Naturally light uncolored and heavy colored superparticles

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Motivation

- Squarks and gluino are heavy
  - $m_h = 125$ GeV $\Rightarrow$ multi-TeV stops with small mixing, or TeV stops with large mixing
  - Meson oscillation and decays $\Rightarrow$ first two generation squarks heavy and degenerate
  - Non-observation of squarks and gluino in 7 and 8 TeV LHC
- Sleptons and weak gauginos may be light
  - Muon $(g-2)$ has 3.5σ discrepancy $\Rightarrow$ light smuons
  - Neutralino as DM expected in 100 GeV range
  - Light staus may slightly alter Higgs diphoton rate
  - Collider bounds on them are not so strong

How to reconcile this splitting between colored and uncolored superparticles?

Fusion of three issues

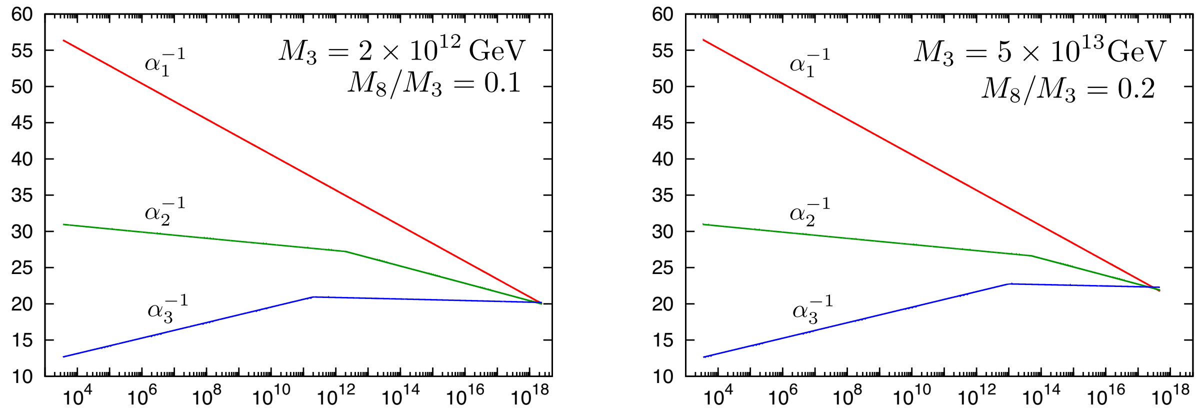
- Gauge coupling unification even with incomplete multiplets at string scale $>$ GUT scale (Bachas, Fabre, Yanagida '96; Bastero-Gil, Brahmachari '97).
  - Adjoint octet (Σ_8) of color SU(3), adjoint triplet (Σ_3) of weak SU(2)
  - Origin of these states can be traced to the non-Goldstone modes of scalar adjoint 24-plet of SU(5)
- Presence of intermediate states characterizing GMSB.

$$W_{\rm mess} = (M_8 + \lambda_8 X){\rm Tr}(\Sigma_8^2) + (M_3 + \lambda_3 X){\rm Tr}(\Sigma_3^2)$$

  F-tern vev of hidden sector field X transmits SUSY breaking to visible sector via messenger multiplets.
- Dynamically ensure $\tilde{m}_{\rm color} >> \tilde{m}_{\rm uncolor}$ by delinking the sources of mass generation for colored and uncolored super-particles (Han, Yanagida, Zhang '98).

