Stop versus Top at the Tevatron and the LHC

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based on work with
Andre de Gouvea (Northwestern) & Werner Porod (Valencia)
hep-ph/0602027, hep-ph/0606296

...

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Introduction

- Supersymmetry stabilizes the weak scale
- Neutrino mass requires adding :
  Right-handed Neutrino (N_R^i) (or Higgs triplet)
  Supersymmetry and $N_R^i \Rightarrow$ Right-handed Sneutrino ($\tilde{N}_R^i$)
- Tevatron, LHC signatures of weak scale $\tilde{N}_R$ LSP
  Colored $\tilde{t}$, $\tilde{g}$, ... production and decay
- Focus on :
  Signal: $\tilde{t}\tilde{t}^*$ production, $\tilde{t} \rightarrow b\ell\tilde{N}_R$
  Background: $t\bar{t}$ production, $t \rightarrow b\ell\nu$

SUSY Sector

ν Superfields: MSSM has $\nu = (\tilde{\nu}_L, \nu_L)$ Add $N = (\tilde{N}_R, N_R)$

Superpotential

$$\mathcal{W} = N^c Y_N L \cdot H_u + N^c \frac{M_N}{2} N^c + W_{\text{MSSM}}$$

SUSY Breaking terms

$$\begin{aligned}\mathcal{L}_{SUSYBr} = & - \tilde{\ell}_L^\dagger m_\ell^2 \tilde{\ell}_L - \tilde{N}_R^\dagger m_N^2 \tilde{N}_R + h.c. \\ & - \tilde{N}_R^\dagger A_N \tilde{\ell}_L \cdot h_u + h.c. \\ & + \tilde{N}_R^T \frac{b_N^2}{2} \tilde{N}_R + h.c.\end{aligned}$$

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) [Asaka et al. '05]

Sneutrino mass matrix

For real : m^2_{LL}, m^2_{RR}, m^2_{RL}, b^2_N can redefine with real fields

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

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

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

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

Depending on SUSY Breaking mech, $\tilde{N}$ can be the LSP

Diagonalization

$$\begin{pmatrix} \tilde{\nu} \\ \tilde{N} \end{pmatrix} = \begin{pmatrix} \cos\theta^{\tilde{\nu}} & -\sin\theta^{\tilde{\nu}} \\ \sin\theta^{\tilde{\nu}} & \cos\theta^{\tilde{\nu}} \end{pmatrix} \begin{pmatrix} \tilde{\nu}' \\ \tilde{N}' \end{pmatrix} \quad ; \qquad s \equiv \sin\theta^{\tilde{\nu}}$$

Mixing angle is:

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

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Assume: $A_N \equiv a_N Y_N m_\ell \quad \Rightarrow \tan 2\theta^{\tilde{\nu}} \sim Y_N \frac{v_u}{m_\ell}$

$Y_N \sim 10^{-6}$; $\theta^{\tilde{\nu}} \sim 10^{-6}$; $\tilde{\nu}_0 \approx \tilde{N}$

Cosmology

- $\tilde{N}_R$ interacts only through tiny Yukawa
- To prevent overclosing the universe
  $\tilde{N}_R$ shouldn't be in thermal equilibrium: need $\langle \sigma v \rangle \, n_{\tilde{N}_R} < 3H$
- When is this realized?

[de Gouvea, S.G., Porod, hep-ph/0602027 - JCAP]

Nonthermal if:

- $Y_N \lesssim 10^{-6}$
- Low Reheat temp $T_{RH} < 100$ GeV ;   Reheat into $\tilde{N}$ + SM

Tevatron and LHC Signatures

[de Gouvea, S.G., Porod, hep-ph/0606296]

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 hadron colliders look for:

q q / g g $\rightarrow \tilde{t}\,\tilde{t}^*$, $\tilde{g}\,\tilde{g}$, ...

