additional scalar that has a VEV (like in the NMSSM)



$\frac{1}{\Lambda^2}\langle H_u\rangle^2\langle S\rangle$ $\quad$ $\frac{1}{\Lambda^3}\langle H_u\rangle^2\langle S\rangle^2$ $\quad$ $\frac{1}{\Lambda^4}\langle H_u\rangle^2\,\langle H_u\rangle\langle H_d\rangle\langle\, S\rangle$

Possible Effective Operators in the NMSSM

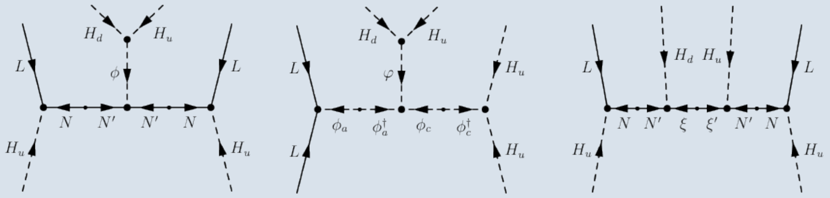
	Op.#	Effective interaction	Charge	Same as
$d=5$	1	LLH_uH_u	$2q_L + 2q_{H_u}$	
$d=6$	2	LLH_uH_uS	$2q_L + q_{H_u} - q_{H_d}$	
$d=7$	3	$LLH_uH_uH_dH_u$	$2q_L + 3q_{H_u} + q_{H_d}$	
	4	LLH_uH_uSS	$2q_L - 2q_{H_d}$	
$d=8$	5	$LLH_uH_uH_dH_uS$	$2q_L + 2q_{H_u}$	#1
	6	LLH_uH_uSSS	$2q_L + 2q_{H_u}$	#1
$d=9$	7	$LLH_uH_uH_dH_uH_dH_u$	$2q_L + 4q_{H_u} + 2q_{H_d}$	
	8	$LLH_uH_uH_dH_uSS$	$2q_L + q_{H_u} - q_{H_d}$	#2
	9	LLH_uH_uSSSS	$2q_L + q_{H_u} - q_{H_d}$	#2

Table: Effective operators generating neutrino mass in the NMSSM up to $d = 9$.

Characteristics

- More constraints in SUSY than in THDM (c.f. Bonnet, Hernandez, Ota, Winter (2009); *arXiv:0907.3143*)
- Condition for discrete charges of fields from neutrality of superpotential
- Rules out some operators as leading contribution to neutrino mass
- Several possible fundamental theories can lead to the same effective operator at low energies

Possible Decompositions for $d = 7$

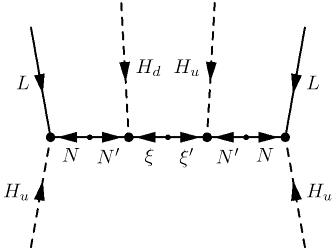


- Same external fields, different mediators
- Scalar mediators potentially problematic:
  VEV of scalar $\rightarrow$ induces $d = 6$ operator

A $d = 7$ example

Superpotential

$$W = W_{\text{NMSSM}} + Y_N \hat{N}\hat{L}\cdot\hat{H}_u - \kappa_1 \hat{N}'\hat{\xi}\cdot\hat{H}_d + \kappa_2 \hat{N}'\hat{\xi}'\cdot\hat{H}_u + m_N \hat{N}\hat{N}' + m_\xi \hat{\xi}\cdot\hat{\xi}'$$



New fields:

- SM singlets N, N'
- $SU(2)_L$ doublets ξ, ξ'

Mass Matrix

- In the basis $f^0 = (\nu, N, N', \xi^0, \xi'^0)$ we obtain the mass matrix

$$M_f^0 = \begin{pmatrix} 0 & Y_N v_u & 0 & 0 & 0 \\ Y_N v_u & 0 & m_N & 0 & 0 \\ 0 & m_N & 0 & \kappa_1 v_d & \kappa_2 v_u \\ 0 & 0 & \kappa_1 v_d & 0 & m_\xi \\ 0 & 0 & \kappa_2 v_u & m_\xi & 0 \end{pmatrix}.$$

