Naturally light uncolored and heavy colored superparticles

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Motivation

- Squarks and gluino are heavy
  - $m_h = 125$ GeV
    $\Rightarrow$ stop $\sim$ TeV (large mixing) or more (small mixing)
  - FCNC $\Rightarrow$ 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 $> \ 3\,\sigma$ discrepancy $\Rightarrow$ light smuons
  - Neutralino as DM expected in $\mathcal{O}(100)$ 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?

GMSB – basic introduction

- Information on SUSY breaking is transmitted to observable sector by gauge interaction. FCNC is suppressed.
- ‘Messenger sector’ comprising of heavy chiral superfields which have gauge charges. SUSY is broken in messenger sector by interaction with ‘spurion’. Consider a set of vector-like superfields $M + \bar{M}$ (e.g. $5 + \bar{5}$ and/or $10 + \bar{10}$ of SU(5) GUT). Complete multiplets do not spoil gauge coupling unification.
- Minimal scenario: $W = \lambda X M \bar{M}$. The messenger fermions acquire a supersymmetric mass $m = \lambda \langle X \rangle$ and messenger scalars are split: $m_{\pm}^2 = m^2 \pm \lambda \langle F_X \rangle$. SUSY breaking scale $\Lambda \equiv \langle F_X \rangle / \langle X \rangle$.
- Gaugino masses are generated at one-loop while sfermion masses are generated at two-loop. When $\Lambda << M$ ($\sim 100\ \mathrm{TeV}\ < M < M_{Pl}$)

$$m_{\tilde{\lambda}_i} \simeq \frac{\alpha_i}{4\pi}\Lambda\,, \qquad \tilde{m}^2 \simeq 2\Lambda^2 \frac{\sum_i c_i \alpha_i^2}{16\pi^2}$$

- Gravitino mass $m_{\tilde{G}} \sim \frac{F}{M_{Pl}}$ is in general much lighter (than in supergravity). It can be ~ 100 eV. In general gravitino is the LSP. Distinct signatures.
- μ and B_μ problem! Essentially, $B_\mu \sim \mu\Lambda$.

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 adjoint 24-plet of SU(5)
- Presence of intermediate states characterizing GMSB.

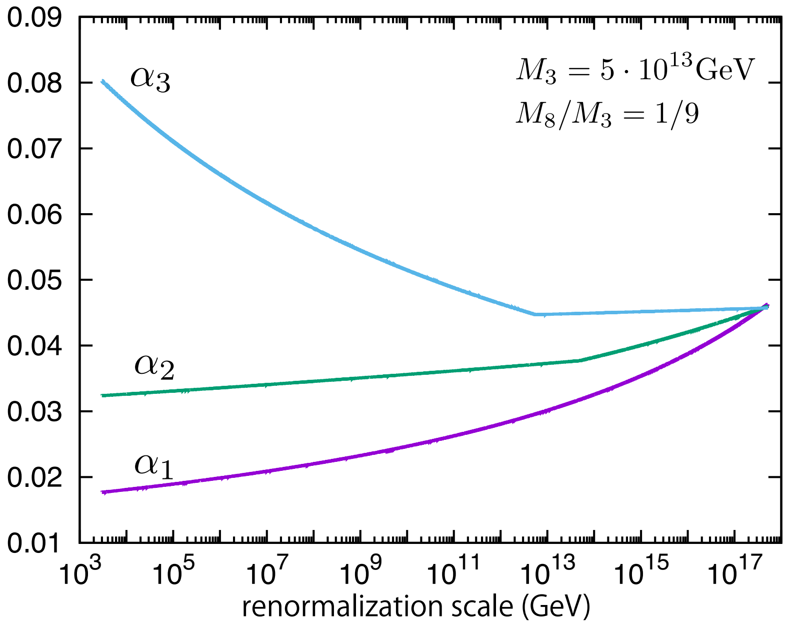
$$W_{\rm mess} = (M_8 + \lambda_8 X)\mathrm{Tr}(\Sigma_8^2) + (M_3 + \lambda_3 X)\mathrm{Tr}(\Sigma_3^2)$$

F-term 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

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

Unification with Σ_3 and Σ_8



$$\begin{aligned}
\alpha_1^{-1}(M_{\rm str}) &= \alpha_1^{-1}(m_{\rm SUSY}) - \frac{(33/5)}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}} \\
\alpha_2^{-1}(M_{\rm str}) &= \alpha_2^{-1}(m_{\rm SUSY}) - \frac{1}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}} - \frac{2}{2\pi}\ln\frac{M_{\rm str}}{M_3} \\
\alpha_3^{-1}(M_{\rm str}) &= \alpha_3^{-1}(m_{\rm SUSY}) - \frac{(-3)}{2\pi}\ln\frac{M_{\rm str}}{m_{\rm SUSY}} - \frac{3}{2\pi}\ln\frac{M_{\rm str}}{M_8}
\end{aligned}$$

- $m_{\rm SUSY} \equiv (m_{Q_3} m_{\bar{U}_3})^{1/2}$ is the average stop mass.
- $\alpha_{1,2,3}^{-1} \simeq (57, 31, 13)$ at $m_{\rm SUSY} = 3$ TeV.

