Lepton number violating right-sneutrino decays

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Outline

My aim in this talk is to

- discuss lepton number violation in sneutrino physics
- review briefly NMSSM with right-handed neutrinos
- discuss right-sneutrino production and decays in NMSSM+RHN
- estimate chances of discovering lepton number violating sneutrino decays at the LHC

This talk is based on work in progress together with Stefano Moretti and Claire Shepherd-Themistocleous.

Majorana neutrinos imply lepton number violation

- Neutrino oscillation data shows that neutrinos have nonzero masses
- Limits from kinematics of nuclear decays and cosmology show that the masses are several orders of magnitude smaller than other fermion masses
- It is widely believed that this is due to a seesaw mechanism (here written for RH neutrinos):

$$M_{\nu,N} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \Rightarrow m_\nu = \frac{m_D^2}{M_R}$$

- In such a case neutrinos are Majorana fermions
- A seesaw mechanism always implies lepton number violation ($\Delta L = 2$), this has been experimentally searched through neutrinoless double beta decay

Sneutrinos have a Majorana character

- Supersymmetry introduces superpartners for neutrinos, sneutrinos
- Sneutrinos have two bases of eigenstates, those of definite lepton number (sneutrino/antisneutrino, $\tilde{\nu}$ and $\tilde{\nu}^*$) and those of definite CP (CP-even/odd, $\Re(\tilde{\nu})$ and $\Im(\tilde{\nu})$)
- Hirsch *et al.* (PLB 403 (1997) 291) proved that Majorana masses for neutrinos generate a mass difference between the CP-even and CP-odd sneutrinos leading to sneutrino-antisneutrino oscillation[1]
- Observable lepton number violation through sneutrino-antisneutrino oscillation requires that a large phase difference accumulates before the sneutrino decays, *i.e.* $\Delta m_{\tilde{\nu}}/\Gamma_{\tilde{\nu}} \gtrsim 1$

[1] If there are complex couplings, the CP eigenstates and mass eigenstates do not coincide.

Conditions for sneutrino-antisneutrino oscillation are hard to fulfil

- If there is a mass difference between a CP-even and a CP-odd sneutrino, this creates a mass for neutrinos via loops — typically $m_\nu \sim 10^{-3} \times \Delta m_{\tilde{\nu}}$ if the contribution is at one-loop order (Grossman, Haber hep-ph/9702421)
- This requires sneutrinos to be degenerate at keV-level and also the decay width to be at this level
- For left-handed sneutrinos these conditions have been reproduced only in some very compressed scenarios
- For right-handed sneutrinos the one-loop contribution is proportional to the Yukawa couplings (tiny in a TeV-scale seesaw model), but two-loop contribution is potentially dangerous (model-dependent)
- Nevertheless also the decay width for right-handed sneutrinos can be small and hence lepton number violation could be possible

NMSSM with RH neutrinos has advantages compared to MSSM

The superpotential

$$\begin{aligned} W &= Y_u Q H_u U^c + Y_d Q H_d D^c + Y_\ell L H_d E^c + Y_\nu L H_u N^c \\ &\quad + \lambda S H_u H_d + \lambda_N S N^c N^c + \frac{\kappa}{3} S^3 \end{aligned}$$

- The NMSSM solves the μ-problem by introducing a singlet, whose scalar component gets a VEV $\Rightarrow \mu_{\text{eff}} = \lambda \langle S \rangle$
- The NMSSM still lacks a mechanism for neutrino masses, but extending the model with RH neutrinos solves this problem
- RH neutrinos can lift the Higgs mass through loops [1303.6465]if λ and λ_N are large
- The singlet generates a mass term for RH neutrinos, too $\Rightarrow$ expect them to be at the electroweak scale $\Rightarrow$ tiny neutrino Yukawa couplings needed

The scalar potential introduces lepton number violation in the RH sneutrino sector

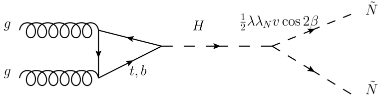
- The scalar potential contains the terms

$$V = |\lambda H_u H_d + \lambda_N \tilde{N}^2 + \kappa S^2|^2 + \dots$$

- The cross terms create $\Delta L = 2$ mass terms for RH sneutrinos after the scalars H_u, H_d and S get a VEV; also soft SUSY breaking terms contribute to $\Delta m_{\tilde{N}}$
- The first non-suppressed[2] loop contribution comes at three-loop level $\Rightarrow$ probably $\Delta m_{\tilde{N}} \simeq 1$ GeV allowed$\Rightarrow$ $\Delta m_{\tilde{N}}/\Gamma_{\tilde{N}} \gg 1$
- The condition $\Delta m_{\tilde{N}} \simeq 1$ GeV requires some cancellation of the soft terms but the values are not unreasonable
- For other seesaw extensions of the NMSSM the unsuppressed contribution to neutrino masses comes at two loops so this seems to be the least fine-tuned model in this sense

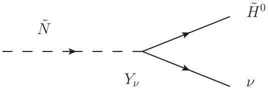
[2] Not proportional to tiny Y_ν

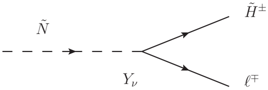
The heavy Higgs is a portal to RH sneutrinos