- By **integrating out** the heavy fields we obtain an **effective mass matrix** for the three SM neutrinos at **low energies**

  $\rightarrow$ Propagators of the mediator fields are expanded in $1/M$

$$\frac{1}{\not{p} - M} \approx -\frac{1}{M} + \cdots$$

Integrating out the heavy fields

$m_\xi > m_N$ $\swarrow$

$m_N > m_\xi$ $\searrow$

Inverse see-saw

$f_0' = (\nu, N, N')$

$$M_f^{0\prime} = \begin{pmatrix} 0 & Y_N\, v_u & 0 \\ Y_N\, v_u & 0 & m_N \\ 0 & m_N & \hat{\mu} \end{pmatrix}$$

with $\hat{\mu} = v_u v_d\,(2\kappa_1\kappa_2)/m_\xi$.

Linear see-saw

$f_0'' = (\nu, \xi^0, \xi'^0)$

$$M_f^{0\prime\prime} = \begin{pmatrix} 0 & \tilde{\kappa}_1\, v_d & \tilde{\kappa}_2\, v_u \\ \tilde{\kappa}_1\, v_d & 0 & m_\xi \\ \tilde{\kappa}_2\, v_u & m_\xi & 0 \end{pmatrix},$$

where $\tilde{\kappa}_{1/2} = \kappa_{1/2}\, Y_N^2/m_N$.

$\searrow$ $\swarrow$

$$m_\nu = v_u^3 v_d Y_N^2 \frac{\kappa_1\kappa_2}{m_\xi m_N^2}$$

Masses at TeV scale for couplings $\mathcal{O}(10^{-3})$

Flavor Structure

- **Flavor structure** of the effective operator has to match the **neutrino mass matrix**

$$M_{\alpha\beta} = v_u^3 v_d (Y_N)_{\alpha i} (M_N^{-1})_{ij} \epsilon_{jk} (M_N^{-1,\mathsf{T}})_{kl} (Y_N^{\mathsf{T}})_{l\beta} \,,$$

where

$$\epsilon_{jk} = \frac{1}{m_\xi} \left((\kappa_1)_{jm} (\kappa_2^{\mathsf{T}})_{mk} + (\kappa_2)_{jm} (\kappa_1^{\mathsf{T}})_{mk} \right) \,.$$

- Can be realized with N fields as **flavor pairs** and the ξ-fields as **flavor singlets**.
- A possible **choice of parameters** fulfilling these **conditions** is

$$Y_N = y_N \begin{pmatrix} \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \,, \quad \kappa_1 = k_1 \begin{pmatrix} -1 \\ 1 \end{pmatrix} \,, \quad \kappa_2 = k_2 \begin{pmatrix} 1 \\ 1 \end{pmatrix} \,, \quad M_N = m_N \begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix}$$

where $\rho = \sqrt{m_2/m_3}$

- The **overall mass scale** requires $v_u^3 v_d y_N^2 k_1 k_2 / (m_N^2 m_\xi) \stackrel{!}{=} m_2$

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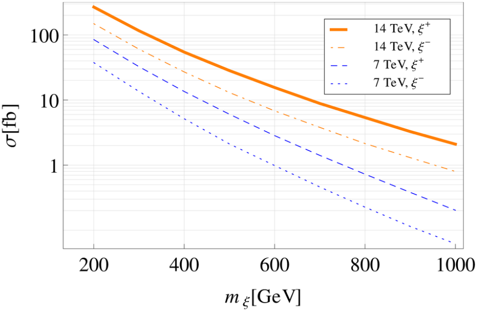
Phenomenology

- Can the new particles be produced?
  - Rare production of $\hat{N}$ and $\hat{N}'$ due to small Yukawa couplings
  - $SU(2)_L$ doublets can be produced in Drell-Yan processes ($\sigma \sim 10^2$ fb) (similarly to charginos and neutralinos)



Phenomenology II

- Possible decays
  - $\xi^+ \to W^+ \nu_k\,,\ H^+ \nu_k$
  - $n_i \to W^\pm l_j^\mp\,,\ H^\pm l_j^\mp$
  - $n_i \to Z \nu_k\,,\ h^0 \nu_k\,,\ H^0 \nu_k\,,\ A^0 \nu_k$