Aim is to reproduce m_h, $(g-2)_\mu$, and other data

Unification with Σ_3 and Σ_8



$$\alpha_1^{-1}(M_{\rm str}) = \alpha_1^{-1}(m_{\rm SUSY}) - \frac{(33/5)}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}}$$

$$\alpha_2^{-1}(M_{\rm str}) = \alpha_2^{-1}(m_{\rm SUSY}) - \frac{1}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}} - \frac{2}{2\pi}\ln\frac{M_{\rm str}}{M_3}$$

$$\alpha_3^{-1}(M_{\rm str}) = \alpha_3^{-1}(m_{\rm SUSY}) - \frac{(-3)}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}} - \frac{3}{2\pi}\ln\frac{M_{\rm str}}{M_8}$$

$$M_{\rm str}^2\sqrt{M_3M_8} = M_{\rm GUT}^3 \;\; \text{with} \;\; M_3 > M_8 \;\; (m_{\rm SUSY}\simeq 3.5 \text{ TeV})$$

Superparticle spectrum

- Define $\Lambda_8 \equiv \frac{\lambda_8 F_X}{M_8}$, $\Lambda_3 \equiv \frac{\lambda_3 F_X}{M_3}$
- Recall $M_3 > M_8$ (unification), tune λ_8 and λ_3 to ensure $\Lambda_8 \gg \Lambda_3$
- Messenger scale spectrum

$$
\begin{aligned}
m_{\tilde{B}} &\simeq 0\,, \quad m_{\tilde{W}} \simeq \frac{g_2^2}{16\pi^2}(2\Lambda_3)\,, \quad m_{\tilde{g}} \simeq \frac{g_3^2}{16\pi^2}(3\Lambda_8) \\
m^2_{\tilde{Q}} &\simeq \frac{2}{(16\pi^2)^2}\left[\frac{4}{3}g_3^4(3\Lambda_8^2) + \frac{3}{4}g_2^4(2\Lambda_3^2)\right]\,, \quad m^2_{\tilde{D}} = m^2_{\tilde{U}} \simeq \frac{2}{(16\pi^2)^2}\frac{4}{3}g_3^4(3\Lambda_8^2), \\
m^2_{\tilde{L}} &\simeq \frac{2}{(16\pi^2)^2}\frac{3}{4}g_2^4(2\Lambda_3^2)\,, \quad m^2_{\tilde{E}} \simeq 0
\end{aligned}
$$

- Bino mass is generated by Planck scale suppressed gravitational interaction (which also generates wino and gluino masses).
  Introduce $M_{1/2}$ as universal gaugino mass at $M_{\rm str}$.

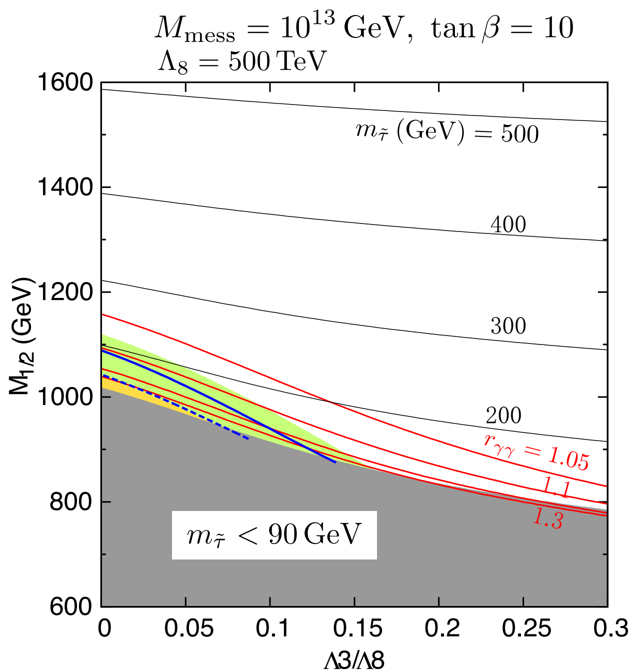
$$
\int d^2\theta\, c_X \frac{X}{M_P} W_\alpha W^\alpha + \text{h.c.} \quad \Rightarrow \quad M_{1/2} = 2c_X F_X/M_P
$$

