Right-handed Sneutrinos LHC Signatures and Inverse

Shrihari Gopalakrishna

Northwestern University

with

Andre de Gouvea (Northwestern) & Werner Porod (Valencia)

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Outline

- Motivation
- The Theory
    - Sneutrino mass matrix & mixing
- Right-handed sneutrino ($\tilde{N}_R$) dark matter
- $\tilde{N}_R$ LHC signatures and Inverse
- Conclusions

Motivation

Dark Matter

WMAP result (2003) $\Omega_m h^2 = 0.135\ ^{+0.008}_{-0.009}$; $h^2 \approx 0.5$

When does $(\tilde{N}_R)$ not overclose the universe?

Neutrino has mass

Old Standard Model (SM) had only left-handed $\nu_L^{e,\mu,\tau}$
Oscillation experiments : $\nu_L^{\alpha} \leftrightarrow \nu_L^{\beta}$: $m_\nu \approx 0.1\mathbf{eV}$
A renormalizable theory for mass requires adding:
Right-handed Neutrino $(N_R^i.)$ OR Higgs triplet
If Supersymmetry and N_R^i. then right-handed sneutrino

SUSY Sector

Most general (renormalizable) theory, with Lepton-# violation

Superpotential

$$\mathcal{W} = N^c Y_N L \cdot H_u - E^c Y_E L \cdot H_d + N^c \frac{M_N}{2} N^c + \mu H_u \cdot H_d$$

SUSY Breaking terms

$$\begin{aligned}\mathcal{L}_{SUSYBr} = & - \tilde{\ell}_L^\dagger m_\ell^2 \tilde{\ell}_L - \tilde{N}_R^\dagger m_N^2 \tilde{N}_R - \tilde{e}_R^\dagger m_e^2 \tilde{e}_R \\ & - \tilde{N}_R^\dagger A_N \tilde{\ell}_L \cdot h_u - \tilde{e}_R^\dagger A_e \tilde{\ell}_L \cdot h_d + h.c. \\ & + (\tilde{\ell} \cdot h_u)^T \frac{c_\ell}{2} (\tilde{\ell} \cdot h_u) + \tilde{N}_R^T \frac{b_N^2}{2} \tilde{N}_R + h.c. \\ & + (b\mu h_u \cdot h_d + h.c.\end{aligned}$$

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& - \tilde{N}_R^\dagger A_N \tilde{\ell}_L \cdot h_u - \tilde{e}_R^\dagger A_e \tilde{\ell}_L \cdot h_d + h.c. \\
& + (\tilde{\ell} \cdot h_u)^T \frac{c_\ell}{2} (\tilde{\ell} \cdot h_u) + \tilde{N}_R^T \frac{b_N^2}{2} \tilde{N}_R + h.c. \\
& + (b\mu h_u \cdot h_d + h.c.
\end{aligned}$$

Neutrino Mass

$$\mathcal{L}^{\nu}_{mass} = -\overline{N} v_u Y_N \nu - \overline{N^c} \frac{M_N}{2} N + h.c.$$

$$m_\nu = \frac{v_u^2 Y_N^2}{M_N}$$

For $m_\nu \sim 0.1\mathrm{eV}$

- If $M_N \sim 10^{14}\mathrm{GeV}$ then $Y_N \sim O(1)$ (Seesaw)
- **If** $M_N \sim 10^{2}\mathrm{GeV}$ **then** $Y_N \sim 10^{-6}$
- If no M_N term then $Y_N \sim 10^{-12}$ (Dirac ν)

Sneutrino mass matrix

$$\mathcal{L}^{\tilde{\nu}}_{mass} = -\begin{pmatrix} \tilde{\nu}_L^\dagger & \tilde{N}_R^\dagger & \tilde{\nu}_L^T & \tilde{N}_R^T \end{pmatrix} \mathcal{M}_{\tilde{\nu}} \begin{pmatrix} \tilde{\nu}_L \\ \tilde{N}_R \\ \tilde{\nu}_L^* \\ \tilde{N}_R^* \end{pmatrix}$$

$$\mathcal{M}_{\tilde{\nu}} = \frac{1}{2}\begin{pmatrix} m_{LL}^2 & m_{RL}^{2\,\dagger} & -v_u^2 c_\ell^\dagger & v_u Y_N^\dagger M_N \\ m_{RL}^2 & m_{RR}^2 & v_u M_N^T Y_N^* & -b_N^{2\dagger} \\ -v_u^2 c_\ell & v_u Y_N^T M_N^* & m_{LL}^{2\,*} & m_{RL}^{2\,T} \\ v_u M_N^\dagger Y_N & -b_N^2 & m_{RL}^{2\,*} & m_{RR}^{2\,*} \end{pmatrix}$$

