A Heavy Higgs and a Light Sneutrino NLSP In the MSSM with Enhanced SU(2) D-terms

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Outline

- Motivation and review of the model.
- Sparticle mass splitting and contributions to ΔT and slepton spectrum with no mixing.
- SUSY breaking model.
- Mixing and low energy SUSY spectrum.
- Cosmological constraints.
- Non-vanishing $SU(2)_1$ gaugino mass model.
- Conclusion.

Motivation

• MSSM solves the hierarchy problem and provides a DM candidate with R-parity.

• Includes a Higgs boson with a mass naturally of order M_z (small quartic coupling).

• LEP bound $\longrightarrow$ large radiative corrections $\longrightarrow$ large squark masses $\longrightarrow$ tension with solving the hierarchy problem.

• Situation may improve by extending weak gauge group to $SU(2)_1 \times SU(2)_2$ (*Batra et al,JHEP 0406.032,2004*):

1. Higgs sector and 3rd generation family charged under $SU(2)_1$.
2. 1st and 2nd generation families charged under $SU(2)_2$.

• SUSY breaking mass associated with scalars that break $SU(2)_1 \times SU(2)_2 \longrightarrow SU(2)_W$ larger than their vevs lead to enhanced D-terms raise Higgs mass (m_h <300 GeV).

• Corrections to EWPT:

1. Gauge boson mixing small if gauge symmetry breaking scalars vev's are large.
2. Large Higgs mass $\longrightarrow$ negative contribution to ΔT.

Review of the Model

- Breakdown $SU(2)_1 \times SU(2)_2 \longrightarrow SU(2)_W$ governed by,

$$W = \lambda_1 S \left(\frac{\Sigma\Sigma}{2} - w^2 \right)$$

- Leads to a Σ potential,

$$V = m_\Sigma^2 \Sigma^\dagger \Sigma + \frac{\lambda_1^2}{4} |\Sigma\Sigma|^2 - \frac{B}{2} (\Sigma\Sigma + h.c.) + \ldots$$

where $B=\lambda_1 \omega$ and m^2_Σ is a soft SUSY breaking mass. Also D-terms contribution,

$$\Delta V = \frac{g_1^2}{8} \left(\mathrm{Tr}[\Sigma^\dagger \tau^a \Sigma] + \mathrm{H}_u^\dagger \tau^a \mathrm{H}_u + \mathrm{H}_d^\dagger \tau^a \mathrm{H}_d + \mathrm{L}^\dagger \tau^a \mathrm{L} + \mathrm{Q}^\dagger \tau^a \mathrm{Q} \right)^2 + \frac{g_2^2}{8} \left(\mathrm{Tr}[\Sigma^\dagger \tau^a \Sigma] + \ldots \right)^2$$

- For $B > m^2_\Sigma$, $\langle \Sigma \rangle = uI$, with $u^2 = (B - m^2_\Sigma) / \lambda_1^2$. Assuming $B \gg v^2$, integrate out heavy d.o.f (Σ decomposes as a triplet plus a singlet under $SU(2)_W$),

$$\Delta V = \frac{g^2}{2} \Delta \sum_a \left(H_u^\dagger \tau^a H_u + H_d^\dagger \tau^a H_d + L_3^\dagger \tau^a L_3 + Q_3^\dagger \tau^a Q_3 \right)^2$$

with

$$\Delta = \frac{1 + \frac{2 m_\Sigma^2}{g_2^2 u^2}}{1 + \frac{2 m_\Sigma^2}{(g_2^2 + g_1^2) u^2}}$$

- Therefore,

$$m_h^2 = \frac{1}{2} \left(g^2 \Delta + g_Y^2 \right) v^2 \cos^2 2\beta + \text{loop corrections}$$

Sparticle mass splitting and contributions to ΔT

- Re-write SU(2) D-term effective potential,

$$V_D = \frac{g^2\Delta}{8}\left(\sum_i \Phi_i^\dagger \Phi_i\right)^2 - \frac{g^2\Delta}{4}\sum_{ij}\left|\Phi_i^T i\sigma_2 \Phi_j\right|^2$$

•Combination of F-term and D-term contributions for 3rd generation l.h. sleptons and squarks imply,

$$\begin{aligned} m^2_{\tilde{\tau}_L} - m^2_{\tilde{\nu}_\tau} &= \Delta_D \\ m^2_{\tilde{b}_L} - m^2_{\tilde{t}_L} &= \Delta_D - m_t^2 \end{aligned}$$

with

$$\begin{aligned} \Delta_D &= \frac{g^2 v^2}{2}\Delta|\cos 2\beta| \\ &= \left(\Delta m_h^2\right)_D / |\cos 2\beta| \end{aligned}$$

