Lepton number violation from right-sneutrinos through the heavy Higgs portal

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Scalars 2019, Warsaw 13/09/2019

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 the preprint 1909.04692 together with Stefano Moretti and Claire Shepherd-Themistocleous.

Majorana neutrinos imply lepton number violation

- Neutrino oscillation data shows that neutrinos have nonzero 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

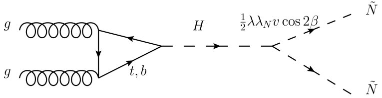
- The scalar potential contains the terms

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

- 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

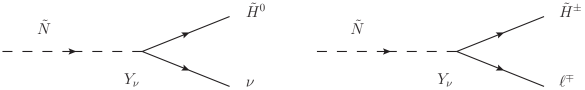
[2]Not proportional to tiny Y_ν

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 ($m_{\tilde{H}} \simeq \mu_{\mathrm{eff}}$) 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

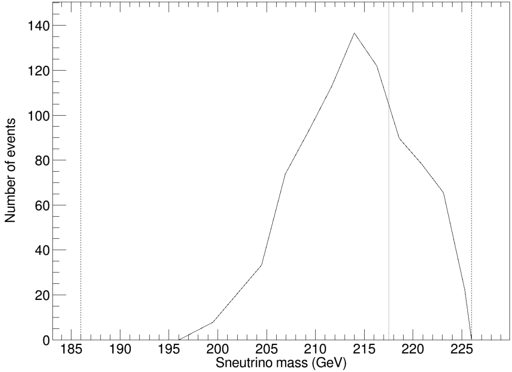
Event selection and cuts

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)

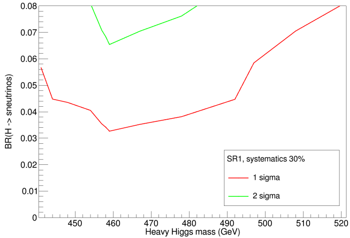
Cut	SR1	SR2
Missing transverse energy $\not{E}_T$	> 50 GeV	> 100 GeV
Lepton pair invariant mass $M(\ell_1\ell_2)$	> 10 GeV < 50 GeV	> 10 GeV < 80 GeV
Veto for b-jets: $N(b)$	0	0
Cut on second lepton M_T $M_T(\ell_2, \not{E}_T)$	> 100 GeV	> 100 GeV

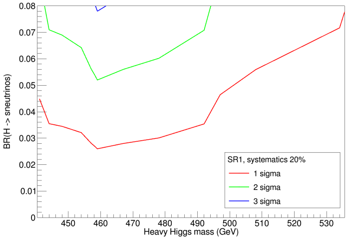
Event selection is efficient only if sneutrinos are somewhat heavier than the chargino

We show the number of events passing the event selection as a function of sneutrino mass (chargino 186 GeV, heavy Higgs 452 GeV)



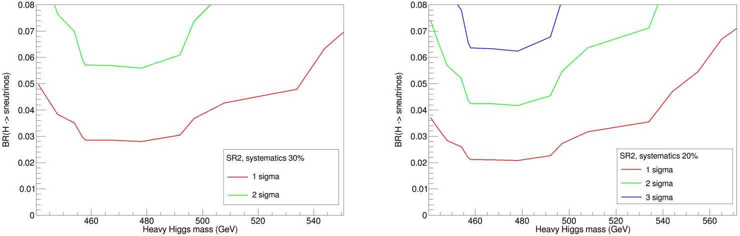
With 20% systematics there is some chance of seeing an excess





- Here sneutrino 220 GeV, chargino 186 GeV, realistic neutrino mixing, lightest sneutrino decays dominantly to muons
- Integrated luminosity corresponds to Run II
- Reach for SR1 is limited to heavy Higgs masses below 500 GeV and it is more efficient with somewhat compressed spectra

With 20% systematics there is some chance of seeing an excess



- Here the same plot for SR2 with the same parameters
- Reach for SR2 slightly beyond 500 GeV heavy Higgs masses and performance better for noncompressed spectra