Unification – key issues

For unification, $M_3 > M_8$ at one-loop.

For $M_{\rm str} = 10^{17}(10^{18})$ GeV, $M_3/M_8 = 7(18)$.

$$M_{\rm str}^2\, m_{\rm mess} = M_{\rm GUT}^3 \qquad \text{where} \qquad m_{\rm mess} \equiv \sqrt{M_3 M_8}.$$

Late Unification avoids proton decay constraints: $p \to K^+\nu$ goes like $1/m_{H_c}^2$ where $m_{H_c} \sim M_{\rm str} \sim 10^{17-18}$ GeV.

Sparticle masses at mess scale

- 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

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

- No messenger is charged under U(1). Right-handed slepton and Bino masses are generated by Planck scale suppressed gravitational interaction and are of the order of the gravitino mass.

$$\boxed{m_{\tilde{E}}(M_{\rm str}) \sim M_{\tilde{B}}(M_{\rm str}) \sim m_{3/2} \sim \frac{F_X}{M_P}}$$

Sample spectra with $\Sigma_{3,8}$

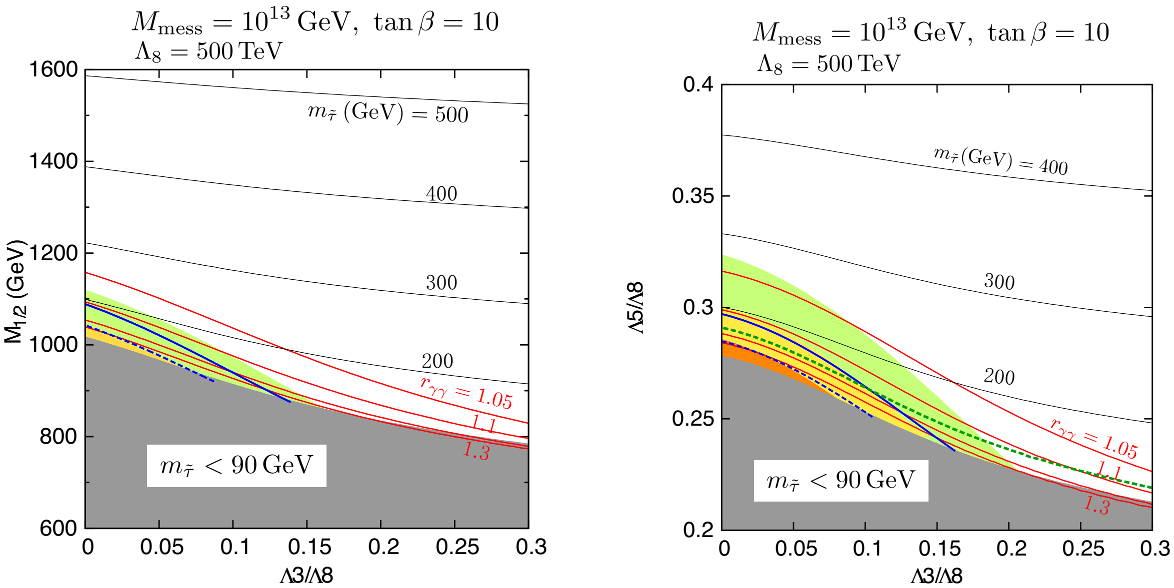
Λ_3/Λ_8	0.10
Λ_8	500 TeV
$M_{1/2}$	920 GeV
M_{mess}	10^{13} GeV
$\tan\beta$	10
μ	5.9 TeV
m_{stop}	8.2 TeV
δa_μ	1.24$\times 10^{-9}$
m_{gluino}	10 TeV
m_{squark}	9.4 TeV
$m_{\tilde{e}_L}(m_{\tilde{\mu}_L})$	601 GeV
$m_{\tilde{e}_R}(m_{\tilde{\mu}_R})$	258 GeV
$m_{\tilde{\tau}_1}$	98 GeV
$m_{\chi_1^0}$	315 GeV
$m_{\chi_1^\pm}$	851 GeV

Phenomenology with $\Sigma_{3,8}$

- 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 sizable diphoton contribution.
- This implies smuon is too heavy to explain muon $(g-2)$ anomaly.