  Small decay widths ($\Gamma \sim 10^{-6} \ldots 1\,\mathrm{keV}$)

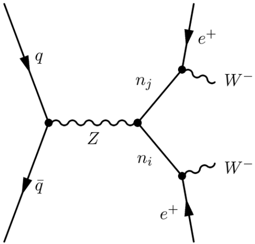
  $\Rightarrow$ decay lengths of $10^{-6} \ldots 1\,\mathrm{mm}$ at LHC (displaced vertices)

Particle	Γ[keV]	BR($W^\pm e^\mp$)	BR($W^\pm \mu^\mp$)	BR($W^\pm \tau^\mp$)	BR($Z\nu$)	BR($h^0\nu$)
n_4	$2.3 \cdot 10^{-5}$	$6.6 \cdot 10^{-3}$	$7.0 \cdot 10^{-2}$	0.18	0.36	0.38
n_5	$1.9 \cdot 10^{-5}$	$1.2 \cdot 10^{-2}$	$0.41 \cdot 10^{-2}$	0.18	0.42	0.34
n_6	1.2	$1.2 \cdot 10^{-11}$	0.21	0.21	0.21	0.37
n_7	1.2	$1.2 \cdot 10^{-11}$	0.21	0.21	0.21	0.37
n_8	2.9	0.14	0.14	0.14	0.20	0.38
n_9	2.9	0.14	0.14	0.14	0.20	0.38

Table: Total decay widths of the neutral mass eigenstates and branching ratios into the possible final states (where ν is the sum over the three light neutrino mass eigenstates).

Phenomenology III

- Tests of the Majorana nature of the leptons?
  $\rightarrow$ Processes with lepton number violation by two units as
  - $u\bar{d} \rightarrow l^+ l'^+ W^-$
  - $q\bar{q} \rightarrow l^+ l'^+ W^- W^-$
  - $u\bar{d} \rightarrow l^+ l'^+ W^- W^+ W^+$
  - ...
- Heavy Majorana neutrinos form pseudo-Dirac particles
- Lepton number violating processes expected to be suppressed
- Numerical analysis with WHIZARD
- LNC cross-section for $pp \rightarrow W\ell\ell$ of $\mathcal{O}(10^2)$ fb
  LNV processes supressed due to pseudo-Dirac pairs ($< \mathcal{O}(10^{-9})$ fb)
- For $pp \rightarrow W\ell W\ell$ LNV processes larger than naively expected ($\mathcal{O}(10^{-2})$ fb)



Conclusions

- **See-saw extensions** from higher than d=5 effective operators lower new physics to **TeV scale**
- In **SUSY framework** more constraints than in THDM
- **Integrating out** heavy fields reproduces **neutrino masses and mixing**
- Possible implementation of **flavor structure** has been presented
- **Phenomenological implications at LHC** have been discussed
  - **Displaced vertices** can be used to identify particles
  - Tests of **Majorana nature**

Backup-Slides

Adding Flavor

- Experimental results $\rightarrow$ three **distinct** neutrino mass eigenstates
  $\Rightarrow$ At least two neutrinos with **non zero mass** required
- In the most simple case one neutrino mass can be **set to zero**
- **Tri-Bimaximal mixing** is an approximation in good accordance with **experimental observation**

$$U = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

In the case of a **normal hierarchy** $(m_1 < m_2 < m_3)$ one obtains a neutrino mass matrix $M_{ij} = \mathrm{diag}(0, m_2, m_3)$, so that

$$M_{\alpha\beta} = U_{\alpha i} M_{ij} U^{\mathsf{T}}_{j\beta} = \begin{pmatrix} \frac{m_2}{3} & \frac{m_2}{3} & \frac{m_2}{3} \\ \frac{m_2}{3} & \frac{m_2}{3} + \frac{m_3}{2} & \frac{m_2}{3} - \frac{m_3}{2} \\ \frac{m_2}{3} & \frac{m_2}{3} - \frac{m_3}{2} & \frac{m_2}{3} + \frac{m_3}{2} \end{pmatrix}$$