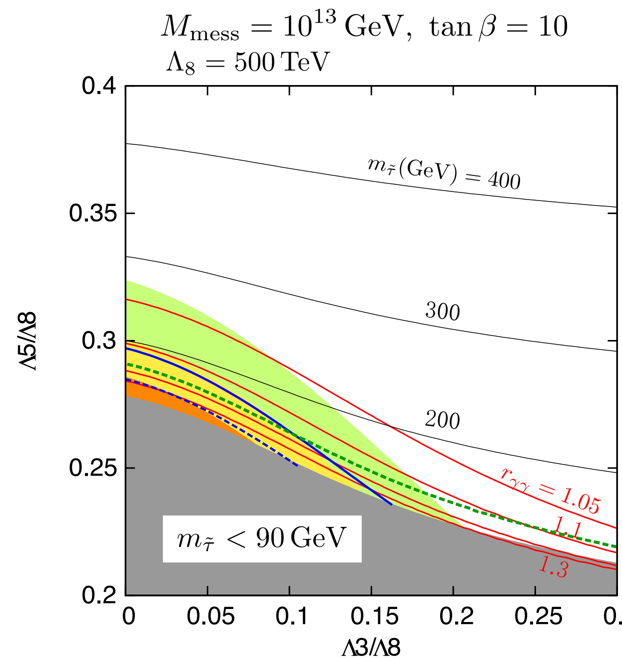
- Gravitino mass is generated roughly in the same order: $m_{3/2} = \frac{F_X}{\sqrt{3}M_P}$

Sparticle spectrum (continued)

- The right-slepton mass is generated by RG running, same order as bino mass, i.e. **bino, slepton and gravitino are of the same order.**
- Due to large left-right stau mixing, one stau can be very light. Light stau can modify diphoton BR of Higgs by 10-20%.
- **Stau is the NLSP, with gravitino LSP.** However, stau is long-lived, as its decay to gravitino of the same order mass is suppressed. CMS limit: $m_{\tilde{\tau}} > 340$ GeV. This is too heavy for diphoton anomaly.
- This implies smuon is too heavy to explain muon $(g-2)$ anomaly.
- **Way out:** Allow mild ($\leq 10^{-7}$) RPV, so that stau can promptly decay to a lepton and neutrino. Then stau can be lighter than 340 GeV. Then muon g-2 can be explained at slightly better than 2σ level.
- **Can we avoid RPV?**

muon $(g-2)$





- **Introduction of $(5+\bar{5})$ messengers explains muon $(g-2)$ better** (right panel).
  Key point: Bino/stau and gravitino mass generation de-linked. Gravitino can be ultra-light, while bino/stau can weigh around 100 GeV (since 5-plets have non-zero Y).
  Unification is not affected by complete multiplets.
- Region below blue solid line is excluded by vac stability limit arising from large LR slepton mixing, which sets an upper limit on $\mu\tan\beta$.

New developments

- <u>3-loop corrections to m_h</u>. **Stop mass in (3-5) TeV range even with minimal mixing can reproduce $m_h = 125$ GeV** (Feng et al '13).
- Since SUSY breaking scale comes down, μ gets smaller.

