Sneutrino dark matter: status and prospectives

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It is great to have a comfortable place, but a change of perspective is important. It is great to have a working hypothesis guiding LHC searches, but let’s not stop there.
Neutrino masses and susy

- Neutrino masses
- Right handed neutrino fields
- Matter - antimatter asymmetry
- Baryogenesis through leptogenesis
- Dark matter candidate
- Supersymmetric realisation (Right handed sneutrino fields)
- Phenomenology?
Neutrino mass generation mechanisms

- SM + right handed fields
- Small Dirac neutrino masses

- RH fields mass term
- Baryogenesis through leptogenesis

\[ \mathcal{M}_\nu = \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix} \]

Dirac mass, usually small \( Y_\nu \)

Majorana mass, can be heavy, can have \( Y_N \sim 1 \), introduces Lepton number violation

See e.g. Deppisch, New J. Phys. 17 (2015) 075019
Simplest GUT scale model

SM + three heavy neutrinos \rightarrow \text{Supersymmetrise (MSSM+RN)}

Note: no additional gauge content
Neutrino mass generation mechanisms

- SM + right handed fields
  - Tiny Yukawa
  - Small Dirac neutrino masses

- RH fields mass term
  - Lepton number violation
  - Baryogenesis through leptogenesis

\[ \mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \cr M_D^T & 0 \end{pmatrix} \]

- Dirac mass, usually small \( Y_\nu \)
- No Majorana mass term

\[ \mathcal{L} \supset Y_{i\bar{j}}^\nu \bar{N}_i \cdot L_j \cdot H - 0 \]
MSSM+RN

Modification of supersymmetric scalar sector due to neutrino mass terms

\[ W = \epsilon_{ij} (\mu \hat{H}_i^u \hat{H}_j^d - Y_l \hat{H}_i^d \hat{L}_j \hat{R} + Y_\nu \hat{H}_i^u \hat{L}_j \hat{N}) \]

\[ V_{\text{soft}} = M_L^2 \tilde{L}_i^* \tilde{L}_i + M_N^2 \tilde{N}^* \tilde{N} - [\epsilon_{ij} (\Lambda_l H_i^d \tilde{L}_j \tilde{R} + \Lambda_\nu H_i^u \tilde{L}_j \tilde{N}) + \text{h.c.}] \]

Note: No lepton number violating terms

Dirac mass for neutrinos

\[ m_D = v_u Y_\nu \]

Sneutrino left - right mixing

\[ \begin{cases} \tilde{\nu}_{\tau_1} = -\sin \theta_{\tilde{\nu}} \tilde{\nu}_L + \cos \theta_{\tilde{\nu}} \tilde{\nu}_N \\ \tilde{\nu}_{\tau_2} = +\cos \theta_{\tilde{\nu}} \tilde{\nu}_L + \sin \theta_{\tilde{\nu}} \tilde{\nu}_N \end{cases} \]

\[ M_{LR}^2 = \begin{pmatrix} m_L^2 + \frac{1}{2} m_Z^2 \cos(2\beta) + m_D^2 & \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin \beta - \mu m_D \cot \beta \\ \frac{v}{\sqrt{2}} A_{\tilde{\nu}} \sin \beta - \mu m_D \cot \beta & m_N^2 + m_D^2 \end{pmatrix} \]

Sneutrino LSP models address two issues at once: DM and neutrino masses
MSSM+RN

- Introduction of three RH neutrino species (one for each flavour) \( \rightarrow \) three RH sneutrino species
- Usually **stau sneutrino lightest** due to Yukawa and RGE

\[
M_{LR}^2 = \begin{pmatrix}
    m_L^2 + \frac{1}{2} m_Z^2 \cos(2\beta) + m_D^2 - \frac{v}{\sqrt{2}} A_\tilde{\nu} \sin \beta - \mu m_D \cot \beta \\
    \frac{v}{\sqrt{2}} A_\tilde{\nu} \sin \beta - \mu m_D \cot \beta & m_N^2 + m_D^2
\end{pmatrix}
\]

