Yukawa Unification in SO(10) with light sparticle spectrum

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based on:
MB, M. Olechowski, S. Pokorski, arXiv:1107.2764 (to appear in JHEP)

Outline

1. Conditions for $t - b - \tau$ Yukawa unification
2. Yukawa unification with $\mu < 0$
    - interplay between BR$(b \to s\gamma)$ and $(g-2)_\mu$
    - implications for SUSY spectrum

Yukawa Unification in SO(10)

Minimal SO(10) models predict unification of the top, bottom and tau Yukawa couplings at M_{GUT}

$b-\tau$ Yukawa unification leads to tree level bottom mass bigger than the observed mass

SUSY loop correction to the bottom mass must be negative:

$$\left(\frac{\delta m_b}{m_b}\right) \approx \frac{g_3^2}{6\pi^2}\mu m_{\tilde{g}} \tan\beta \, I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{g}}^2) + \frac{h_t^2}{16\pi^2}\mu A_t \tan\beta \, I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)$$

For $\mu > 0$

- The gluino-sbottom contribution has wrong sign so has to be suppressed ⇒ multi-TeV squarks
- The chargino-stop contribution must dominate ⇒ A_t negative and very large to account for the observed bottom mass

Baer et al. '2008

For $\mu < 0$

- The gluino-sbottom contribution has correct sign
  ⇒ squark masses may be small
  ⇒ The sign and the magnitude of A_t much less restricted

Negative μ and $(g-2)_\mu$

SM prediction for $a_\mu \equiv (g-2)_\mu/2$ is more than 3σ below experimental result:

$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.7 \pm 8) \cdot 10^{-10}$$

Dominant SUSY contribution $\sim \mathrm{sgn}(\mu M_2) \tan\beta$

For phenomenologically acceptable models:

$$\mu < 0 \quad \Rightarrow \quad M_2 < 0$$

Is it natural to consider $M_2 < 0$ in the context of SO(10) GUT?

YES ⇒ non-singlet F-terms give non-universal gaugino masses at M_{GUT}.

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YES $\Rightarrow$ non-singlet F-terms give non-universal gaugino masses at M_{GUT}.

Non-singlet F-terms

Gaugino masses in SUGRA can arise from dimension 5 operator:

$$\mathcal{L} \supset -\frac{F^{ab}}{2M_{\rm Planck}}\lambda^a\lambda^b + \text{c.c.}$$

- $\langle F^{ab}\rangle$ must transform as a singlet under the SM gauge group
- $\langle F^{ab}\rangle$ must belong to the symmetric part of $\mathbf{45}\times\mathbf{45}$
- $\langle F^{ab}\rangle$ can be in a non-singlet representation of SO(10)

$$(\mathbf{45}\times\mathbf{45})_S = \mathbf{1}+\mathbf{54}+\mathbf{210}+\mathbf{770}$$

If $\langle F^{ab}\rangle$ transforms as **54**, gaugino masses are given by:

Martin, 2009

$$M_1 : M_2 : M_3 = -\frac{1}{2} : -\frac{3}{2} : 1$$

$M_2 < 0 \Rightarrow \mu < 0$ can be consistent with $(g-2)_\mu$ constraint!

Yukawa Unification and REWSB

At large $\tan\beta$ proper REWSB requires $m_{H_d}^2 - m_{H_u}^2 \gtrsim M_Z^2$

For universal soft terms at the GUT scale:

- RG evolution results in positive (negative) contribution to $m_{H_d}^2 - m_{H_u}^2$ proportional to $M_{1/2}^2$ (m_0^2)
- REWSB possible only if $M_{1/2} > m_0$
- μ^2 strongly correlated with $M_{1/2}^2$
  $\Rightarrow$ too large SUSY threshold correction to the bottom mass

Carena, Olechowski, Pokorski, Wagner '1994

proper REWSB requires e.g. Higgs splitting at M_{GUT}: $m_{H_u} < m_{H_d}$

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Non-universal scalar masses in SO(10)

All sfermions in **16**-dim rep. of SO(10) while Higgses in **10**-dim rep.
⇒ Pattern of soft scalar masses restricted by SO(10) gauge symmetry:

$$m_{H_d,H_u} = m_{10}$$
$$m_{Q,U,D,L,E} = m_{16}$$

This is not enough for $t - b - \tau$ Yukawa unification with proper REWSB

D-term contribution

Rank of SO(10) is larger than the rank of SM gauge group
⇒ in the effective theory below the GUT scale soft scalar masses acquire new contribution proportional to D-term and charges of the broken U(1):

Kawamura, Murayama, Yamaguchi '1994

$$m^2_{H_d} = m^2_{10} + 2D$$
$$m^2_{H_u} = m^2_{10} - 2D$$
$$m^2_{Q,U,E} = m^2_{16} + D$$
$$m^2_{D,L} = m^2_{16} - 3D$$

