Phenomenology in the MSSM with Enhanced SU(2) D-terms

Anibal D. Medina
Department of Physics
UC Davis


Co-authors: Nausheen Shah and Carlos Wagner.
**Outline**

- Motivation and review of the model.
- Sparticle mass splitting and contributions to $\Delta T$ 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 $\rightarrow$ large radiative corrections $\rightarrow$ large squark masses $\rightarrow$ 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, 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 masses associated with scalars that break SU(2)$_1 \times$SU(2)$_2 \rightarrow$ 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 $\rightarrow$ negative contribution to $\Delta T$. 
Review of the Model

• Breakdown $SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_W$ governed by,

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

• Leads to a $\Sigma$ potential,

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

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

$$\Delta V = \frac{g_1^2}{8} \left( \text{Tr}[\Sigma^\dagger \tau^a \Sigma] + H_u^\dagger \tau^a H_u + H_d^\dagger \tau^a H_d + L^\dagger \tau^a L + Q^\dagger \tau^a Q \right)^2 + \frac{g_2^2}{8} \left( \text{Tr}[\Sigma^\dagger \tau^a \Sigma] + ... \right)^2$$

• 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 ($\Sigma$ decomposes as a triplet plus a singlet under $SU(2)_W$),

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

with

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

• Therefore,

$$m_h^2 = \frac{1}{2} (g^2 \Delta + g_Y^2) v^2 \cos^2 2\beta + \text{loop corrections}$$
Sparticle mass splittings and contributions to $\Delta T$

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

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

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

\[
\begin{align*}
    m_{\tau_L}^2 - m_{\tilde{\tau}}^2 &= \Delta_D \\
m_{\tilde{b}_L}^2 - m_{\tilde{t}_L}^2 &= \Delta_D - m_t^2
\end{align*}
\]

with

\[
\Delta_D = \frac{g^2 v^2}{2} - \Delta |\cos 2\beta| = \frac{(\Delta m_h^2)_D}{|\cos 2\beta|}
\]

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

\[ m_{H^\pm}^2 - m_A^2 = \frac{g^2 \Delta}{2} v^2 \]

- Upper and lower component mass splitting of SU(2) doublet lead to (no mixing) corrections to $\Delta T$ similar to the inert Higgs doublet model (Barbieri et al 2006),

\[
\Delta T = \frac{N_c}{12\pi s_W^2 m_W^2} (\Delta m_{ud})^2 \\
= \frac{N_c}{12\pi s_W^2 m_W^2} \frac{(\Delta m_{ud})^2}{(m_u + m_d)^2}
\]

\[
\Delta T = -\frac{3}{8\pi c_W^2} \ln \frac{m_h}{m_{h_{ref}}} \\
\Delta S = \frac{1}{6\pi} \ln \frac{m_h}{m_{h_{ref}}}
\]

- Which must be added to
Slepton spectrum with no mixing

Small $\Delta T$ contribution from triplet,

$$\Delta T \simeq \frac{4\pi g_1^4}{s_W^2 c_W^2 g_4^4} \frac{m_W^2 u^2}{M_T^4}$$

$$\Delta T_{150} \simeq 0.10 \pm 0.06$$
$$\Delta T_{300} \simeq 0.24 \pm 0.07$$

Fit provided by Jen Erler.
Slepton spectrum with no mixing

- We will assume that 3\textsuperscript{rd} generation l.h sleptons are the main contributor to $\Delta T$.

- 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.

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

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

- Evade Tevatron bounds for Higgs mass in the range 150 GeV-200 GeV (J.Quian CDF-D0 2008.)

- Constraints from $\Delta T$ become weaker for light Higgs mass ($m_h \sim 150$ GeV).
• 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 $\rightarrow$ hard leptons in the final state.
Supersymmetric Model

• Input at high energy: Moderate tan $\beta$, universal gaugino mass $M_{1/2}$, universal soft scalar mass $M_0$ for squarks and sleptons, soft SUSY breaking Higgs masses $m_{H_u}^2 = m_{H_d}^2$, positive sign($\mu$) and $A_t = A_b = A_\tau = 0$, at the messenger scale $M \sim M_{\text{GUT}}$.