- The RH sneutrinos are gauge singlets so no couplings to gluons or EW gauge bosons
- The lepton number violating term of the scalar potential creates a coupling between the Higgs doublets and RH sneutrinos $\Rightarrow$ if $m_H > 2m_{\tilde{N}}$ resonant production of sneutrinos possible through the heavy Higgs
- In the alignment limit the heavy Higgs has a stronger coupling to sneutrinos (assuming $\tan\beta > 1.5$)
- The heavy Higgs can be produced with a cross section $\mathcal{O}(1\ \mathrm{pb})$ if it is lighter than 500 GeV

Light higgsinos would lead to visible sneutrino decays





- While RH sneutrinos can be viable dark matter candidates, we are interested in the case, where sneutrinos can decay visibly
- If the singlet VEV is at the electroweak scale, the higgsinos ($m_{\tilde{H}} \simeq \mu_{\rm eff}$) and RH neutrinos ($m_N \simeq \lambda_N v_S/\sqrt{2}$) are, too
- Due to soft SUSY breaking we expect RH sneutrinos to be somewhat heavier than these $\Rightarrow$ visible decay to a lepton and a charged higgsino possible, decays determined by neutrino Yukawa couplings
- Due to LNV mass term, sneutrinos have 50% chance of decaying to either sign leptons

The same-sign dilepton channel has a relatively small background

- The interesting signature is when both sneutrinos decay visibly and result in the same-sign dilepton signature
- Usual dilepton triggers sufficient to capture a good number of signal events
- The chargino will further decay to $W^* \tilde{H}^0 \to$ jets+MET or lepton+MET
- The third lepton, if there is one, is always soft $\Rightarrow$ veto against hard third lepton
- The SM backgrounds arise from same-sign WW, WZ with one lepton having small p_T or misidentified and nonprompt leptons (majority from $t\bar{t}$, where one lepton comes from a W and another from a B-meson)

Event selection and cuts

1. At least two same-sign same-flavor leptons, leading lepton $p_T > 25$ GeV, second lepton $p_T > 12$ GeV
2. Veto for a third lepton with $p_T > 20$ GeV
3. Veto for Z-bosons (OSSF lepton pair with invariant mass $\in [80, 100]$ GeV)
4. Missing transverse energy $\not{E}_T > 50$ GeV
5. Veto for b-jets (no hadrons identified as b-jets with "loose" identification criteria)
6. Invariant mass of lepton pair with two highest p_T's between 10 and 80 GeV

We investigate a rather optimistic benchmark

Here I shall consider only a single benchmark, more comprehensive scans are in progress.

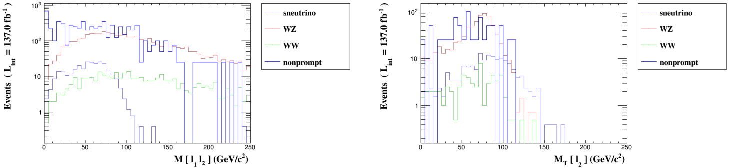
- Heavy Higgs around 455 GeV, lightest sneutrino 220 GeV ($\Delta m = 0.3$ GeV), higgsinos around 180 GeV
- We set $\lambda = 0.5$ and $\lambda_N = 0.62$, altogether $\mathrm{BR}(H \to \tilde{N}\tilde{N}) = 5\%$
- The visible decay of the lightest sneutrino is mainly to electrons or positrons, decay width around 10^{-12} GeV, decay lengths hundreds of microns (this depends on the overall neutrino mass scale, can lead to displaced vertices at mm-scale)
- We consider $\sqrt{s} = 13$ TeV with $\int \mathcal{L} = 137\ \mathrm{fb}^{-1}$, simulate signal and background at LO with MadGraph5, Pythia8 and Delphes3, correct with K-factors, implement the cuts with MadAnalysis5

Cutflow of the signal and backgrounds

Cut	Signal	WZ	$W^{\pm}W^{\pm}$	Nonprompt
2 SSSF leptons	305	11602	457	10495
$p_{T,1} > 25$, $p_{T,2} > 12$ GeV	287	11421	420	8268
Z-veto	287	4613	420	7497
reject $p_{T,3} > 20$ GeV	286	4394	420	6725
$\not{E}_T > 50$ GeV	200	1854	285	3941
$M_{\ell_1,\ell_2} \in [10, 80]$ GeV	174	748	58	2099
b-veto	160	740	47	643

- Total background 1430 events, signal about 11% of it, systematics not likely to be smaller than this (statistics only: $\gtrsim 3\sigma$)
- However, if the signal has a nonuniversal flavor structure, the difference of events in electron/muon/tau channels can be statistically significant

A cut on $M_T(\ell_2, \not{E}_T)$ can give an excess



- Left plot: After cuts 1–3 the signal is concentrated on low values of $\ell_1\ell_2$ invariant mass, hence we select $M(\ell_1\ell_2) \in [10, 80]$ GeV
- Right plot: A cut $M_T(\ell_2 \not{E}_T) > 100$ GeV will give $S/B \gtrsim 1$ and even with conservative systematic errors a 3σ excess
- Definition of M_T: $M_T(i, \not{E}_T) = \sqrt{2\not{p}_T p_T^i (1 - \cos(\Delta\phi))}$

Summary

- The Majorana character of neutrinos can lead to lepton number violation in the sneutrino sector
- NMSSM with RH neutrinos allows LNV sneutrino mass terms without a too large backreaction to neutrino masses
- The heavy Higgs coupling to sneutrinos can be large even in the alignment limit
- Sneutrino pair production can lead to same-sign dilepton events
- With suitable cuts there can be sensitivity to some benchmarks even with Run II data