Couplings of the Mass Eigenstates

Rotation of couplings from flavor to mass basis:

- Gauge couplings
  - to Z boson

$$g_Z Z(\bar{\nu}_\alpha \nu_\alpha + \bar{\xi}^0 \xi^0 + \bar{\xi}'^0 \xi'^0) \longrightarrow (g'_Z)_{ij} Z \bar{n}_i n_j$$

where $(g'_Z)_{ij} = g_Z (U^\dagger_{i\alpha} U_{\alpha j} + U^\dagger_{i\xi} U_{\xi j} + U^\dagger_{i\xi'} U_{\xi' j})$

  - to W boson

$$g_W W^+ (\bar{\nu}_\alpha \ell^-_\alpha + \bar{\xi}^- \xi^0 - \bar{\xi}'^0 \xi'^-)$$

- Yukawa like couplings

$$(Y_N)_{\alpha\beta} \bar{N}_\alpha \ell_\beta H_u + (\kappa_1)_\alpha \bar{N}'_\alpha \xi H_d + (\kappa_2)_\alpha \bar{N}'_\alpha \xi' H_u$$
$$\longrightarrow (Y'_N)_{\alpha i} \bar{n}_i \ell_\beta H^+_u + (\kappa'_1)_i \bar{n}_i \xi^+ H^-_d + (\kappa'_2)_i \bar{n}_i \xi'^- H^+_u$$

Process	σ [fb] (7 TeV)	σ [fb] (14 TeV)
$pp \to W^+e^+e^-$	$(1.651 \pm 0.024) \cdot 10^2$	$(4.161 \pm 0.023) \cdot 10^2$
$pp \to W^-e^+e^-$	$(9.240 \pm 0.033) \cdot 10$	$(2.671 \pm 0.042) \cdot 10^2$
$pp \to W^+e^+\mu^-$	(1.068 ± 0.099)	(2.848 ± 0.011)
$pp \to W^+e^-\mu^+$	(1.057 ± 0.013)	(2.871 ± 0.012)
$pp \to W^-e^+\mu^-$	$(5.748 \pm 0.015) \cdot 10^{-1}$	(1.742 ± 0.015)
$pp \to W^-e^-\mu^+$	$(5.755 \pm 0.015) \cdot 10^{-1}$	(1.753 ± 0.017)
$pp \to W^+e^+\tau^-$	(1.058 ± 0.096)	(2.861 ± 0.011)
$pp \to W^+e^-\tau^+$	(1.056 ± 0.095)	(2.854 ± 0.011)
$pp \to W^-e^+\tau^-$	$(5.714 \pm 0.015) \cdot 10^{-1}$	(1.754 ± 0.015)
$pp \to W^-e^-\tau^+$	$(5.750 \pm 0.015) \cdot 10^{-1}$	(1.744 ± 0.019)
$pp \to W^+\mu^+\mu^-$	$(1.676 \pm 0.014) \cdot 10^2$	$(4.116 \pm 0.023) \cdot 10^2$
$pp \to W^-\mu^+\mu^-$	$(9.242 \pm 0.033) \cdot 10$	$(2.677 \pm 0.035) \cdot 10^2$
$pp \to W^+\mu^+\tau^-$	$(2.668 \pm 0.024) \cdot 10^{-1}$	$(7.092 \pm 0.028) \cdot 10^{-1}$
$pp \to W^+\mu^-\tau^+$	$(2.652 \pm 0.026) \cdot 10^{-1}$	$(7.187 \pm 0.029) \cdot 10^{-1}$
$pp \to W^-\mu^+\tau^-$	$(1.432 \pm 0.006) \cdot 10^{-1}$	$(4.424 \pm 0.038) \cdot 10^{-1}$
$pp \to W^-\mu^-\tau^+$	$(1.439 \pm 0.004) \cdot 10^{-1}$	$(4.433 \pm 0.037) \cdot 10^{-1}$
$pp \to W^+\tau^+\tau^-$	$(1.665 \pm 0.023) \cdot 10^2$	$(4.138 \pm 0.063) \cdot 10^2$
$pp \to W^-\tau^+\tau^-$	$(9.265 \pm 0.034) \cdot 10$	$(2.652 \pm 0.035) \cdot 10^2$