$D > 0$ may allow for proper REWSB

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The model

$$\boxed{\mu < 0}$$

- Non-universal scalar masses:

$$\begin{aligned} m_{H_d}^2 &= m_{10}^2 + 2D \\ m_{H_u}^2 &= m_{10}^2 - 2D \\ m_{Q,U,E}^2 &= m_{16}^2 + D \\ m_{D,L}^2 &= m_{16}^2 - 3D \end{aligned}$$

- Non-universal gaugino masses:

$$\begin{aligned} M_1 &= -\frac{1}{2} M_{1/2} \\ M_2 &= -\frac{3}{2} M_{1/2} \\ M_3 &= M_{1/2} \end{aligned}$$

- Universal trilinear couplings: $A_U = A_D = A_E = A_0$

5 parameters + $\tan\beta$

$(g-2)_\mu$ vs $b \to s\gamma$

$(g-2)_\mu$

SM prediction is more than 3σ below the experimental result
$\Rightarrow$ light SUSY spectrum is required for significant (positive) SUSY contribution

BR($b \to s\gamma$)

SM prediction is in 1σ agreement with the experimental data
Charged Higgs contribution increases SM result
$\Rightarrow$ heavy SUSY spectrum is preferred

How to disentangle $(g-2)_\mu$ from $b \to s\gamma$?

SUSY contributions to $(g-2)_\mu$

1. $\tilde{\chi}^\pm - \tilde{\nu}_\mu$ contribution:

$$a_\mu^{\chi^\pm} \approx \frac{g_2^2}{32\pi^2}\frac{m_\mu^2}{M_{\rm SUSY}^2}\,{\rm sgn}(\mu M_2)\tan\beta$$

2. $\tilde{\chi}^0 - \tilde{\mu}$ contribution:

$$a_\mu^{\chi^0} \approx \frac{1}{192\pi^2}\frac{m_\mu^2}{M_{\rm SUSY}^2}\left[g_1^2\,{\rm sgn}(\mu M_1) - g_2^2\,{\rm sgn}(\mu M_2)\right]\tan\beta$$

Our model: $m_{\tilde{\nu}_\mu} \approx m_{\tilde{\mu}_L} < m_{\tilde{\mu}_R}$ (due to D-term splitting)

$$\Downarrow$$

chargino contribution dominates

SUSY contributions to $b \to s\gamma$

Chargino - squarks contribution enhanced at large $\tan\beta$:

$$C^{\chi}_{7,8} \supset s_{\tilde{t}}\, c_{\tilde{t}} \frac{\tilde{U}_{a2}\, \tilde{V}_{a2}\, m_t}{\sin 2\beta\, m_{\chi_a^+}} \left[F^{(3)}_{7,8}\left(\frac{m^2_{\tilde{t}_1}}{m^2_{\chi_a^+}}\right) - F^{(3)}_{7,8}\left(\frac{m^2_{\tilde{t}_2}}{m^2_{\chi_a^+}}\right)\right]$$
$$- \frac{\tilde{U}_{a2}\tilde{V}_{a1} M_W}{\sqrt{2}\cos\beta m_{\chi_a^+}} \left[F^{(3)}_{7,8}\left(\frac{m^2_{\tilde{q}}}{m^2_{\chi_a^+}}\right) - c^2_{\tilde{t}}\, F^{(3)}_{7,8}\left(\frac{m^2_{\tilde{t}_1}}{m^2_{\chi_a^+}}\right) - s^2_{\tilde{t}}\, F^{(3)}_{7,8}\left(\frac{m^2_{\tilde{t}_2}}{m^2_{\chi_a^+}}\right)\right]$$

Degrassi, Gambino, Giudice '2000

Signs (relative to SM contribution) are the same as:
$\mathrm{sgn}(\mu A_t)$ for the stop-mixing part; $\mathrm{sgn}(-\mu M_2)$ for the "gaugino" part

Chargino contribution should be negative to satisfy $b \to s\gamma$

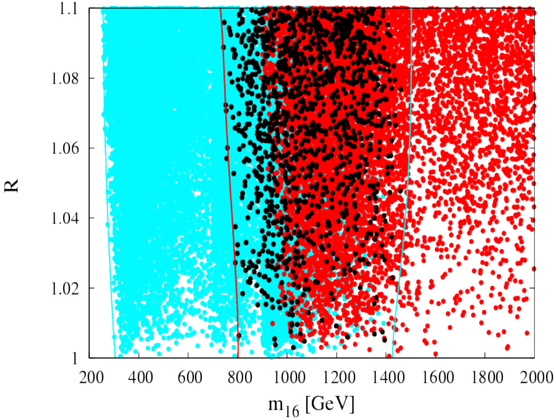
A_t is often driven to negative values by RGEs and the stop-mixing part has wrong (positive) sign for $\mu < 0$