- For the charged Higgs H^+ and CP-odd Higgs A,

$$m^2_{H^\pm} - m^2_A = \frac{g^2\Delta}{2}v^2$$

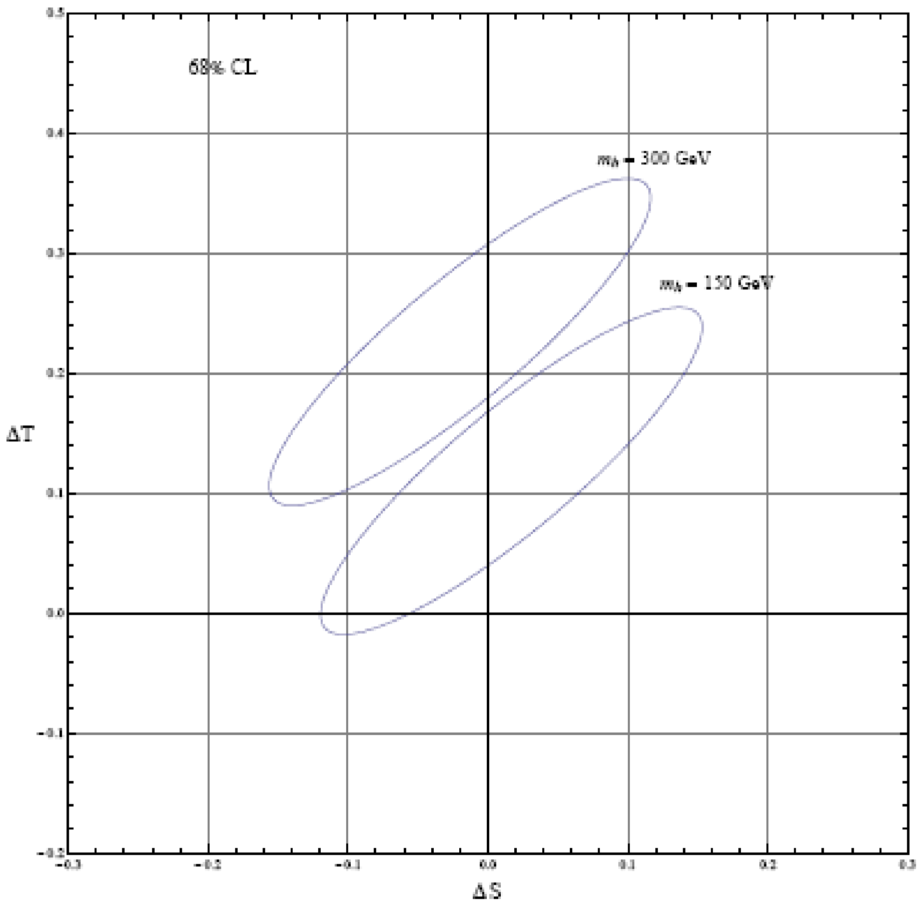
•Upper and lower component mass splitting of SU(2) doublet lead to (no mixing),

$$\begin{aligned} \Delta T &= \frac{N_c}{12\pi s_W^2 m_W^2}(\Delta m_{ud})^2 \\ &= \frac{N_c}{12\pi s_W^2 m_W^2}\frac{(\Delta m^2_{ud})^2}{(m_u + m_d)^2} \end{aligned}$$

- Which must be added to

$$\begin{aligned} \Delta T &= -\frac{3}{8\pi c_W^2}\ln\frac{m_h}{m_{h_{\rm ref}}} \\ \Delta S &= \frac{1}{6\pi}\ln\frac{m_h}{m_{h_{\rm ref}}}, \end{aligned}$$

Slepton spectrum with no mixing



Small ΔT contribution from triplet,

$$\Delta T \simeq \frac{4\pi g_1^4}{s_W^2 c_W^2 g^4} \frac{m_W^2 u^2}{M_T^4}$$

$$\longrightarrow \boxed{\begin{array}{lcl} \Delta T_{150} & \simeq & 0.10 \pm 0.06 \\ \Delta T_{300} & \simeq & 0.24 \pm 0.07 \end{array}}$$

❖Fit provided by Jen Erler.