Process	σ [fb] (7 TeV)	σ [fb] (14 TeV)
$pp \to W^- e^+ e^+$	$(4.711 \pm 0.069) \cdot 10^{-12}$	$(4.847 \pm 0.030) \cdot 10^{-11}$
$pp \to W^+ e^- e^-$	$(1.423 \pm 0.008) \cdot 10^{-12}$	$(1.818 \pm 0.071) \cdot 10^{-11}$
$pp \to W^- e^+ \mu^+$	$(1.017 \pm 0.014) \cdot 10^{-11}$	$(9.869 \pm 0.054) \cdot 10^{-11}$
$pp \to W^+ e^- \mu^-$	$(3.184 \pm 0.015) \cdot 10^{-12}$	$(3.22 \pm 0.15) \cdot 10^{-11}$
$pp \to W^- e^+ \tau^+$	$(1.169 \pm 0.015) \cdot 10^{-11}$	$(1.050 \pm 0.054) \cdot 10^{-10}$
$pp \to W^+ e^- \tau^-$	$(4.173 \pm 0.020) \cdot 10^{-12}$	$(4.12 \pm 0.28) \cdot 10^{-11}$
$pp \to W^- \mu^+ \mu^+$	$(5.861 \pm 0.082) \cdot 10^{-9}$	$(2.278 \pm 0.013) \cdot 10^{-8}$
$pp \to W^+ \mu^- \mu^-$	$(2.377 \pm 0.010) \cdot 10^{-9}$	$(1.153 \pm 0.017) \cdot 10^{-8}$
$pp \to W^- \mu^+ \tau^+$	$(1.184 \pm 0.013) \cdot 10^{-8}$	$(4.584 \pm 0.023) \cdot 10^{-8}$
$pp \to W^+ \mu^- \tau^-$	$(4.788 \pm 0.018) \cdot 10^{-9}$	$(2.363 \pm 0.039) \cdot 10^{-8}$
$pp \to W^- \tau^+ \tau^+$	$(5.956 \pm 0.080) \cdot 10^{-9}$	$(2.292 \pm 0.031) \cdot 10^{-8}$
$pp \to W^+ \tau^- \tau^-$	$(2.383 \pm 0.010) \cdot 10^{-9}$	$(1.120 \pm 0.014) \cdot 10^{-8}$

Table: Cross-sections for the processes with $W^\pm \ell^\pm \ell^\pm$ as final states. A cut on the invariant lepton mass of 10 GeV has been assumed.