• 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

$$16\pi^2 \frac{d}{dt} m_{L_3}^2 = -\frac{6}{5} g_Y^2 |M_Y|^2 - \frac{3}{5} g_Y^2 S$$
$$16\pi^2 \frac{d}{dt} m_{\tau_R}^2 = -\frac{24}{5} g_Y^2 |M_Y|^2 + \frac{6}{5} g_Y^2 S$$

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

• Approximate solutions,

$$m_{L_3}^2 \simeq m_0^2 + 0.04 M_{1/2}^2, \quad m_{\tau_R}^2 \simeq m_0^2 + 0.15 M_{1/2}^2 \quad M_Y \simeq 0.35 M_{1/2}, \quad M_2 \simeq 0.8 M_{1/2}$$

imply that tau sneutrino is the lightest SM partner.

• For a fixed Higgs mass and no mixing → ellipsoidal area in $M_0$ vs $M_{1/2}$ plane from demanding consistency with EWPT.
$M_0$ vs $M^{1/2}$

Correlation of soft scalar mass with universal soft gaugino mass for $m_0$

100 GeV for $m_{1/2}$

Correlation of soft scalar mass with universal soft gaugino mass for $m_0$

200 GeV for $m_{1/2}$

Correlation of soft scalar mass with universal soft gaugino mass for $m_0$

300 GeV for $m_{1/2}$
Mixing

- The more general expression for $\Delta T$ in the case of right-handed mixing is,

$$
\Delta T = \frac{N_c}{12\pi s_W^2 m_W^2} \left( \sin^2 \theta_u \sin^2 \theta_d (m_{u2} - m_{d2})^2 
+ \sin^2 \theta_u \cos^2 \theta_d (m_{u2} - m_{d1})^2 + \cos^2 \theta_u \sin^2 \theta_d (m_{u1} - m_{d2})^2 
+ \cos^2 \theta_u \cos^2 \theta_d (m_{u1} - m_{d1})^2 - \sin^2 \theta_u \cos^2 \theta_u (m_{u2} - m_{u1})^2 
- \sin^2 \theta_d \cos^2 \theta_d (m_{d2} - m_{d1})^2 \right),
$$

- Examples of contributions to $\Delta T$ in the case of mixing,

<table>
<thead>
<tr>
<th>$m_h$ [GeV]</th>
<th>$m_0$ [GeV]</th>
<th>$M_{1/2}$ [GeV]</th>
<th>$\Delta T_{\tilde{\tau}}$</th>
<th>$\Delta T_{\tilde{\bar{Q}_3}}$</th>
<th>$\Delta T_{H^+}$</th>
<th>$\Delta T_{tot}$</th>
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<tbody>
<tr>
<td>169</td>
<td>90</td>
<td>500</td>
<td>$1.5 \times 10^{-1}$</td>
<td>$8.7 \times 10^{-4}$</td>
<td>$7.8 \times 10^{-4}$</td>
<td>$1.56 \times 10^{-1}$</td>
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<td>210</td>
<td>150</td>
<td>700</td>
<td>$1.9 \times 10^{-1}$</td>
<td>$2.6 \times 10^{-3}$</td>
<td>$8 \times 10^{-3}$</td>
<td>$2.03 \times 10^{-1}$</td>
</tr>
<tr>
<td>210</td>
<td>150</td>
<td>(700,350)</td>
<td>$1.5 \times 10^{-1}$</td>
<td>$2.4 \times 10^{-2}$</td>
<td>$1.9 \times 10^{-2}$</td>
<td>$1.98 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

Results lie in the 68 % C.L. ellipse in the $\Delta S-\Delta T$ plane.
Low energy spectrum

- Calculate low energy particle spectrum using SDECAY. Hard leptons from W decay in $\tilde{\tau}^\pm \rightarrow W^\pm \tilde{\nu}_\tau$. Presence of many tau’s and copious missing energy in the final states.

Example for $m_h=210$ GeV, $M_{1/2}=700$ GeV, $\tan \beta=10$, $M_0=150$ GeV, $m_{H_u}=m_{H_d}=(100$ GeV)$^2$ and $\Delta=6.13$.