$$m_{LL}^2 = (m_\ell^2 + v_u^2 Y_N^\dagger Y_N + \Delta_\nu^2)\ ; \quad \Delta_\nu^2 = (m_Z^2/2)\cos 2\beta$$

$$m_{RR}^2 = (M_N M_N^* + m_N^2 + v_u^2 Y_N Y_N^\dagger)$$

$$m_{RL}^2 = (-\mu^* v_d Y_N + v_u A_N)$$

Real fields

Mixing effects

- m^2_{RL} : $\tilde{\nu}_L \leftrightarrow \tilde{N}_R$ mixing
- c_ℓ : $\tilde{\nu}_L \leftrightarrow \tilde{\nu}^*_L$ mixing
- M_N : $\tilde{\nu}_L \leftrightarrow \tilde{N}^*_R$ mixing
- b^2_N : $\tilde{N}_R \leftrightarrow \tilde{N}^*_R$ mixing

From now assume as real : m^2_{LL}, m^2_{RR}, m^2_{RL}, c_ℓ, b^2_N
Redefine:

$$\begin{aligned} \tilde{\nu}_L &= (\tilde{\nu}_1 + i\tilde{\nu}_2)/\sqrt{2} \\ \tilde{N}_R &= (\tilde{N}_1 + i\tilde{N}_2)/\sqrt{2} \end{aligned}$$

Mass matrix becomes...

$$\mathcal{L}^{\tilde{\nu}}_{mass} = -\frac{1}{2}\begin{pmatrix}\tilde{\nu}_1^T & \tilde{N}_1^T & \tilde{\nu}_2^T & \tilde{N}_2^T\end{pmatrix}\mathcal{M}^r_{\tilde{\nu}}\begin{pmatrix}\tilde{\nu}_1\\ \tilde{N}_1\\ \tilde{\nu}_2\\ \tilde{N}_2\end{pmatrix}$$

$$\mathcal{M}^r_{\tilde{\nu}} = \begin{pmatrix} m^2_{LL} - c_\ell & m^{2\,T}_{RL} + v_u Y_N^T M_N^* & 0 & 0 \\ m^2_{RL} + v_u M_N^\dagger Y_N & m^2_{RR} - b^2_N & 0 & 0 \\ 0 & 0 & m^2_{LL} + c_\ell & m^{2\,T}_{RL} - v_u Y_N^T M_N^* \\ 0 & 0 & m^2_{RL} - v_u M_N^\dagger Y_N & m^2_{RR} + b^2_N \end{pmatrix}$$

[Hirsch et al., Grossman et al. '97]

c_ℓ, b_N and M_N split $\tilde{\nu}_1 \leftrightarrow \tilde{\nu}_2$ degeneracy, and $\tilde{N}_1 \leftrightarrow \tilde{N}_2$ degeneracy
Denote LSP as $\tilde{\nu}_0$; Heavy states as $\tilde{\nu}_H$
Bose symmetry forbids $Z\tilde{\nu}_0\tilde{\nu}_0$ coupling
$\therefore$ leads to acceptable relic density [Hall et al. '97]

Diagonalization

$$\begin{pmatrix} \tilde{\nu}_i \\ \tilde{N}_i \end{pmatrix} = \begin{pmatrix} \cos\theta_i^{\tilde{\nu}} & -\sin\theta_i^{\tilde{\nu}} \\ \sin\theta_i^{\tilde{\nu}} & \cos\theta_i^{\tilde{\nu}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}'_i \\ \tilde{N}'_i \end{pmatrix} \quad ; \quad s_i \equiv \sin\theta_i^{\tilde{\nu}}$$

Mixing angle is:

$$\tan 2\theta_i^{\tilde{\nu}} = \frac{2\left|-\mu^* v_d Y_N + v_u A_N \pm v_u M_N^\dagger Y_N\right|}{(m_{LL}^2 \mp c_\ell) - (m_{RR}^2 \mp b_N^2)}$$