RPV: 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. Not any more!! LHC limits are sometimes stronger in RPV environment.

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). Bino/stau mass $\propto \Lambda_5$.

  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 $\mu\tan\beta$.

Further improvements

- **Including 3-loop corrections to m_h, 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.

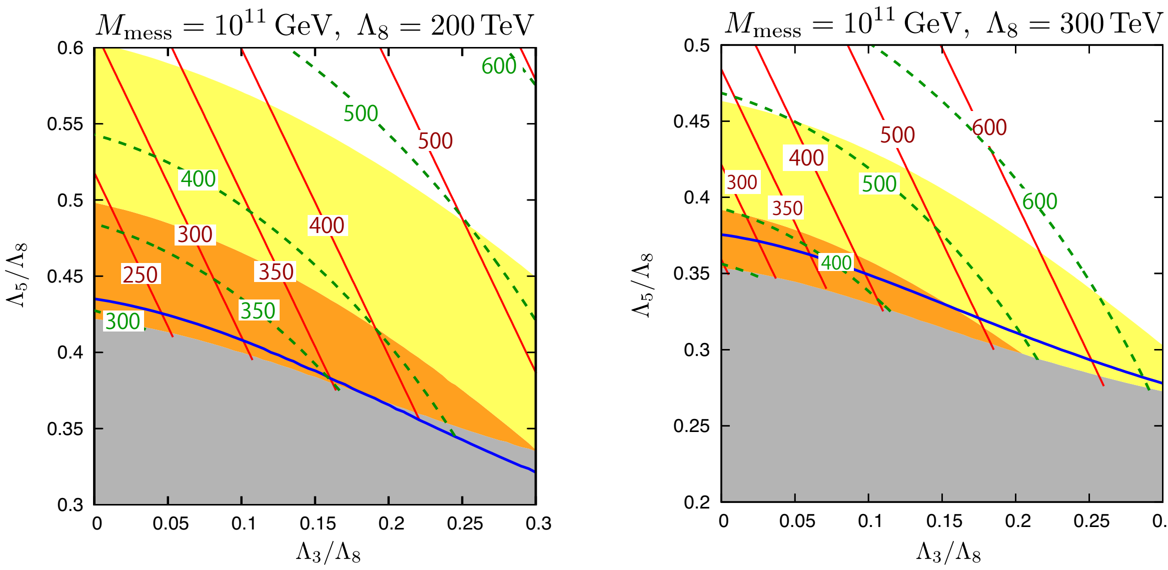
$$\mu^2 \sim (-m_{H_u}^2) \sim \frac{3}{4\pi^2} y_t^2 (m_{\rm stop}^2) \ln \left(\frac{M_{\rm mess}}{m_{\rm stop}} \right)$$

- 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. $\boxed{\text{At messenger scale } m_{\tilde{B}} = \frac{\alpha_1}{4\pi}\Lambda_5, \quad m_{\tilde{E}}^2 = \frac{1}{8\pi^2}\left[\frac{3}{5}\alpha_1^2 \Lambda_5^2\right]}$.
- Gravitino can be made light

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

- 100 GeV Neutralino decays into 10 MeV gravitino in a BBN safe way (Kawasaki et al '08).

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.

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

- 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!

Focus point

A region where EWSB seems natural even if superparticles are very heavy. One or more fixed ratios of soft SUSY breaking parameters are introduced which reduce the fine-tuning of the potential.

In GMSB, F.P. was achieved with different number of weakly (N_2) and strongly (N_3) interacting messenger multiplets. But gauge couplings do not unify (Brummer, Buchmuller'12; Brummer, Ibe, Yanagida'13).

The EWSB conditions are

$$\begin{aligned}
\frac{g_1^2+g_2^2}{4}v^2 &= \left[-\mu^2 - \frac{(m_{H_u}^2 + \frac{1}{2v_u}\frac{\partial\Delta V}{\partial v_u})\tan^2\beta}{\tan^2\beta - 1} + \frac{m_{H_d}^2 + \frac{1}{2v_d}\frac{\partial\Delta V}{\partial v_d}}{\tan^2\beta - 1}\right]_{m_{\rm SUSY}}, \\
\frac{\tan^2\beta+1}{\tan\beta} &= \left[\frac{1}{B\mu}\left(m_{H_u}^2 + \frac{1}{2v_u}\frac{\partial\Delta V}{\partial v_u} + m_{H_d}^2 + \frac{1}{2v_d}\frac{\partial\Delta V}{\partial v_d} + 2\mu^2\right)\right]_{m_{\rm SUSY}}.
\end{aligned}$$

where ΔV is the one-loop correction to the Higgs potential.