Process	σ [fb] (7 TeV)	σ [fb] (14 TeV)
$pp \to W^+e^-W^-e^+$	$(3.447 \pm 0.87) \cdot 10^{-1}$	(1.277 ± 0.66)
$pp \to W^+e^-W^-\mu^+$	$(7.06 \pm 0.15) \cdot 10^{-3}$	$(3.141 \pm 0.027) \cdot 10^{-2}$
$pp \to W^+e^+W^-\mu^-$	$(6.99 \pm 0.16) \cdot 10^{-3}$	$(3.206 \pm 0.027) \cdot 10^{-2}$
$pp \to W^+e^-W^-\tau^+$	$(1.037 \pm 0.020) \cdot 10^{-2}$	$(4.293 \pm 0.036) \cdot 10^{-2}$
$pp \to W^+e^+W^-\tau^-$	$(1.015 \pm 0.021) \cdot 10^{-2}$	$(4.411 \pm 0.036) \cdot 10^{-2}$
$pp \to W^+\mu^-W^-\mu^+$	$(3.74 \pm 0.10) \cdot 10^{-1}$	(1.279 ± 0.017)
$pp \to W^+\mu^-W^-\tau^+$	$(2.913 \pm 0.048) \cdot 10^{-3}$	$(1.096 \pm 0.007) \cdot 10^{-1}$
$pp \to W^+\mu^+W^-\tau^-$	$(2.990 \pm 0.042) \cdot 10^{-2}$	$(1.139 \pm 0.007) \cdot 10^{-1}$
$pp \to W^+\tau^-W^-\tau^+$	$(4.27 \pm 0.10) \cdot 10^{-1}$	(1.606 ± 0.017)
$pp \to W^+e^-W^+e^-$	$(1.112 \pm 0.013) \cdot 10^{-4}$	$(4.261 \pm 0.028) \cdot 10^{-4}$
$pp \to W^+e^-W^+\mu^-$	$(1.537 \pm 0.023) \cdot 10^{-3}$	$(5.810 \pm 0.050) \cdot 10^{-3}$
$pp \to W^+e^-W^+\tau^-$	$(4.721 \pm 0.055) \cdot 10^{-3}$	$(1.761 \pm 0.016) \cdot 10^{-2}$
$pp \to W^+\mu^-W^+\mu^-$	$(4.099 \pm 0.052) \cdot 10^{-3}$	$(1.514 \pm 0.013) \cdot 10^{-2}$
$pp \to W^+\mu^-W^+\tau^-$	$(2.704 \pm 0.036) \cdot 10^{-2}$	$(1.062 \pm 0.093) \cdot 10^{-1}$
$pp \to W^+\tau^-W^+\tau^-$	$(4.614 \pm 0.065) \cdot 10^{-2}$	$(1.729 \pm 0.016) \cdot 10^{-1}$

Table: Cross-sections for the processes with $W^+\ell^-W^\pm\ell^\mp$ as final states. A cut on the invariant lepton mass of 10 GeV has been assumed.

GUT completion

- Additional particles modify running of the gauge couplings
- Spoils unification
- Add complete SU(5) multipletts to avoid this

$$\bar{5}_M = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ -\nu_e \end{pmatrix}_L = \begin{pmatrix} d_L^c \\ L \end{pmatrix} \qquad \bar{5}_{\xi'} = \begin{pmatrix} d_1'^c \\ d_2'^c \\ d_3'^c \\ \xi'^- \\ -\xi'^0 \end{pmatrix}_L = \begin{pmatrix} d_L'^c \\ \xi_L' \end{pmatrix} \qquad 5_\xi = \begin{pmatrix} d_1'' \\ d_2'' \\ d_3'' \\ \xi^+ \\ -\xi^0 \end{pmatrix}_R = \begin{pmatrix} d_R'' \\ \xi_R \end{pmatrix}$$

$$H_5 = \begin{pmatrix} H_1 \\ H_2 \\ H_3 \\ H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} H_{\mathrm{col}} \\ H_u \end{pmatrix} \qquad H_{\bar{5}} = \begin{pmatrix} H_1' \\ H_2' \\ H_3' \\ H_d^- \\ H_d^0 \end{pmatrix} = \begin{pmatrix} H_{\mathrm{col}}' \\ H_d \end{pmatrix} \qquad N, N'(S) \ \text{fermionic singlets}$$

Possible Scenarios

Extension of MSSM

$$
\begin{aligned}
W \quad = \quad & y_1\, N\, 5_\xi\, H_{\bar{5}} + y_2\, N\, \bar{5}_{\xi'}\, H_5 + y_3\, N\, \bar{5}_M\, H_5 + \\
& y_1',\, N'\, 5_\xi\, H_{\bar{5}} + y_2'\, N'\, \bar{5}_{\xi'}\, H_5 + y_3'\, N'\, \bar{5}_M\, H_5 + \\
& m_{\xi'}\, \bar{5}_M\, 5_\xi + m_\xi\, \bar{5}_{\xi'}\, 5_\xi + m_N N' N + m_{NN} NN + m_{N'N'} N' N' + \\
& y_d\, \bar{5}_M\, 10\, H_{\bar{5}} + y_d'\, \bar{5}_{\xi'}\, 10\, H_{\bar{5}} + y_u\, 10\, 10\, H_5\, .
\end{aligned}
$$