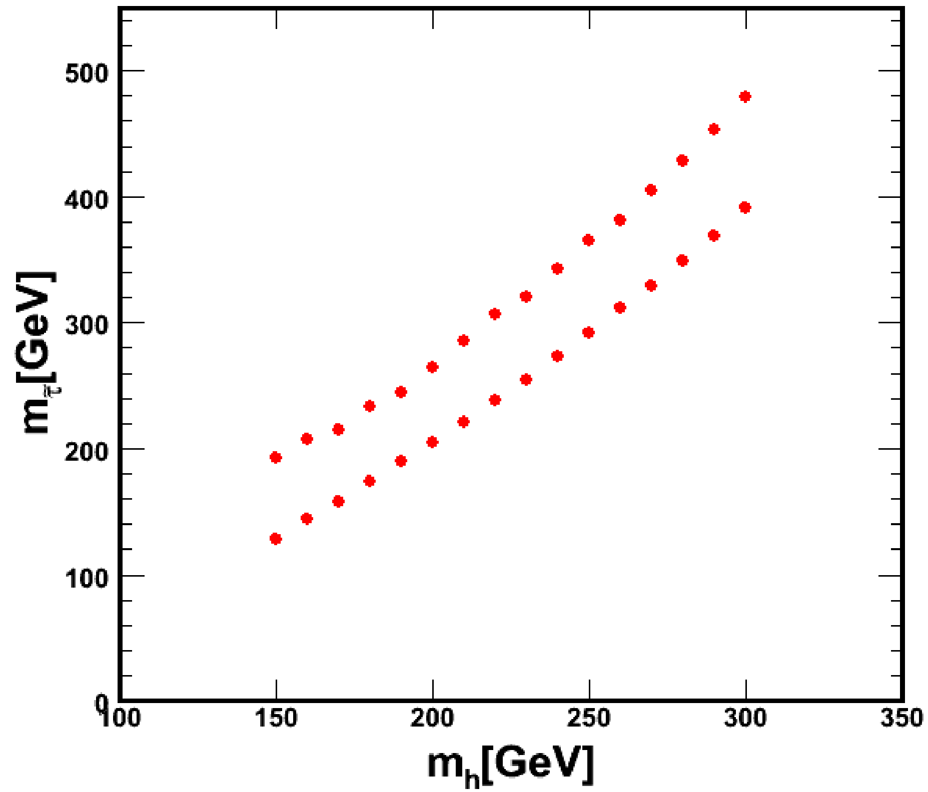
Slepton spectrum with no mixing

• We will assume that 3rd generation l.h sleptons are the main contributor to ΔT.

• Stau mass between 120 GeV and 480 GeV.

• For a fixed Higgs mass, the stau mass range is 80 GeV.

• Higgs decays mostly into W and Z pairs as in the MSSM.



Slepton spectrum with no mixing

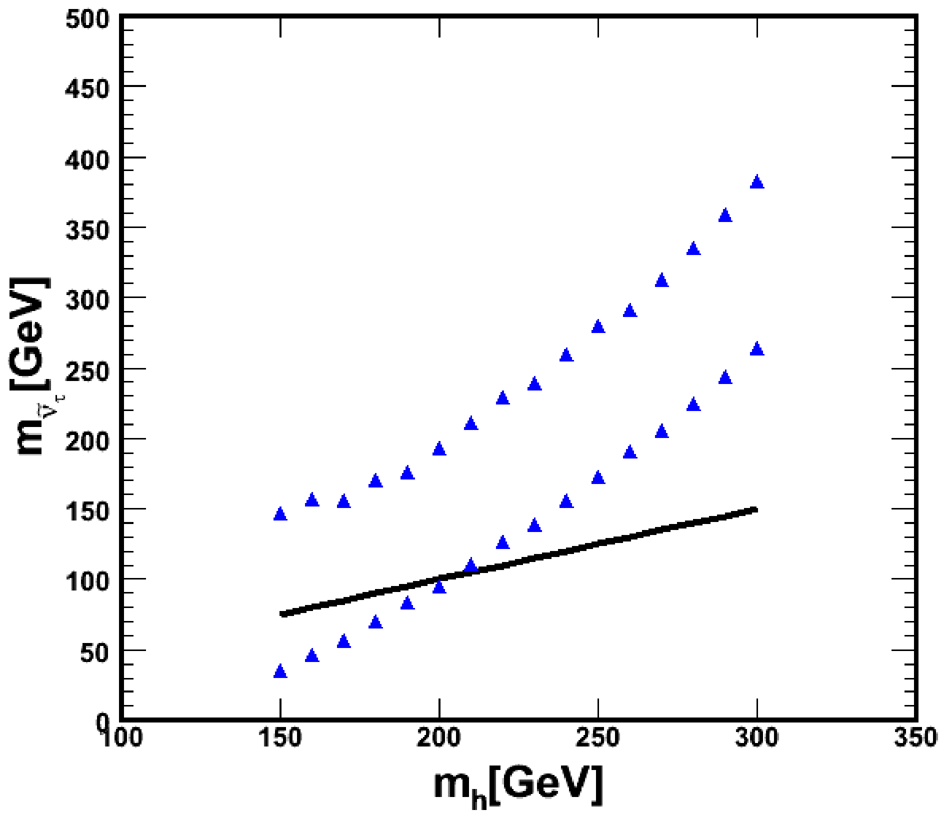
- Tau sneutrino mass between 40 GeV and 380 GeV.