Assume: $A_N \equiv a_N Y_N m_\ell \; ; \Rightarrow \; s_1 \approx Y_N \frac{v_u}{m_\ell} \alpha_m$

$$Y_N \sim 10^{-6} \; ; \quad A_N \sim a_N \cdot 0.1 \text{ MeV} \; ; \quad s_1 \sim 10^{-6} \alpha_m \; ; \quad \tilde{\nu}_0 \approx \tilde{N}_1$$

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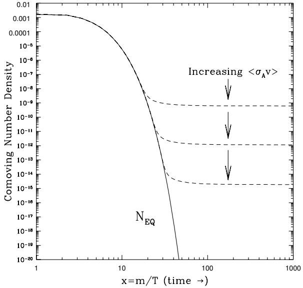
Boltzmann Equation

Big Bang $\rightarrow$ Inflation $\rightarrow \cdots \rightarrow$ BBN $\rightarrow$ Today

Thermal equilibrium if $\langle \sigma v \rangle_{SI} \, n_{\tilde{\nu}_0} > 3H$

Freeze-out



[Kolb & Turner, Early Universe]

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

Thermalization

Thermalization conditions not met $\Rightarrow$ Nonthermal $\tilde{\nu}_0$

$\tilde{N}_R$ interacts only through tiny Yukawa, so Nonthermal for:

- $Y_N \lesssim 10^{-6}$ i.e., $\tilde{\nu}_0$ is almost pure right-handed
- Low Reheat temp $T_{RH} < 100$ GeV ; Reheat into $\tilde{\nu}_0$ + SM

[S.G., Porod, de Gouvea, hep-ph/0602027; To appear in JCAP]

Monte Carlo Tools

Pythia 6.327: With my hack to include angular dep of 3-body stop decays

MadGraph & Comp-HEP Some checks made

SMadEvent Yet to be released

Ongoing work. Preliminary results presented here

[Special thanks to Stephen Mrenna & Peter Skands for help with Pythia]

LHC Signatures/Inverse

Unique features

- Heavier SUSY decays thro Y_N (tiny?) .... Disp vtx?
- All SUSY decays must have a lepton (charged or neutrino)
- Expect non-universality in e, μ, τ events
- 3 gens of $\tilde{N}_R$.... Cascade decays give leptons (how soft?)

At the LHC look for:

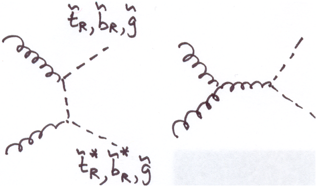
g g $\longrightarrow$ Colored Objects (squark, gluino)

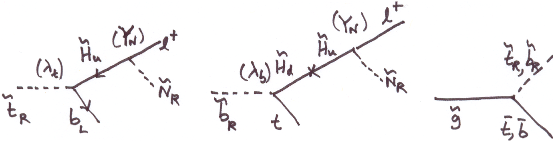
Can we find new:

(a) colored scalar (b) colored fermion ....Angular distributions?

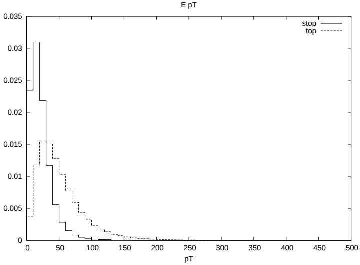
Some possibilities

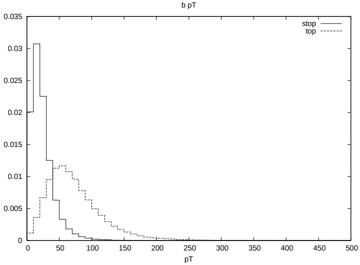
- $\tilde{t}_R$, $\tilde{b}_R$ production and decay
- $\tilde{g}$ production and decay
- $\tilde{\chi}$ production and decay