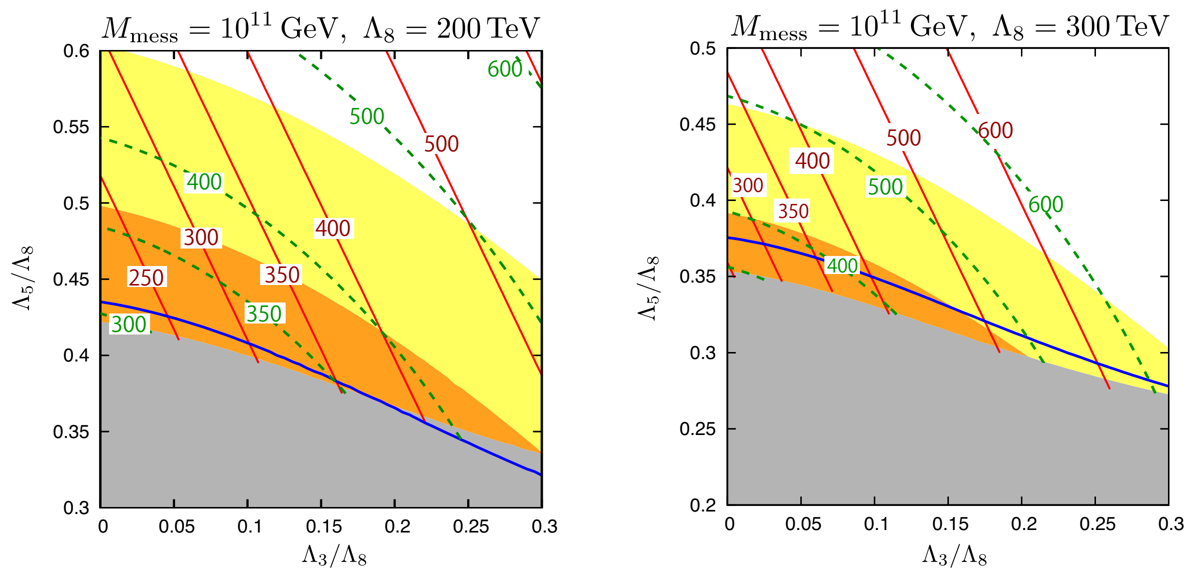
$$\mu^2 \sim (-m^2_{H_u}) \sim \frac{3}{4\pi^2} y_t^2 (m^2_{\rm stop}) \ln \left(\frac{M_{\rm mess}}{m_{\rm stop}} \right)$$

- LR mixing also goes down. So $\tilde{\tau}_1$ need not be that light.
- **Bino/RH-slepton and gravitino masses de-correlated, thanks to 5-plets.** Bino is NLSP. $\boxed{\text{At messenger scale } m_{\tilde{B}} = \frac{\alpha_1}{4\pi}\Lambda_5, \quad m^2_{\tilde{E}} = \frac{1}{8\pi^2}\left[\frac{3}{5}\alpha_1^2 \Lambda_5^2\right]}$.
- Gravitino can be made light

$$m_{3/2} \simeq 0.01\,\text{GeV} \left(\frac{\Lambda_8}{200\text{TeV}}\right) \left(\frac{(\Lambda_3/\Lambda_8)}{0.2}\right) \left(\frac{M_8}{10^{11}\text{GeV}}\right) \left(\frac{(M_3/M_8)}{10}\right)$$

- 100 GeV Neutralino decays into 10 MeV gravitino in a BBN safe way (Kawasaki et al '08). <u>**No need of RPV**</u>.

Muon $(g-2)$ (updated)



- $(g-2)_\mu$ is dominated by bino-smuon loop. In the orange (yellow) region it is explained at 1 (2)-σ level. In the gray region, stau is lighter than 90 GeV.

$$(\Delta a_\mu)_{\rm SUSY} \simeq \frac{3}{5}\frac{g_1^2}{8\pi^2}\frac{m_\mu^2 \mu \tan\beta}{M_1^3} F_b\left(\frac{m_{\tilde{L}}^2}{M_1^2}, \frac{m_{\tilde{E}}^2}{M_1^2}\right)$$

- Viable regions are above the blue solid line where bino is NLSP. A stau NLSP is stable inside the detector (hence > 340 GeV (CMS '13)), which makes smuons too heavy!

Conclusions

- Does naturalness demand that super-particles all have to be simultaneously heavy? OR, sleptons/weak gauginos can remain significantly lighter than squarks/gluino by internal dynamics?

- **Key observation:** With unconventional choice of matter multiplets, a color SU(3) octet and a weak SU(2) triplet, GMSB works:
  - unification at string scale (between GUT and Planck scale).
  - colored mass $\gg$ uncolored mass of sparticles by intrinsic dynamics.
  - Introducing in addition the SU(5) 5-plets, it is possible to explain Muon $(g-2)$ within 1σ. Consequences of 3-loop correction to Higgs mass have been crucial.
  - Lighter stau is in (100-200) GeV range which can be a target at ILC.

GMSB with incomplete matter multiplets is an attractive option.