- For a fixed Higgs mass, the tau sneutrino mass range is 190 GeV.

- Black line represents $m_h/2$. Small region where Higgs can decay into tau sneutrino pairs. Enhanced by the coupling:

$$g_{h\tilde{\nu}_\tau\tilde{\nu}_\tau} \simeq -i\,\frac{(g^2\Delta + g_Y^2)\;v}{2\sqrt{2}}$$

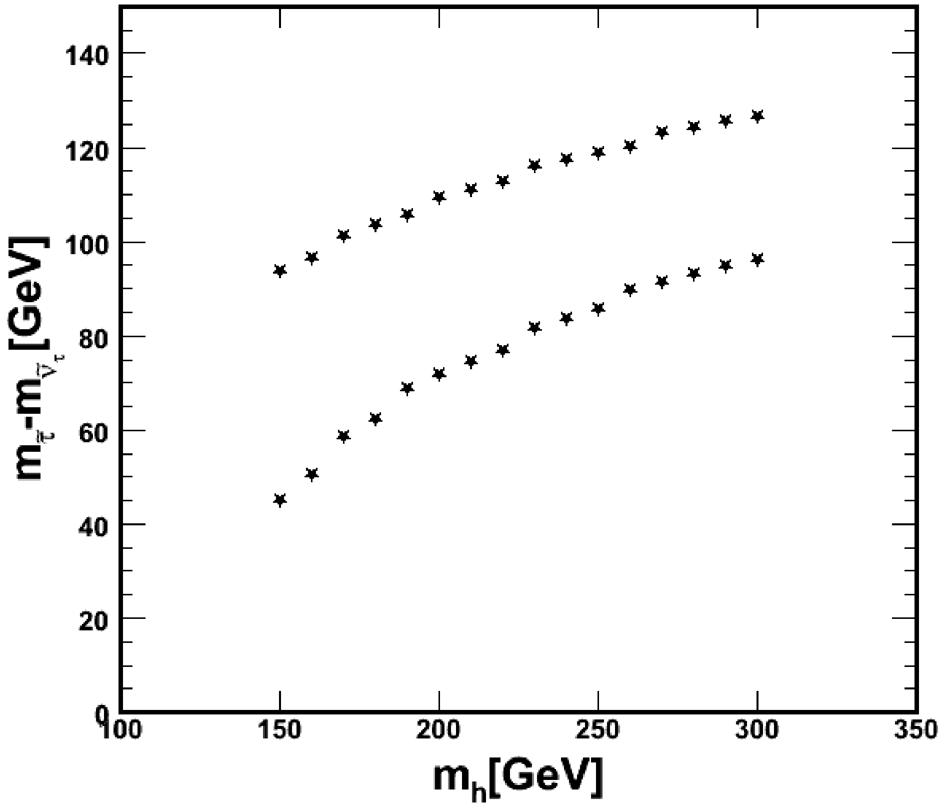
- Constraints from ΔT become weaker for light Higgs mass (m_h ~150 GeV).



Slepton spectrum with no mixing

- Mass difference grows with m_h .

- For m_h >225 GeV, mass difference big enough for stau decays into on-shell W's and sneutrinos ⟶ hard leptons in the final state.



Supersymmetric Model

- Input at high energy: Moderate tan β, universal gaugino mass $M_{1/2}$, universal soft scalar mass M_0 for squarks and sleptons, soft SUSY breaking Higgs masses $m^2_{Hu}=m^2_{Hd}$, positive sign(μ) and $A_t=A_b=A_\tau=0$, at the messenger scale $M\sim M_{GUT}$.
- SUSY breaking transmitted to the visible sector only via $SU(3)_c\times SU(2)_2\times U(1)_Y$ gauginos ($M_1=0$) for 3rd generation sleptons to remain light.
- One loop RGE for 3rd generation sleptons and gauginos

$$16\pi^2\frac{d}{dt}m^2_{L_3} = -\frac{6}{5}g^2_Y|M_Y|^2-\frac{3}{5}g^2_Y S$$
$$16\pi^2\frac{d}{dt}m^2_{\tilde{\tau}_R} = -\frac{24}{5}g^2_Y|M_Y|^2+\frac{6}{5}g^2_Y S$$

$$16\pi^2\frac{d}{dt}M^2_i = 4b_i\, g^2_i\, M^2_i$$

where b_i =(36/5,-1,1,-3) at high energy and after gauge breakdown b_i =(33/5,1,-3).