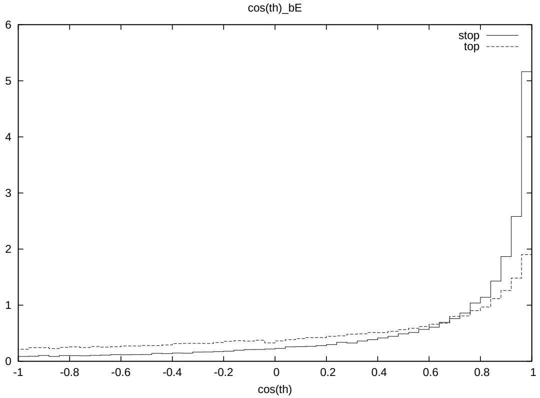


$\tilde{t}_R$ production and decay : pT

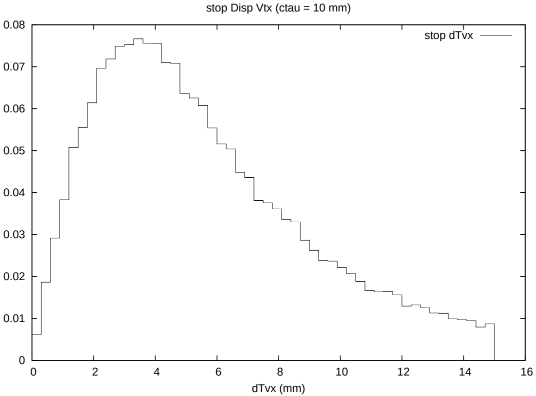




$\tilde{t}_R$ production and decay : $\cos\theta_{bE}$



$\tilde{t}_R$ production and decay : Disp Vtx



Conclusions

- Mixed $\tilde{\nu}$ well explored in the literature
- Pure right-handed $\tilde{\nu}$ investigated here
  - When SUSY breaking, $L_{\#}$ violating masses at weak scale
  - When $Y_N \sim 10^{-6}$
  - Has to be nonthermal in order not to overclose the universe
  - Possible dark matter candidate
- LHC Signature
  - Look for nonuniversal lepton signature
  - Displaced Vertex
- Inverse problem eased by many unique signatures

Backup Slides

Backup Slides

Thermal History of the Universe

Big Bang $\to$ Inflation $\to \cdots \to$ BBN $\to$ Today

Hubble rate:

$$H \equiv \frac{\dot{a}}{a} \; ; \quad H^2 = \frac{8\pi G}{3}\rho$$

$$H = 1.66\sqrt{g_*}\frac{T^2}{M_{Pl}} \quad \text{(Rad Dom)}$$

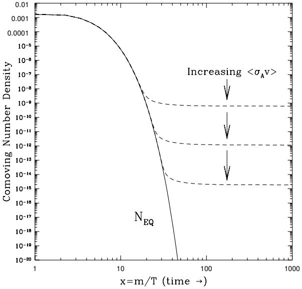
Boltzmann Equation

Big Bang → Inflation → ⋯ → BBN → Today

$$\frac{d}{dt} n_{\tilde{\nu}_0} = -3Hn_{\tilde{\nu}_0} - \langle \sigma v \rangle_{SI} \left(n^2_{\tilde{\nu}_0} - n^2_{\tilde{\nu}_0\ eq} \right) - \langle \sigma v \rangle_{CI} \left(n_{\tilde{\nu}_0} n_\phi - n_{\tilde{\nu}_0\ eq} n_{\phi\ eq} \right) + C_\Gamma$$

Thermal equilibrium if $\langle \sigma v \rangle_{SI} n_{\tilde{\nu}_0} > 3H$; $\langle \sigma v \rangle_{CI} n_\phi > 3H$

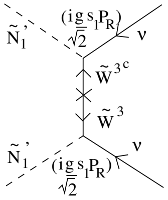
Freeze-out



[Kolb & Turner, Early Universe]

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

Mixed $\tilde{\nu}_0$ Dark Matter



$$\Omega_0 h^2 = \frac{10^{-4}}{s_1^4} \left\{ \left[g^2 \left(\frac{100\ \mathrm{GeV}}{M_{\tilde{W}}} \right) + g'^2 \left(\frac{100\ \mathrm{GeV}}{M_{\tilde{B}}} \right) \right]^2 \right\}^{-1}$$

$\therefore s_1 \approx 0.2$ results in observed relic density

Relic from Decays

Contribution from $C_\Gamma \sim n_\chi \Gamma\left(\chi \to \tilde{\nu}_0 X\right)$

- $\tilde{H}_u \longrightarrow \tilde{\nu}_0 L$

$$\Omega_{0\,(a_D)} h^2 \sim 10^{26} c_1^2 \, Y_N^2 \, \frac{M_{\mathrm{LSP}}}{M_{\tilde{H}}} \, f_{PS}^2$$

- $\tilde{\nu}_H \longrightarrow \tilde{\nu}_0 \overline{\psi} \psi$ $\qquad h_u$ exchange

$$\Omega_{0\,(b_D)} h^2 = 10^{24} (c_1^2 - s_1^2)^2 \, Y_c^2 \, \frac{A_N^2 M_{\tilde{\nu}_H} M_{\mathrm{LSP}}}{M_{h_u}^4} \, f_{3PS}^2$$

Does not overclose if

$Y_N \lesssim 10^{-13}$; $\quad A_N \lesssim 10\ \mathrm{eV}$; $\quad s_1 \lesssim 10^{-12}$

(Decays just before BBN!)

