Exploring neutrino physics with sneutrinos

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Neutrino masses
Sneutrinos in NMSSM+RHN
Exploring neutrino physics at the LHC

Exploring neutrino physics with sneutrinos
Outline

Question:

"Given that we were to find one or several sneutrinos, what could they tell us about neutrinos?"

This question leads to ask

- what kind of neutrino dynamics do we expect to find?
- how can we find sneutrinos?
- can sneutrinos tell us something that neutrinos cannot?

The talk is based on 1909.04692 (Moretti, Shepherd-Themistocleous, HW).
Neutrino masses require new physics

- It is known for 20 years already, that neutrinos can oscillate from one flavor to another.
- This requires:
  1. Mass differences between different neutrino species
  2. A mismatch in the alignment of the mass and flavor eigenstates
- The mixing matrix is known as Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, the absolute values of the elements are known rather well.
- The absolute mass scale is still unknown, but at least below 1.1 eV (KATRIN), if standard cosmology holds, below 0.12 eV.
- Neutrino oscillation experiments give lower bounds for the heaviest neutrino around 0.04 eV.
- The Standard Model does not include neutrino masses (there are too many ”minimal” ways to add them).
Weinberg operator leads to standard seesaw mechanisms

- There are three minimal ways to compose the Weinberg operator from renormalizable interactions:
  1. singlet (right-handed) neutrinos as mediators
  2. SU(2) triplet scalars as mediators
  3. SU(2) triplet fermions (exotic leptons) as mediators

- These are known as seesaw mechanisms of types I, II and III, respectively.

- If the mediator is heavy, the neutrino masses are naturally small, even if the couplings are large.

- The seesaw scale can be anything between the EW scale and $10^{14}$ GeV.
The dynamics is either in the form of new particles or Higgs-neutrino couplings

- The obvious thing to search are the new particles — exotic leptons (type III), triplet Higgses (including a doubly charged one!)
- Singlet neutrinos very hard to find, RH neutrinos might not be singlets in gauge extensions of the SM (B-L models, left-right models)
- If new states are light, Higgs decays to them might be possible, but in simple TeV-scale seesaws the couplings are tiny
- Similarly Higgs-mediated neutrino pair production has a tiny cross section
- If supersymmetry exists, sneutrinos inherit the couplings responsible for neutrino mass generation
Sneutrinos may decay visibly

- Left-sneutrinos cannot be the LSP, right-sneutrinos might, provided their annihilation cross section is large enough
- Typically we still expect that the sneutrinos will decay to lighter superpartners + SM particles
- If there would be a charged superpartner that is lighter than the sneutrino a decay to a charged lepton and a chargino would be possible, the chargino then would give further visible tracks
- If the charginos are pure higgsinos, the decays of right-sneutrinos are dictated by the neutrino Yukawa couplings
NMSSM with RH neutrinos has advantages compared to MSSM

The superpotential

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

- The NMSSM solves the $\mu$-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 $\lambda$ and $\lambda_N$ 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 couples the Higgses to right-sneutrinos

- The scalar potential contains the terms

\[ V = |\lambda H_u H_d + \lambda_N \tilde{N}^2 + \kappa S^2|^2 + \ldots \]

- The cross terms create \( \Delta L = 2 \) mass terms for RH sneutrinos after the scalars \( H_u, H_d \) and \( S \) get a VEV \( \Rightarrow \) states with definite CP are eigenstates of Hamiltonian

- The CP eigenstates do not have a definite lepton number \( \Rightarrow 50\% \) chance of decaying to either sign leptons

- The cross terms also generate a coupling between the Higgses and a pair of right-sneutrinos \( \Rightarrow \) pair production through the Higgs portal possible, the heavy Higgs has the larger coupling
Lepton number violation can lead to same-sign dilepton signature

- Assume: Light higgsinos (EW scale $\mu$-parameter), then right-neutrinos are at the same scale
- Right-sneutrinos quite naturally somewhat heavier than higgsinos $\Rightarrow$ decays to neutrino+neutralino and charged lepton+chargino possible
- Heavy Higgs heavier than $2m_{\tilde{N}}$, produce heavy Higgs through gluon fusion with a subsequent decay to sneutrinos
- Both sneutrinos decay visibly giving rise to same-sign dilepton + MET final state
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)

<table>
<thead>
<tr>
<th>Cut</th>
<th>SR1</th>
<th>SR2</th>
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<tbody>
<tr>
<td>Missing transverse energy $E_T$</td>
<td>$&gt; 50$ GeV</td>
<td>$&gt; 100$ GeV</td>
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<tr>
<td>Lepton pair invariant mass $M(\ell_1\ell_2)$</td>
<td>$&gt; 10$ GeV</td>
<td>$&gt; 10$ GeV</td>
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<tr>
<td></td>
<td>$&lt; 50$ GeV</td>
<td>$&lt; 80$ GeV</td>
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<tr>
<td>Veto for b-jets: $N(b)$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cut on second lepton $M_T$</td>
<td>$&gt; 100$ GeV</td>
<td>$&gt; 100$ GeV</td>
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<tr>
<td>$M_T(\ell_2, E_T)$</td>
<td></td>
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</tbody>
</table>
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 $|y_{ik}^\nu/y_{jk}^\nu|^2$.
- A upper limit on the absolute size can be obtained from the upper limit on the neutrino masses:
  $$\sum m_\nu = \text{Tr}(m^\nu) = \sum_{i,j} |y_{ij}^\nu|^2 v^2 \sin^2 \beta / 2 m_{N_j},$$
  RH neutrino can be assumed to be lighter than the sneutrino, i.e. less than $m_H/2$.
- 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), if we know the masses of the neutralino and chargino.
- The sizes of the Yukawa couplings can be determined within an order of magnitude or so.
Conclusions

- The neutrino mass generation mechanism involves new particles and interactions
- If supersymmetry exists, sneutrinos inherit these interactions
- Sneutrinos may decay visibly at detectors
- There is some chance of seeing a signal of sneutrinos through lepton number violation
- Sneutrinos give us a handle on neutrino Yukawa couplings — neutrino physics could be possible at colliders