<table>
<thead>
<tr>
<th>Sparticle</th>
<th>Mass [GeV]</th>
<th>Dominant decay modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g}$</td>
<td>1564</td>
<td>$q_L q$ (16.2)%, $q_R q$ (31.4)%, $b_{12}b$ (20)%</td>
</tr>
<tr>
<td>$\tilde{u}_L, \tilde{d}_L$</td>
<td>1428, 1429</td>
<td>$\tilde{\chi}^0_2 q$ (32)%, $\tilde{\chi}^0_1 q'$ (64)%, $\tilde{\chi}^0_1 q$ (99)%</td>
</tr>
<tr>
<td>$\tilde{u}_R, \tilde{d}_R$</td>
<td>1374, 1368</td>
<td>$\tilde{\chi}^+ b$ (19)%, $\tilde{\chi}^0 t$ (25)%, $\tilde{\chi}^0 t$ (17)%, $\tilde{\chi}^+ b$ (23)%</td>
</tr>
<tr>
<td>$\tilde{t}_1$</td>
<td>1112</td>
<td>$\tilde{\chi}^\pm W^\pm$ (56)%, $\tilde{\chi}^0 h$ (19)%</td>
</tr>
<tr>
<td>$H^+$</td>
<td>967</td>
<td>$\tilde{\chi}^0 W^\pm$ (28)%, $\tilde{\chi}^0 Z$ (28)%, $\tilde{\chi}^0 h$ (20)%</td>
</tr>
<tr>
<td>$A$</td>
<td>946</td>
<td>$\tilde{\chi}^0 W^\pm$ (56)%, $\tilde{\chi}^0 Z$ (28)%, $\tilde{\chi}^0 h$ (20)%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_4$</td>
<td>864</td>
<td>$\tilde{\nu}<em>\tau \nu</em>\tau$ (47)%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2$</td>
<td>864</td>
<td>$\tilde{\eta}^+ \tau^+$ (39)%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_3$</td>
<td>852</td>
<td>$\tilde{\nu}_\tau \tau^+$ (49)%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_2$</td>
<td>551</td>
<td>$\tilde{\nu}<em>\tau \nu</em>\tau$ (37)%</td>
</tr>
<tr>
<td>$\tilde{\chi}^0_1$</td>
<td>551</td>
<td>$\tilde{\nu}_e$ (100)%</td>
</tr>
<tr>
<td>$\tilde{e}_L$</td>
<td>486</td>
<td>$\tilde{\nu}_e$ (100)%</td>
</tr>
<tr>
<td>$\tilde{\nu}_e$</td>
<td>480</td>
<td>$\tilde{\nu}_e$ (100)%</td>
</tr>
<tr>
<td>$\tilde{e}_R$</td>
<td>300</td>
<td>$\tilde{\chi}^0_1 \tau$ (72)%, $\tilde{\nu}_\tau W$ (28)%</td>
</tr>
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<td>$\tilde{\tau}_2$</td>
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<td>$\tilde{\nu}<em>\tau \nu</em>\tau$ (90)%</td>
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<td>$\tilde{\chi}^0_1$</td>
<td>249</td>
<td>$\tilde{\nu}_\tau W$ (100)%</td>
</tr>
<tr>
<td>$\tilde{\tau}_1$</td>
<td>217</td>
<td>$\tilde{\nu}_\tau W$ (100)%</td>
</tr>
<tr>
<td>$\tilde{\nu}_\tau$</td>
<td>132</td>
<td>$\tilde{\nu}_\tau W$ (100)%</td>
</tr>
</tbody>
</table>
Cosmological Constraints

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

• Sneutrino NLSP \(\tilde{\nu}_\tau \rightarrow \tilde{G} + \nu_\tau\). Bino NLSP excluded by late decay into photon and gravitino.

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

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

\[
\nu_\tau + \bar{\nu}_{i,BG} \rightarrow (e^\pm, \mu^\pm \tau^\pm)
\]

and multibody sneutrino decays,

\[
\tilde{\nu}_\tau \rightarrow \tilde{G} \nu_\tau q\bar{q}, \quad \tilde{\nu}_\tau \rightarrow \tilde{G} \nu_\tau Z, \quad \tilde{\nu}_\tau \rightarrow \tilde{G} \tau W.
\]

which would lead to overproduction of D and \(^6\text{Li}\) induced by hadron showers, lead to almost no constraint \((m_{\text{snu}} - m_{\text{grav}} < 300 \text{ GeV} \text{ for } m_{\text{grav}} < 10 \text{ GeV})\) (Feng et al 2004, Moroi et al 2007) except for the larger Higgs masses.
Non-vanishing $SU(2)_1$ gaugino masses

• Assume non-vanishing $M_1 \rightarrow$ 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 $\beta$ limit, since $m_{H_u}$ and $m_{H_d}$ are both affected in analogous way. It is up to the non-standard Higgs bosons to compensate for $\Delta T$.