- LR mixing depends on trilinear parameter
- Usually **trilinear proportional to Yukawa** \( A_\tilde{\nu} \propto Y_\nu \)
  - Negligible mixing between left and right states
  - Interactions via SM portals suppressed
  - Non-thermal dark matter
- \( A_\tilde{\nu} \) free parameter \( \rightarrow \) Left-right mixed dark matter, possible to achieve thermal dark matter
MSSM+RN

Proportional to Yukawa

Z, h

Proportional to LR mixing

SM

Rest of the supersymmetric particle content and LHC production channels unmodified

RH sneutrino
MSSM+RN

Neutralino LSP

Can be the same

Spin 0

\[ \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 + l \]

Spin 1/2

\[ \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + W^\pm \]

Can be very different

Spin 0

\[ \tilde{g} \rightarrow \tilde{\chi}_1^0 + \bar{q} \]

Sneutrino LSP

Spin 1/2

\[ \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \tilde{\nu} \]

Suppressed coupling

\[ \tilde{g} \rightarrow q + \bar{q} + \nu \]

Long lived gluino

\[ \tilde{g} \rightarrow q + \tilde{\nu} \]

Typical signatures

\[ \tilde{\nu} \]

\[ \tilde{\nu} \]

\[ \tilde{\nu} \]

\[ \tilde{\nu} \]

\[ \tilde{\nu} \]

\[ \tilde{\nu} \]

\[ \tilde{\nu} \]

Dev et al, JHEP 09, 110 (2012)

Arina et al, JHEP04(2014)100
MSSM+RN

\[ M_1, M_2, M_3, m_L, m_R, m_N, m_Q, m_H, A_l, A_{\tilde{\nu}}, A_q, \tan \beta, \text{sgn} \mu \]

- Parameters defined at GUT scale, non-universality assumed

- Dilepton searches have stronger reach due to higher signal production cross sections
- Potentially* entire region (up to 700 GeV chargino mass) within LHC13 reach
- Great showcase of using neutralino LSP SMS results from LHC collaborations

*Usual SMS caveats apply, assumes flavour universal BR
\[ \sqrt{s} = 8 \text{ TeV} \]

- Most of the times, lepton is too soft for single lepton + MET searches to be applicable, can addition of ISR help?
- **Reinterpret compressed stop search**: soft lepton plus ISR (CMS-SUS-PAS-16-052)
As mentioned in Sec. 3.2, a considerable number of the scan points comprise long-lived sparticles. These occur mostly when enforcing light gluinos or squarks; in this case about 30% of the points feature long-lived particles, while the fraction is below 1% without this constraint.

The long-lived particles are predominantly gluinos (85%), mostly in the case where it is the NLSP, and in a few points where $\tilde{\chi}^0_1$ is slightly (up to about 50 GeV) lighter than the gluino.

Apart from that we find points with long-lived stops or staus in case they are the NLSP, as well as single points with long-lived charginos. Here we will focus on the long-lived gluinos and stops, long-lived staus have been discussed before in [27].

Figure 14: Lifetimes $c_\tau$ in [m] for long-lived gluinos, the color code indicates the LSP mass (left) and the sneutrino mixing angle (right).

In the MSSM long-lived gluinos appear when all squarks are extremely heavy, e.g. in split-SUSY scenarios. In case of the MSSM+RN with a sneutrino LSP additional causes come into play. If the gluino is the NLSP, its decay will proceed only via virtual squarks and gauginos, yielding an effective four body decay, $\tilde{g} \rightarrow q\overline{q}\nu\tilde{\nu}$ (virtual $\tilde{q}$ and $\tilde{\chi}^0_1$) or $\tilde{g} \rightarrow q\overline{q}\nu\tilde{\chi}^0_1$ (virtual $\tilde{q}$ and $\tilde{\chi}^\pm$). The gluino lifetime will therefore depend not only on the squark mass, but also on the gaugino masses and mixings, as well as the sneutrino mixing angle. Meta-stable gluinos can thus appear even if the squarks are not completely decoupled. The gluino lifetime as a function of its mass is shown in Fig. 14. The left plot illustrates the dependence on the sneutrino mass, the right plot the dependence on the sneutrino mixing. We can distinguish two general regions. First, we observe an exponential dependence of the lifetime on the gluino mass for decay lengths of 10 mm up to $10^4$ m. Here the lifetime is largely independent of the sneutrino mass. Moreover lifetimes at constant gluino masses are longer for heavier squarks and gauginos. In this region we generally find large mixing angles $\sin \beta \gamma \tilde{\chi}^0_1$, but heavy gauginos and squarks. Points with very small mixing angles may also appear in this region, in the case that the mass of the lightest neutralino is below the gluino mass. The second region, with lifetimes longer than $10^4$ m, and up to $10^{17}$ m, shows a very different behaviour. We can see a clear correlation between gluino