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At hadron colliders look for:

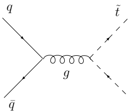
$$\mathrm{q\,q} \;/\; \mathrm{g\,g} \rightarrow \tilde{t}\,\tilde{t}^* \;,\; \tilde{g}\,\tilde{g} \;,\; \ldots$$

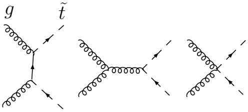
Monte Carlo Program: **Pythia** 6.327:

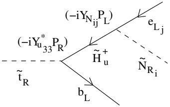
With modification to include angular dep of 3-body $\tilde{t}$ decays

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

$\tilde{t}_R$ production and decay







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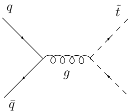
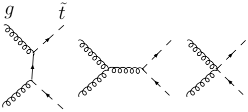
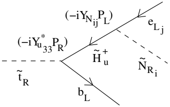






Level 1 cuts:

The rapidity cuts $\eta_\ell < 2.5$, $\eta_b < 2.5$.

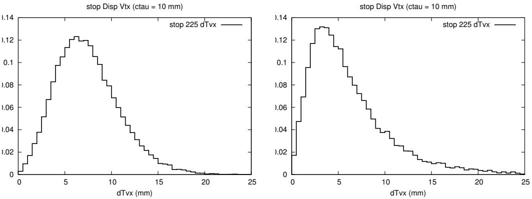
The transverse momentum cuts $p_{T\,\ell} > 20$ GeV, $p_{T\,b} > 10$ GeV.

The isolation cut $R_{b\ell} > 0.4$, where $R^2_{b\ell} \equiv (\phi_b - \phi_\ell)^2 + (\eta_b - \eta_\ell)^2$

Efficiency:

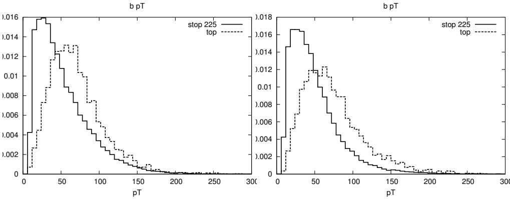
$\epsilon_b = 0.5$, $\epsilon_\ell = 0.9$