Sneutrino decays can tell us about neutrino Yukawa couplings

- The sneutrino decay amplitude is proportional to the corresponding neutrino Yukawa coupling
- If we can measure the decays in more than one lepton flavor, we get ratios $|y^{\nu}_{ik}/y^{\nu}_{jk}|^2$
- A upper limit on the absolute size can be obtained from the upper limit on the neutrino masses (but involves some mild assumptions)
- A lower limit on the absolute size can be obtained from the decay width if the decays are prompt (and from the decay length, if they are not)

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 is some sensitivity if the systematic errors are not too large

Backup

Some example benchmarks

Parameter	BP1	BP2	BP3	BP4	BP5	BP6
m_H	455	569	484	478	490	448
m_A	441	562	470	464	476	434
Lightest sneutrino mass	220	233	220	227	214	210
Second sneutrino mass	310	321	240	338	338	340
Chargino mass	177	190	178	178	185	186
λ	0.50	0.50	0.50	0.50	0.52	0.52
λ_N	0.62	0.62	0.62, 0.68	0.64	0.46	0.46
$\tan\beta$	2.5	4.0	2.5	2.5	2.7	2.7
BR$(H \to \tilde{N}\tilde{N})$	5.1%	5.0%	4.9% + 1.6%	4.7%	2.6%	3.7%
BR $(A \to \tilde{N}\tilde{N})$	0.5%	2.3%	1.3%	0.9%	1.1%	1.5%
Lightest sneutrino decay	$e^\pm$	$e^\pm$	$e^\pm$, $\mu^\pm$	$\mu^\pm$	$\mu^\pm$	$\mu^\pm$

Cutflows for the background and signal benchmarks: SR1

Cut	WZ	WW	nonpr.	Σ bgnd	BP1	BP2	BP3	BP4	BP5	BP6
Two SSSF lept.	11625	465	10349	22439	305	42	354	479	199	361
$p_T(\ell_1) > 25$	11507	448	9536	21491	294	40	343	469	158	177
$p_T(\ell_2) > 12$	11442	431	8530	20403	287	40	338	461	150	166
Z-veto	4604	431	7630	12665	287	39	337	459	150	166
$p_T(\ell_3) < 20$	4395	431	6759	11585	286	39	337	459	150	165
$\not{E}_T > 50$	1825	295	3854	5974	200	28	246	322	97	112
$M(\ell\ell)$: [10, 50]	321	33	992	1346	82	8.7	84	108	52	87
b-veto	315	28	371	714	76	7.7	77	98	46	80
$M_T(\ell_2) > 100$	7.7	1.3	13.3	22.3	20.0	1.1	23.8	36.7	4.6	6.1

Units are in GeV's, where applicable. Integrated luminosity$= 137$ fb^{-1}.

Cutflows for the background and signal benchmarks: SR2

Cut	WZ	WW	nonpr.	Σ bgnd	BP1	BP2	BP3	BP4	BP5	BP6
Two SSSF lept.	11625	465	10349	22439	305	42	354	479	199	361
$p_T(\ell_1) > 25$	11507	448	9536	21491	294	40	343	469	158	177
$p_T(\ell_2) > 12$	11442	431	8530	20403	287	40	338	461	150	166
Z-veto	4604	431	7630	12665	287	39	337	459	150	166
$p_T(\ell_3) < 20$	4395	431	6759	11585	286	39	337	459	150	165
$\not{E}_T > 100$	273	131	1035	1439	94	14.5	115	160	52	70
$M(\ell\ell)$: [10, 80]	74	30	600	704	82	10.4	85	115	49	66
b-veto	71	27	186	284	72	9.3	76	101	43	61
$M_T(\ell_2) > 100$	8.3	3.3	30.9	42.5	34.1	2.9	34.6	50.4	12.2	10.1

Expected significances for benchmarks

Benchmark	SR1 (30%)	SR1 (20%)	SR2 (30%)	SR2 (20%)
BP1	2.4σ	3.1σ	2.4σ	3.2σ
BP2	0.13σ	0.17σ	0.20σ	0.27σ
BP3	2.9σ	3.7σ	2.4σ	3.2σ
BP4	4.5σ	5.6σ	3.5σ	4.7σ
BP5	0.56σ	0.71σ	0.85σ	1.1σ
BP6	0.74σ	0.94σ	0.70σ	0.94σ

These correspond to an integrated luminosity of 137 fb^{-1}. Numbers in parentheses are the assumed systematic errors.