- Approximate solutions,

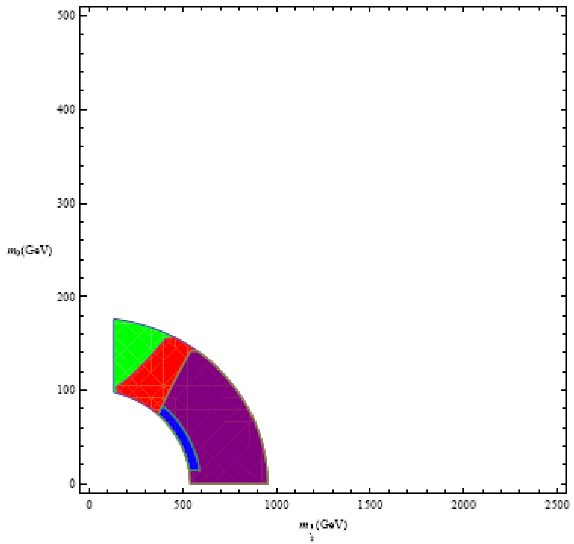
$$m^2_{L_3}\simeq m^2_0+0.04\,M^2_{1/2},\qquad m^2_{\tilde{\tau}_R}\simeq m^2_0+0.15\,M^2_{1/2}\qquad M_Y\simeq 0.35\,M_{1/2},\qquad M_2\simeq 0.8\,M^2_{1/2}$$

imply that tau sneutrino is the lightest SM partner.

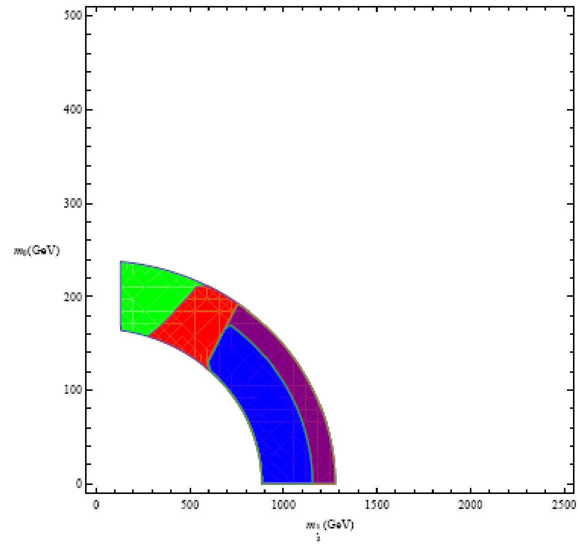
- For a fixed Higgs mass and no mixing$\longrightarrow$ ellipsoidal area in M_0vs $M_{1/2}$ plane from demanding consistency with EWPT.

M_0 vs $M_{1/2}$

Correlation of soft scalar mass with universal soft gaugino mass for m_h 150 GeV for Tanβ=10



Correlation of soft scalar mass with universal soft gaugino mass for m_h 200 GeV for Tanβ=10



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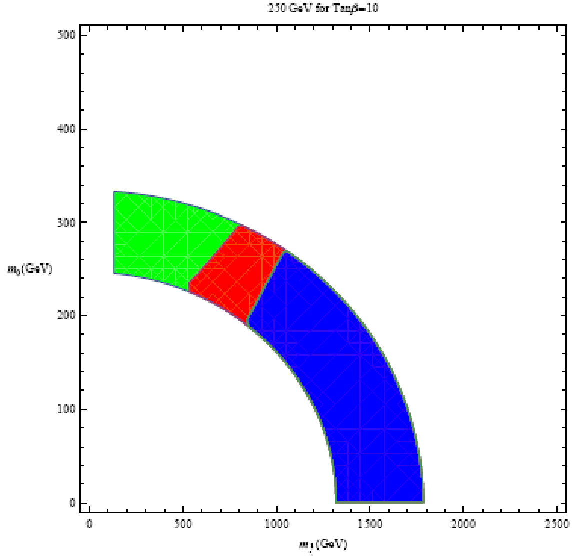

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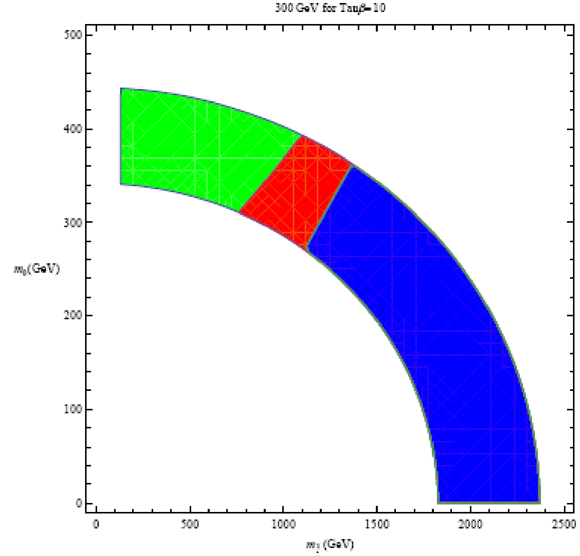