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

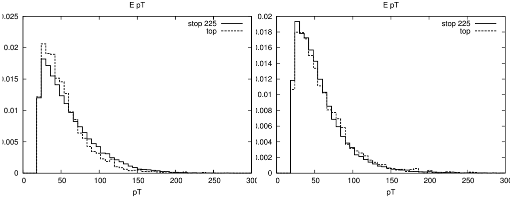


p_T distributions

$b\ p_T$

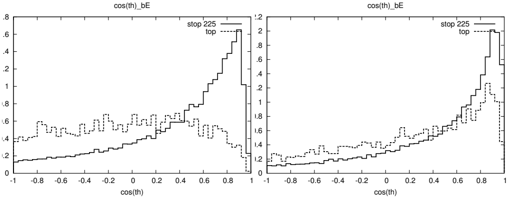


$\ell\ p_T$

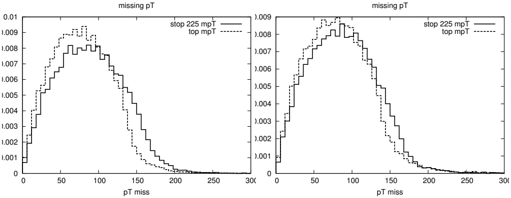


distributions

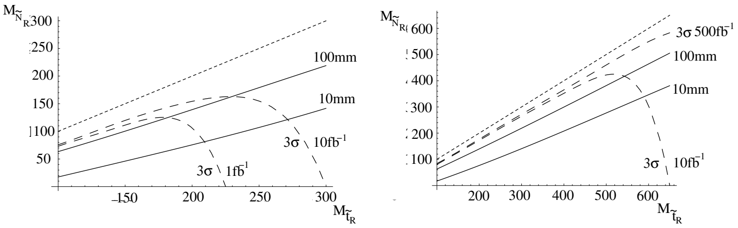
$\cos(\theta_{b\ell})$



$p_{T\ miss}$



Disp Vtx and Reach



Tevatron

Fraction α passes level 1 cuts, S and B for 1 fb^{-1}

$M_{\tilde{t}_R}$	$M_{\tilde{N}_R}$	σ_S(pb)	σ_B(pb)	α	S	B	S/B	$S/\sqrt{B}$	$S/\sqrt{S+B}$
100	50	11.83	6.77	0.26	162	9	18.93	55.36	12.4
	75	11.83	6.77	0.04	4	9	0.45	1.31	1.09
150	100	1.24	6.77	0.29	21	9	2.46	7.21	3.87
	125	1.24	6.77	0.05	1	9	0.07	0.21	0.21
175	100	0.48	6.77	0.47	22	9	2.53	7.39	3.93
	150	0.48	6.77	0.05	0.2	9	0.03	0.08	0.08
250	100	0.04	6.77	0.71	4	9	0.48	1.4	1.15
	200	0.04	6.77	0.31	1	9	0.09	0.27	0.26

LHC

Fraction α passes level 1 cuts, S and B for 10 fb^{-1}

$M_{\tilde{t}_R}$	$M_{\tilde{N}_R}$	σ_S(pb)	σ_B(pb)	α	S	B	S/B	$S/\sqrt{B}$	$S/\sqrt{S+B}$
100	75	1332.5	873	0.03	1938	8662	0.22	20.82	18.82
	83	1332.5	873	0.01	73	8662	0.01	0.78	0.78
150	100	228.79	873	0.23	25325	8662	2.92	272.1	137.37
	128	228.79	873	0.02	144	8662	0.02	1.54	1.53
250	200	21.32	873	0.26	2886	8662	0.33	31.01	26.86
	225	21.32	873	0.03	40	8662	0.01	0.43	0.43
500	400	0.56	873	0.59	398	8662	0.05	4.28	4.19
	425	0.56	873	0.48	263	8662	0.03	2.83	2.78
650	250	0.14	873	0.83	195	8662	0.02	2.10	2.08

Future Directions

Make it realistic

- Optimize cuts to maximize significance ($\theta_{b\ell}$)
- Detector Simulation
- Combinatorics

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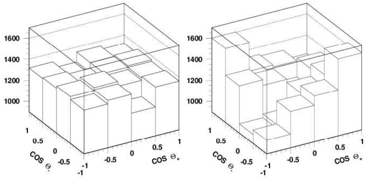
- $t\bar{t}$ spin correlation vs. $\tilde{t}\tilde{t}^*$

Generalize

- Valid for any SUSY spectrum?

$t\bar{t}$ spin correlation

Default Pythia (left) : Modified to incl spin corr (right) (With CMSJET)



[From Bernreuther et al.]

To do

- Use this to suppress $t\bar{t}$ background from $\tilde{t}\tilde{t}^{*}$signal
  Compute Significance

Conclusions

- $t\bar{t}$ and $\tilde{t}\tilde{t}^*$seperation can be challenging.
- Here looked at $\tilde{t}_R \longrightarrow b\ell\tilde{N}_R$ when $Y_N \sim 10^{-6}$, $M_N \sim v$
  - Significance depends on $M_{\tilde{t}_R}$, $M_{\tilde{N}_R}$
  - $\tilde{t}_R$ displaced vertex
- Distributions valid more generally
- To do: Spin correlation analysis

Backup Slides

Backup Slides

Sneutrino mass matrix

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

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

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

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

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

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...

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

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

[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]

Thermal History of the Universe

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

Hubble rate:

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

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

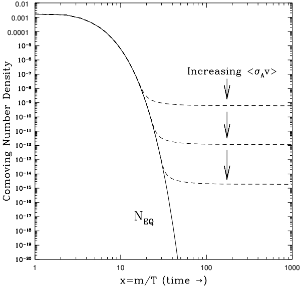
Boltzmann Equation

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

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

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

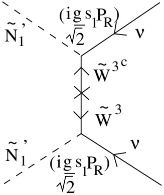
Freeze-out



[Kolb & Turner, Early Universe]

$\Omega_0 = \frac{n_0 M}{\cdots} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\cdots} \right)$

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

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

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

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

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

Does not overclose if

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

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

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

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Self-interaction processes

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

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

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

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

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  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