- Possible reach of LHC13 via R-hadron searches? → Reinterpretation needed (ongoing)
- Ideal conditions ($\beta \gamma = 1$, large mass difference), up to $c_\tau = 10^4$ covered at LHC 13
- Also possible, long lived stops
- Necessity of unified analysis tool, just finished extending SModelS, stay tuned for update
MSSM+RN exotic signatures

Long lived staus

- Occurs for small mass splitting and suppressed mixing angles
- Targets DM coannihilation region
- Also a signature for purely RH sneutrino LSP

See also: Banarjee et al: JHEP 1809 (2018) 143

Same sign dileptons

- Sleptons lighter than weakinos
- Stau lightest slepton due to RGE (tan beta, trilinear can increase mass splitting with other sleptons)

See HL-LHC (BSM chapter): 1812.07831
MSSM+RN

- Direct detection limits LR mixing of sneutrino

- Neutrino lines generated via annihilation of sneutrino* could be searched for at indirect detection experiment

(*Needs astrophysical enhancement)

See also Dumont et al, JCAP09(2012)013

\[
\tilde{\nu}_{\tau_1} \quad \text{vs.} \quad \nu_\tau
\]

\[
\tilde{\nu}_{\tau_1} \quad \text{vs.} \quad \tilde{\nu}_{\tau_1}
\]

\[
\tilde{\nu}_{\tau_1} \quad \text{vs.} \quad \tilde{\nu}_{\tau_1}
\]
Specific GUT realisation

\[ \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \times \text{U}(1)_{B-L} \longrightarrow \text{Supersymmetrise (BLSSM)} \]
Adding LFV terms

- SM + right handed fields
- Tiny Yukawa
- Small Dirac neutrino masses
- RH fields mass term
- Lepton number violation
- Baryogenesis through leptogenesis

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix}$$

- Dirac mass, usually small $Y_\nu$
- Majorana mass, can be heavy, can have $Y_N \sim 1$, introduces Lepton number violation
U(1)$_{B-L}$ promote to local

SU(3)$_C$ X SU(2)$_L$ X U(1)$_Y$ X U(1)$_{B-L}$ → Gauge U(1)$_{B-L}$

Gauged sector comes with it's own Higgs and gauge boson

Needs three additional SM singlet fermions for anomaly cancellation → RH neutrinos

Supersymmetrization leads to

- Right handed sneutrino fields
- New gaugino fields → impact on neutralino composition
- New dark matter phenomenology
BLSSM

SM

Suppress Z, h

Z', h'

RH sneutrino
• GUT scale parameters, unification assumed
• $g_{B-L}$ fixed from unification, LHC constraints push mass spectra higher
Astrophysical probes

- Challenging prospects for indirect detection searches

![Graph showing DM mass vs. $<\sigma_{WW}\rangle$]

- Solid line: 15 dSphs, Ackermann 2015
- Dashed line: 60 dSphs, 15 years projection

- Orange dots: CP-odd
- Blue dots: CP-even

DM mass [GeV]

$<\sigma_{WW}\rangle$ [cm$^3$ s$^{-1}$]

$10^{-19}$

$10^{-23}$

$10^{-27}$

$10^{-31}$

100 200 500 1000 2000
LHC phenomenology

- Heavy sneutrino, needs off shell Higgs
- Heavy Z’ needs larger $\sqrt{s}$ to probe
- Possible: slepton should decay to sneutrino, difficult due to small Yukawa
- Best chance at future colliders? → ongoing
- Large width Z’
  Abdallah et al JHEP 1602 (2016) 157
- Non-universal GUT scenarios
Conclusions

• Rich interplay of LHC searches in SUSY sector and EXO sector (LLP searches) for sneutrino dark matter