Mixing: Part 1

- Tree level stau mass matrix,

$$m^2_{\tilde{\tau}} = \begin{pmatrix} m^2_{L_3} + \Delta_{L_3} - \frac{g^2}{4}(\Delta - 1)v^2 \cos 2\beta & m_\tau(A_\tau - \mu \tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & m^2_{\tilde{\tau}_R} + \Delta e_3 \end{pmatrix}$$

where $\Delta_{L_3} = (-1/2 + \sin^2\theta_w)\cos 2\beta \; m^2_Z$ and $\Delta_{e_3} = \sin^2\theta_w \cos 2\beta \; m^2_Z$.

- Similarly for the tau sneutrino we have $m^2_{\tilde{\nu}_\tau} = m^2_{L3} + \Delta\nu_\tau + \frac{g^2}{4}(\Delta - 1)v^2\cos 2\beta$

where $\Delta_{\nu_\tau} = \cos 2\beta \; m^2_Z/2.$.

- Minimizing the Higgs potential, $\mu^2 = \frac{1}{2}\left(\frac{m^2_{H_u} - m^2_{H_d}}{\cos 2\beta} - m^2_{H_u} - m^2_{Hd} - m^2_\Delta\right)$

where $m^2_\Delta = (g_1^2 + g_2^2\Delta)v^2/2,$ and

$$\begin{aligned} m^2_A &= \frac{m^2_{H_u} - m^2_{H_d}}{\cos 2\beta} - m^2_\Delta, \\ m^2_{h^0} &= \frac{1}{2}\left(m^2_A + m^2_\Delta - \sqrt{(m^2_A - m^2_\Delta)^2 + 4m^2_\Delta m^2_A \sin 2\beta}\right), \\ m^2_{H^0} &= \frac{1}{2}\left(m^2_A + m^2_\Delta + \sqrt{(m^2_A - m^2_\Delta)^2 + 4m^2_\Delta m^2_A \sin 2\beta}\right), \\ m^2_{H+} &= m^2_A + \frac{g^2}{2}\Delta v^2. \end{aligned}$$

Mixing: Part 2

- The more general expression for ΔT in the case of right-handed mixing is,

$$
\begin{aligned}
\Delta T &= \frac{N_c}{12\pi s_W^2 m_W^2}\left(\sin^2\theta_u \sin^2\theta_d (m_{u_2}-m_{d_2})^2\right. \\
&+ \sin^2\theta_u \cos^2\theta_d (m_{u_2}-m_{d_1})^2 + \cos^2\theta_u \sin^2\theta_d (m_{u_1}-m_{d_2})^2 \\
&+ \cos^2\theta_u \cos^2\theta_d (m_{u_1}-m_{d_1})^2 - \sin^2\theta_u \cos^2\theta_u (m_{u_2}-m_{u_1})^2 \\
&- \left.\sin^2\theta_d \cos^2\theta_d (m_{d_2}-m_{d_1})^2\right),
\end{aligned}
$$

- Examples of contributions to ΔT in the case of mixing,

m_h [GeV]	m_0 [GeV]	$M_{1/2}$ [GeV]	$\Delta T_{\tilde{\tau}}$	$\Delta T_{\tilde{Q}_3}$	ΔT_{H+}	ΔT_{tot}
169	90	500	1.5×10^{-1}	8.7×10^{-4}	7.8×10^{-4}	1.56×10^{-1}
210	150	700	1.9×10^{-1}	2.6×10^{-3}	8×10^{-3}	2.03×10^{-1}
210	150	(700,350)	1.5×10^{-1}	2.4×10^{-2}	1.9×10^{-2}	1.98×10^{-1}

Results lie in the 68 % C.L. ellipse in the ΔS-ΔT plane.

Low energy spectrum

• Calculate low energy particle spectrum using SDECAY. Hard leptons from W decay in $\tilde{\tau}_1^{\pm} \to W^{\pm}\tilde{\nu}_{\tau}$. Presence of many tau's and copious missing energy in the final states. Example for m_h =210 GeV, $M_{1/2}$=700 GeV, tan β=10, M_0=150 GeV, m_{Hu} =m_{hd} =(100 GeV)^2 and Δ=6.13.