Extension of NMSSM

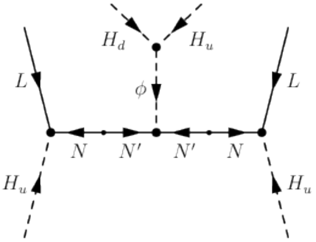
$$
\begin{aligned}
W \quad = \quad & y_1\, N\, 5_\xi\, H_{\bar{5}} + y_2\, N\, \bar{5}_{\xi'}\, H_5 + y_3\, N\, \bar{5}_M\, H_5 + \\
& y_1',\, N'\, 5_\xi\, H_{\bar{5}} + y_2'\, N'\, \bar{5}_{\xi'}\, H_5 + y_3'\, N'\, \bar{5}_M\, H_5 + \\
& \lambda_{\xi'}\, S\, \bar{5}_M\, 5_\xi + \lambda_\xi\, S\, \bar{5}_{\xi'}\, 5_\xi + \lambda_N S\, N' N + \lambda_{NN} S\, NN + \lambda_{N'N'} S\, N' N' + \\
& y_d\, \bar{5}_M\, 10\, H_{\bar{5}} + y_d'\, \bar{5}_{\xi'}\, 10\, H_{\bar{5}} + y_u\, 10\, 10\, H_5\, .
\end{aligned}
$$

Challenges

- in MSSM-like scenario: mass-terms @ TeV by hand
- NMSSM-like seesaw extension: not possible to find appropriate charge assignment
- Additional heavy d-quark like states d' and d''
  $\rightarrow$ Stability? Abundancies? Constraints?
- ...

Mediators in super-multiplets

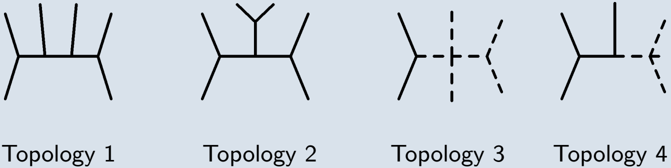
Decompositions with fermionic and scalar mediators:



- Mediators can be part of the same super-multiplet (e.g., ϕ is SUSY partner of N) $\rightarrow$ Scalar and fermionic component have different R-Parity $\rightarrow$ Tree-level decomposition requires R-Parity violating couplings
- If R-Parity is broken the sneutrino will get a VEV, which generates a contribution to neutrino mass via a d=5 operator

Topologies

There are 4 possible topologies for an effective $d = 7$ operator in the THDM:



(dashed lines are always scalars, solid lines can be both)

Only topology 1 and 2 are allowed in SUSY

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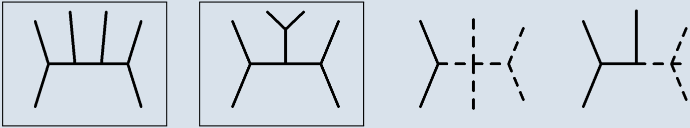
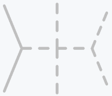


Topology 1 Topology 2 Topology 3 Topology 4

(dashed lines are always scalars, solid lines can be both)

Only topology 1 and 2 are allowed in SUSY

Excluding Topology 3 and 4



Topology 3

Topology 4

Effective Operator: $LLH_uH_uH_uH_d$

Topology 4

- Right vertex must be $HHH\phi^\dagger$
- In **SUSY** only **4-vertices** of the type $\phi_a^\dagger\phi_b^\dagger\phi_c\phi_d$ are possible because of **holomorphy of the superpotential**

$\Rightarrow$ Topology 4 is forbidden in SUSY

Topology 3

- SUSY only allows $HH\phi^\dagger$ for the right vertex
- Middle vertex must be $HH\phi_a^\dagger\phi_b^\dagger$
- Vertices can not be connected by a propagator

$\Rightarrow$ Topology 3 is forbidden in SUSY

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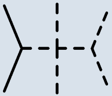

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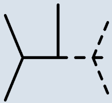

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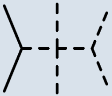

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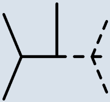

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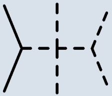

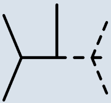

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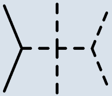

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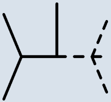

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