"gaugino" part is always negative (as preferred by phenomenology)

BR($b \to s\gamma$) prefers:

- the lightest chargino is gaugino-like ($\mu^2 > M_2^2$)
- small or positive A_t
- large mass splitting between stops and 1st/2nd generation of squarks

$$R \equiv \left. \frac{\max\left(h_t, h_b, h_\tau\right)}{\min\left(h_t, h_b, h_\tau\right)} \right|_{\mathrm{GUT}}$$



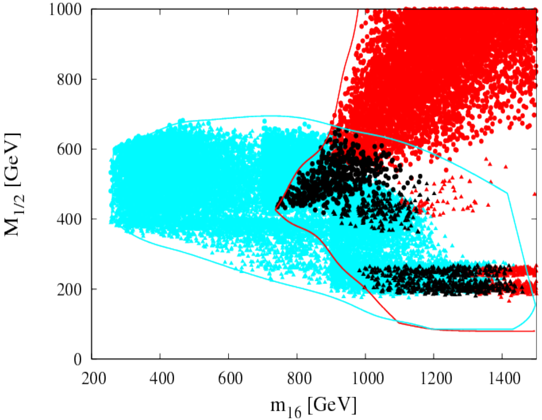
$(g-2)_\mu$ satisfied at 2σ

$b \to s\gamma$ satisfied at 2σ

$b \to s\gamma$ and $(g-2)_\mu$ satisfied at 2σ

$t-b-\tau$ Yukawa unification consistent with $b \to s\gamma$ and $(g-2)_\mu$

The WMAP bound on Ω_{LSP} is also important



$R \leqslant 1.1$

$(g-2)_\mu$ satisfied at 2σ

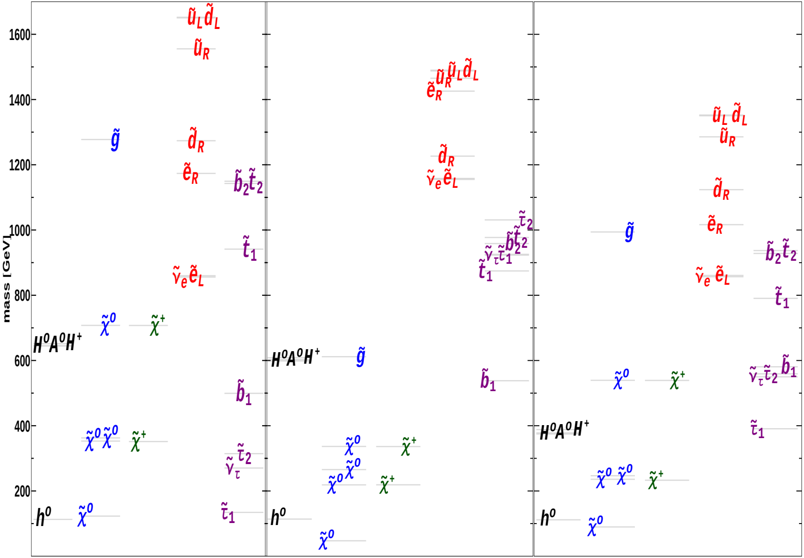
$b \to s\gamma$ satisfied at 2σ

$b \to s\gamma$ and $(g-2)_\mu$ satisfied at 2σ

The WMAP bound selects two allowed regions of $M_{1/2}$ (and gluino mass):

- resonant annihilation through Z or h^0 $\Rightarrow$ gluino mass $\sim 500 - 700$ GeV
- stau co-annihilations, A-funnel $\Rightarrow$ gluino mass $\sim 900 - 1600$ GeV

Typical spectra



Conclusions

- $t-b-\tau$ Yukawa coupling unification much more natural for $\mu<0$
- Non-universality of soft terms at $M_{\rm GUT}$ are necessary for proper REWSB
- Appropriate pattern of non-universalities easily accommodated in SUSY SO(10) GUT:
  - $m_{10}-m_{16}$ splitting and D-term contribution to scalar masses
  - gaugino masses from non-singlet F-term in **54** of SO(10)
- $(g-2)_\mu$ anomaly explained without violating $b\to s\gamma$
- bino-like LSP (with small admixture of higgsino) may play a role of dark matter in the Universe:
  - stau coannihilations,
  - resonant annihilations through h^0, Z or A^0
- Light SUSY spectrum:
  - the whole SUSY spectrum easily below 1.5 TeV
  - predicted gluino mass is 500-700 GeV or 900-1600 GeV