Sparticle	Mass[GeV]	Dominant decay modes
$\tilde{g}$	1564	$\tilde{q}_L q$ (16.2)%, $\tilde{q}_R q$ (31.4)%, $\tilde{b}_{1,2} b$ (20) %, $\tilde{t}_1 t$ (24) %
$\tilde{u}_L, \tilde{d}_L$	1428, 1429	$\tilde{\chi}_2^0 q$ (32) %, $\tilde{\chi}_1^{\pm} q'$ (64) %
$\tilde{u}_R, \tilde{d}_R$	1374,1368	$\tilde{\chi}_1^0 q$ (99) %
$\tilde{t}_1$	1112	$\tilde{\chi}_1^+ b$ (19) %, $\tilde{\chi}_1^0 t$ (25) %, $\tilde{\chi}_3^0 t$ (17) %, $\tilde{\chi}_2^+ b$ (23) %
H^+	967	
A	946	
$\tilde{\chi}_4^0$	864	$\tilde{\chi}_1^{\pm} W^{\mp}$ (56) %, $\tilde{\chi}_2^0 h$ (19) %
$\tilde{\chi}_2^{\pm}$	864	$\tilde{\chi}_2^0 W^{\pm}$ (28) %, $\tilde{\chi}_1^{\pm} Z$ (28) %, $\tilde{\chi}_1^{\pm} h$ (20) %
$\tilde{\chi}_3^0$	852	$\tilde{\chi}_1^{\pm} W^{\mp}$ (56) %, $\tilde{\chi}_2^0 Z$ (26) %
$\tilde{\chi}_2^0$	551	$\tilde{\nu}_\tau \nu_\tau$ (47) %, $\tilde{\tau}_1^{\pm} \tau^{\mp}$ (39) %
$\tilde{\chi}_1^{\pm}$	551	$\tilde{\nu}_\tau \tau^{\pm}$ (49) %, $\tilde{\tau}_1^{\pm} \nu_\tau$ (37) %
$\tilde{e}_L$	486	$\tilde{\chi}_1^0 e$ (100) %
$\tilde{\nu}_e$	480	$\tilde{\chi}_1^0 \nu_e$ (100) %
$\tilde{e}_R$	300	$\tilde{\chi}_1^0 e$ (100) %
$\tilde{\tau}_2$	303	$\tilde{\chi}_1^0 \tau$ (72) %, $\tilde{\nu}_\tau W$ (28) %
$\tilde{\chi}_1^0$	249	$\tilde{\nu}_\tau \nu_\tau$ (90) %, $\tilde{\tau}_1^{\pm} \tau^{\mp}$(10) %
$\tilde{\tau}_1$	217	$\tilde{\nu}_\tau W$ (100) %
$\tilde{\nu}_\tau$	132	$\tilde{G} \nu_\tau$

Low energy spectrum

• Compactified spectrum obtained with M_3=350 GeV and M_1=M_2=700 GeV with m_h = 208 GeV. Light stops. Most decays chains end in neutralinos and tau sneutrinos without passing through the lightest stau. Example for m_h =208 GeV, M_Y=M_2=700 GeV, M_3=350 GeV, tan β=10, M_0=150 GeV, m_{Hu} =m_{hd} =(100 GeV)^2 and Δ=6.13.