Dirac case [Asaka et al. '05]

When is $\tilde{\nu}_0$ Thermal? $\langle \sigma v \rangle \, n > 3H$

Self-interaction processes

(a_s) $\tilde{\nu}_0\tilde{\nu}_0 \to \nu_L \nu_L$ $\tilde{W}^3$; $\tilde{B}$ exchange

(d_s) $\tilde{\nu}_0\tilde{\nu}_0 \to \nu_L \overline{\nu_L}$; $e_L \overline{e_L}$ $\tilde{H}_u^+$; $\tilde{H}_u^0$ exchange

Process	Cross-section	Limit
(a_s)	$\frac{s_1^4}{16\pi}\left(\frac{g^2}{M_{\tilde{W}}} + \frac{g'^2}{M_{\tilde{B}}}\right)^2$	$\alpha_m Y_N > 10^{-3}$
(d_s)	$\frac{Y_N^4 c_1^4}{16\pi}\frac{1}{M_{\tilde{H}}^2}\left(\frac{m_e}{M_{\rm LSP}}\right)^2$	$Y_N > 10^{-3}$

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(d_s)	$\frac{Y_N^4 c_1^4}{16\pi}\frac{1}{M_{\tilde{H}}^2}\left(\frac{m_e}{M_{\rm LSP}}\right)^2$	$Y_N > 10^{-3}$

When is $\tilde{\nu}_0$ Thermal?

Co-interaction processes with other SUSY particles
Boltzmann suppressed by

$$\beta_\phi \equiv e^{-(\Delta M_\phi / T)} \; ; \quad \Delta M_\phi \equiv (M_\phi - M_{\rm LSP})$$

Co-interaction with SUSY

(b_c) $\tilde{\nu}_0 \tilde{s} \longrightarrow \tilde{e}_L \tilde{s}'$ $W^\pm$ exchange

(e_c) $\tilde{\nu}_0 \tilde{\nu}_H \longrightarrow c\bar{c}\;;\; t\bar{t}$ h_u exchange

Process	Cross-section	Limit
(b_c)	$\frac{g^4 s_1^2}{16\pi} \frac{{M_{\rm LSP}}^2}{M_Z^4} f_{PS}^2$	$\beta_{\tilde{s}} \alpha_m f_{PS} Y_N > 10^{-6.5}$
(e_c)	$\frac{(c_1^2 - s_1^2)^2 Y_u^2}{16\pi} \frac{1}{M_{h_u}^2} \left(\frac{A_N}{M_{h_u}}\right)^2 f_{PS}^2$	$Y_u \beta_{\tilde{\nu}_H} \alpha_m f_{PS} Y_N > 10^{-7}$

When is $\tilde{\nu}_0$ Thermal?

Co-interaction with SM

(a_M) $\tilde{\nu}_0 t_{R,L} \to \tilde{\nu}_L t_{L,R}$ h_u exchange

(b_M) $\tilde{\nu}_0 t_L \to \nu_L \tilde{t}_R$ $\tilde{H}_u$ exchange

Process	Cross-section	Limit
(a_M)	$\frac{A_N^2 Y_t^2}{16\pi} \frac{1}{M_{h_u}^4} f_{PS}^2$	$\beta_t \alpha_m f_{PS} Y_N > 10^{-7}$
(b_M)	$\frac{Y_N^2 Y_t^2}{16\pi} \frac{1}{M_{\tilde{H}}^2} f_{PS}^2$	$\beta_t f_{PS} Y_N > 10^{-7}$

Nonthermal $\tilde{\nu}_0$

Thermalization conditions not met $\Rightarrow$ Nonthermal $\tilde{\nu}_0$

Happens when :

- $Y_N \lesssim 10^{-6}$ i.e., $\tilde{\nu}_0$ is almost pure right-handed
- Low Reheat temp $T_{RH} < 100$ GeV ; Reheat into $\tilde{\nu}_0$ + SM

  No Relic-from-decay of heavier SUSY particles
  No $\tilde{\nu}_0$ thermalization from co-interaction with SUSY or Top

$\tilde{N}$ Relic density depends on Inflaton coupling to SM and $\tilde{N}$

- Work in progress

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