• Added phenomenology from neutrino measurements and $0\nu\beta\beta$ and astrophysics
  • Neutrino measurements: determine Yukawa, masses of heavy neutrinos
  • $0\nu\beta\beta$: smoking gun of LNV

• MSSM+RN sneutrino dark matter (GUT scale, non-universal):
  • Phenomenology driven by SM $Z$, $h$ exchange
  • Expect multi lepton signatures
  • Expect long lived particles due to suppressed couplings

• B-L sneutrino dark matter (GUT scale, universal):
  • Phenomenology primarily driven by heavy $Z'$, $h'$ exchange
  • LHC searches already put strong constraints on mediation mechanisms
  • Best explored at FCC

• (Personal) wish list:
  • Global fits with sneutrino dark matter
  • Reinterpretation for leptonic final state searches from ATLAS/CMS
  • Analysis of parameter space with LLPs
  • Studies at future colliders
Left handed sneutrino

- Left handed sneutrino as dark matter, couples to SM Z with gauge strength
- Excluded by direct detection constraints and Z invisible width
Monochromatic neutrino lines from annihilation

$\tilde{\nu}_\tau \rightarrow \nu_\tau$

$\tilde{\nu}_\tau \rightarrow \nu_\tau$

High line to continuum ratio

Neutrino spectrum at source

$\frac{dN}{dE} [\text{GeV}^{-1}]$

Neutrino spectrum at detection

For light sneutrino masses see e.g. Belanger et al, JCAP 1011:017, 2010


Low annihilation cross section

$\sigma_{\tilde{\nu}_\tau \rightarrow \nu_\tau}$

$[\text{cm}^3 \text{s}^{-1}]$

$\log_{10}(\frac{dN}{dE_{\tilde{\nu}_\tau}})$ [GeV$^{-1}$]

$E_{\tilde{\nu}_\tau}$ [GeV]

$E_\nu$ [GeV]

$\nu_e$

$\nu_\mu$

$\nu_\tau$
Depends on astrophysics as well

\[
\frac{d\Phi_\nu}{dE} = \frac{1}{8\pi} \frac{\xi^2}{m^2_{\nu_{\tau_1}}} \frac{dN_\nu}{dE} \Phi_{\text{Astro}}
\]

\[
\frac{dN_\nu}{dE} = \begin{cases} 
B_\nu \frac{dN_{\nu_{\text{line}}}}{dE} \delta(E - m_\nu) \\
\sum_k B_k \frac{dN_{\nu_k}}{dE}
\end{cases}
\]

\[
\Phi_{\text{Astro}} \equiv J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega' \int_{\text{los}} \rho_{\text{dwarf}}^2(r(s, \theta)) ds
\]

Can astrophysics environment provide additional boost factor?
Depends on astrophysics as well

\[ \frac{d\Phi_{\nu}}{dE} = \frac{1}{8\pi} \xi^2 \frac{\langle \sigma v \rangle}{m_{\nu_{\tau1}}^2} \frac{dN_{\nu}}{dE} \Phi_{\text{Astro}} \]

\[ \frac{dN_{\nu}}{dE} = \left\{ \begin{array}{c} B_{\nu} \frac{dN_{\nu_{\text{line}}}}{dE} \delta(E - m_{\nu}) \\ \sum_k B_{\nu} \frac{dN_{\nu_k}}{dE} \end{array} \right\} \]

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\]

Can astrophysics environment provide additional boost factor?
Neutrino lines: distinct possibility for sneutrino dark matter

Idealist neutrino telescope setup

Point source sensitivity extended to low energies
Direct detection detects how much LH part of sneutrino can survive (Z coupling)

Strong exclusion from LUX experiment
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- Under ideal conditions ($\beta\gamma = 1$, large mass difference), the entire region up to $c_\tau = 10^4$ covered at LHC 13
- Also possible, long lived stops
• $m_{\tilde{\tau}} = 665$ GeV, DY stau pair production,
• Stau track should have no other track with $p_T > 0.5$ GeV within $\Delta R = 0.05$
• Stau must travel a distance of at least 514 mm i.e. decays inside the hadronic calorimeter
• Convoluted with efficiencies given in ATLAS-CONF-2013-058