Sparticle	Mass[GeV]	Dominant decay modes
$\tilde{g}$	829	$\tilde{q}_R q$ (42)%, $\tilde{b}_{1,2} b$ (16) %, $\tilde{t}_1 t$ (42) %
$\tilde{u}_L$	853	$\tilde{\chi}_2^+ q'$ (46) %, $\tilde{\chi}_4^0 q$ (23) %, $\tilde{\chi}_1^+ q'$ (15) %
$\tilde{d}_L$	857	$\tilde{\chi}_2^- q'$ (51) %, $\tilde{\chi}_4^0 q$ (25) %
$\tilde{u}_R, \tilde{d}_R$	750,737	$\tilde{\chi}_1^0 q$ (92) %
H^+	620	
A	588	
$\tilde{t}_1$	539	$\tilde{\chi}_1^+ b$ (79) %, $\tilde{\chi}_1^0 t$ (20) %
$\tilde{\chi}_4^0$	580	$\tilde{\chi}_1^\pm W^\mp$ (27) %, $\tilde{\tau}_1^\pm \tau^\mp$ (22) %, $\tilde{\nu}_\tau \nu_\tau$ (30) %
$\tilde{\chi}_2^\pm$	580	$\tilde{\chi}_2^0 W^\pm$ (13) %, $\tilde{\chi}_1^\pm Z$ (28) %, $\tilde{\chi}_3^0 W^\pm$ (10) %, $\tilde{\nu}_\tau \tau^\pm$ (28) %, $\tilde{\tau}_1^\pm \nu_\tau$ (24) %
$\tilde{\chi}_3^0$	400	$\tilde{\chi}_1^0 Z$ (88) %
$\tilde{\chi}_2^0$	387	$\tilde{\tau}_2^\pm \tau^\mp$ (14) %, $\tilde{\tau}_1^\pm \tau^\mp$ (54) %
$\tilde{\chi}_1^\pm$	378	$\tilde{\nu}_\tau \tau^\pm$ (41) %, $\tilde{\chi}_1^0 W^\pm$ (47) %
$\tilde{e}_L$	495	$\tilde{\chi}_1^0 e$ (65) %, $\tilde{\chi}_2^0 e$ (20) %, $\tilde{\chi}_2^0 e$ (20) %, $\tilde{\chi}_1^\pm \nu_e$ (14) %
$\tilde{\nu}_e$	489	$\tilde{\chi}_1^0 \nu_e$ (80) %, $\tilde{\chi}_1^\pm e^\mp$ (18) %
$\tilde{e}_R$	302	$\tilde{\chi}_1^0 e$ (100) %
$\tilde{\tau}_2$	299	$\tilde{\chi}_1^0 \tau$ (94) %
$\tilde{\chi}_1^0$	249	$\tilde{\nu}_\tau \nu_\tau$ (99) %
$\tilde{\tau}_1$	242	$\tilde{\nu}_\tau W$ (100) %
$\tilde{\nu}_\tau$	163	$\tilde{G} \nu_\tau$

Cosmological Constraints

- Gravitino LSP produced by scattering processes at reheating epoch ($\Omega_{\tilde{\nu}_\tau} h^2 \approx \mathcal{O}(10^{-3})$)

- Sneutrino NLSP $\tilde{\nu}_\tau \to \tilde{G} + \nu_\tau$. Bino NLSP excluded by late decay into photon and gravitino .

- For the range of masses considered (40 GeV< m_{snu} <400 GeV, 1 GeV< m_{grav} <100 GeV) the lifetime Γ_{snu} > 10^7 seconds.

- Possible constraints from high energy neutrinos scattering off of BG neutrinos

$$\nu_\tau + \bar{\nu}_{i,BG} \to (e^\pm, \mu^\pm \tau^\pm)$$

and multibody sneutrino decays,

$$\tilde{\nu}_\tau \to \tilde{G}\nu_\tau q\bar{q}, \;\; \tilde{\nu}_\tau \to \tilde{G}\nu_\tau Z, \;\; \tilde{\nu}_\tau \to \tilde{G}\tau W$$

which would lead to overproduction of D and ^{6}Li induced by hadron showers, lead to almost no constraint (m_{snu} – m_{grav} <300 GeV for m_{grav} <10 GeV) except for the larger Higgs masses.

Non-vanishing $SU(2)_1$ gaugino masses

• Assume non-vanishing $M_1 \longrightarrow$ slepton and squark masses increase at low energy.

• At tree level, M_2 effect is small for m_A and m_{H+} in the large tan β limit, since m_{Hu} and m_{Hd} are both affected in analogous way. It is up to the non-standard Higgs bosons to compensate for ΔT.

• Phenomenology similar to light stau NLSP in gaugino mediation models. Model constraint by searches at Tevatron (m_A >170 GeV).

• If the messenger scale M is very close to M_{GUT} we can have neutralino NLSP which co-annihilates with stau giving proper DM relic density.

• Point example, for $M_Y=M_2=M_3$ 700 GeV, M_1=400 GeV, tan β=48, M_0=360 GeV, m_{Hu} =m_{hd} =(200 GeV)^2 and Δ=5.9.

m_h [GeV]	m_A [GeV]	m_{H+} [GeV]	$m_{\tilde{\tau}_R}$ [GeV]	$m_{\tilde{\tau}_L}$ [GeV]	$m_{\tilde{\chi}_1^0}$ [GeV]	μ [GeV]	ΔT_{tot}
200	176	255	293	1020	275	321	0.12

Conclusions

- By D-term induced mass splitting in 3rd generation fermions and non-standard Higgs bosons, we are able to consistently raise the SM like Higgs mass up to 300 GeV.

- Phenomenological viable scenario of SUSY breaking that provides light sleptons determined by re-establishing agreement with EWP data.

- Collider signatures characterized by the presence of many tau's and copious missing energy in the final states. Presence of hard leptons for large values of Higgs mass.

- Small region of parameter space where Higgs can decay into sneutrinos (avoid Tevatron bounds).

- Alternative scenario with non-vanishing $M_1 \longrightarrow$ large $\tan\beta$ for light non-standard Higgs A and H^+ to remain light.