• 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 $\beta=48$, $M_0=360$ GeV, $m_{H_u}=m_{H_d}=(200$ GeV)$^2$ and $\Delta=5.9$.

<table>
<thead>
<tr>
<th>$m_h$ [GeV]</th>
<th>$m_A$ [GeV]</th>
<th>$m_{H^+}$ [GeV]</th>
<th>$m_{\tilde{\tau}_R}$ [GeV]</th>
<th>$m_{\tilde{\tau}_L}$ [GeV]</th>
<th>$m_{\chi^0_1}$ [GeV]</th>
<th>$\mu$ [GeV]</th>
<th>$\Delta T_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>176</td>
<td>255</td>
<td>293</td>
<td>1020</td>
<td>275</td>
<td>321</td>
<td>0.12</td>
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</table>
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 $M_1 \rightarrow$ large $\tan \beta$ for light non-standard Higgs $A$ and $H^+$ to remain light.
Extra Slides
Mixing

• Tree level stau mass matrix,

\[
m_{\tilde{\tau}}^2 = \begin{pmatrix}
m_{L3}^2 + \Delta_{L3} - \frac{g^2}{4}(\Delta - 1)v^2 \cos 2\beta & m_\tau(\Delta_{\tau} - \mu \tan \beta) \\
m_\tau(\Delta_{\tau} - \mu \tan \beta) & m_{\tilde{\tau}}^2 + \Delta_{\tau_R}
\end{pmatrix}
\]

where \( \Delta_{L3} = (-1/2 + \sin^2 \theta_w) \cos 2\beta \) \( m_Z^2 \) and \( \Delta_{\tau_R} = \sin^2 \theta_w \cos 2\beta \) \( m_Z^2 \).

• Similarly for the tau sneutrino we have

\[
m_{\tilde{\nu}_\tau}^2 = m_{L3}^2 + \Delta_{\nu_\tau} + \frac{g^2}{4}(\Delta - 1)v^2 \cos 2\beta
\]

where \( \Delta_{\nu_\tau} = \cos 2\beta \) \( m_Z^2 / 2 \).

• Minimizing the Higgs potential,

\[
\mu^2 = \frac{1}{2} \left( \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - m_\Delta^2 \right)
\]

where \( m_\Delta = (g_1^2 + g_2^2 \Delta)v^2 / 2 \), and

\[
m_A^2 = \frac{m_{H_u}^2 - m_{H_d}^2}{\cos 2\beta} - m_\Delta^2,
\]

\[
m_{h_0}^2 = \frac{1}{2} \left( m_A^2 + m_\Delta^2 - \sqrt{(m_A^2 - m_\Delta^2)^2 + 4m_\Delta^2 m_A^2 \sin 2\beta} \right),
\]

\[
m_{H^0}^2 = \frac{1}{2} \left( m_A^2 + m_\Delta^2 + \sqrt{(m_A^2 - m_\Delta^2)^2 + 4m_\Delta^2 m_A^2 \sin 2\beta} \right),
\]

\[
m_{H^+}^2 = m_A^2 + \frac{g_2^2}{2} \Delta v^2.
\]
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, $\tan \beta=10$, $M_0=150$ GeV, $m_{Hu}=m_{hd}=(100$ GeV$)^2$ and $\Delta=6.13$.

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<tr>
<th>Sparticle</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{q}$</td>
<td>829</td>
<td>$\tilde{q}_{Rq}$ (42)%, $b_1b$ (16)%, $t_1t$ (42) %</td>
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<tr>
<td>$\tilde{u}_L$</td>
<td>853</td>
<td>$\tilde{q}_Lq$ (23)%, $\tilde{t}_1q$ (15) %</td>
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<tr>
<td>$\tilde{d}_L$</td>
<td>857</td>
<td>$\tilde{b}_2'q'$ (51)%, $\tilde{\chi}_1^0q$ (25) %</td>
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<tr>
<td>$H^+$</td>
<td>750,737</td>
<td>$\chi_1^0 (20)$ %</td>
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<tr>
<td>$A$</td>
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<td>$\tilde{\nu}<em>\tau \nu</em>\tau$ (99) %</td>
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<tr>
<td>$\tilde{\nu}_\tau$</td>
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<td>$\tilde{\chi}_1^0\tau$ (94) %</td>
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