RG running and cancellations

- $m^2_{H_u}$ (weak) receives negative contributions from colored super-partners.
- $m^2_{H_u}$ (weak) receives positive contribution from wino loop and tree level $m^2_{H_u}$.

$$\begin{aligned}
m^2_{H_u}(3\mathrm{TeV}) &= 0.704 m^2_{H_u} + 0.019 m^2_{H_d} \\
&- 0.336 m^2_{Q} - 0.167 m^2_{\bar{U}} - 0.056 m^2_{\bar{E}} \\
&+ 0.055 m^2_{L} - 0.054 m^2_{\bar{D}} \\
&+ 0.011 M^2_{\tilde{B}} + 0.192 M^2_{\tilde{W}} - 0.727 M^2_{\tilde{g}} \\
&- 0.003 M_{\tilde{B}} M_{\tilde{W}} - 0.062 M_{\tilde{W}} M_{\tilde{g}} - 0.010 M_{\tilde{B}} M_{\tilde{g}}
\end{aligned}$$

$$m^2_{H_u}(\mathrm{weak}) \quad \sim \quad 0.9\, m^2_{\mathrm{uncolor}} \quad - \quad 1.3\, m^2_{\mathrm{color}}$$

In minimal GMSB with 5 and $\bar{5}$ messengers, the negative contributions substantially dominate over the positive contributions.

RG invariant parameter

With only Σ_3 and Σ_8 messengers, introduce $\boxed{r_3 \equiv \frac{\Lambda_3}{\Lambda_8} = \frac{\lambda_3 M_8}{\lambda_8 M_3}}$

This parameter is RG invariant

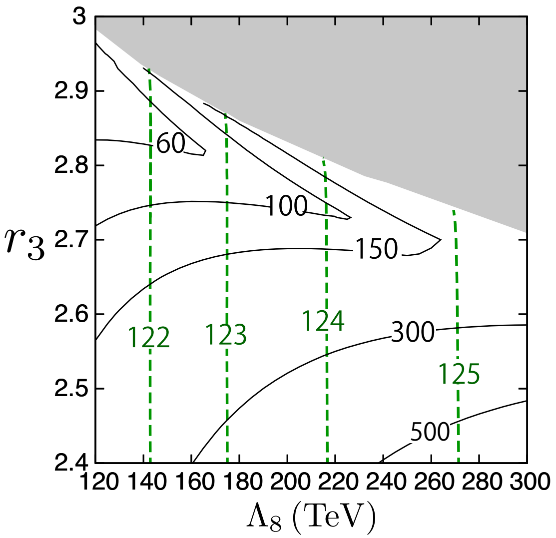
$$\begin{aligned}\lambda_{(3,8)}(t) &= \lambda_{(3,8)}(t_0) \exp\left[\int_{t_0}^{t} dt' (\gamma_X + 2\gamma_{\Sigma_{(3,8)}})\right] \\ M_{(3,8)}(t) &= M_{(3,8)}(t_0) \exp\left[\int_{t_0}^{t} dt' (2\gamma_{\Sigma_{(3,8)}})\right]\end{aligned}$$

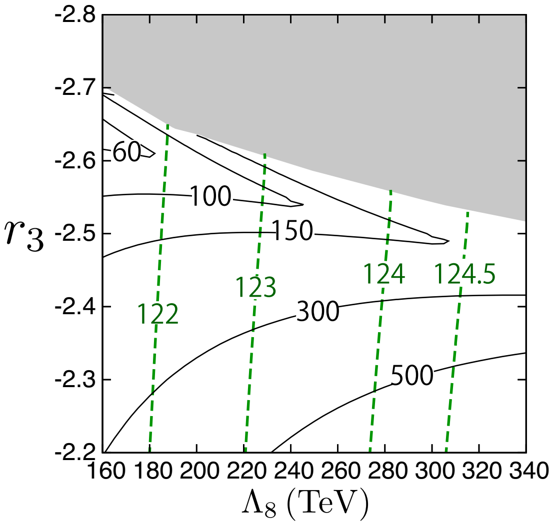
$$\frac{\lambda_3(t) M_8(t)}{\lambda_8(t) M_3(t)} = \frac{\lambda_3(t_0) M_8(t_0)}{\lambda_8(t_0) M_3(t_0)}$$

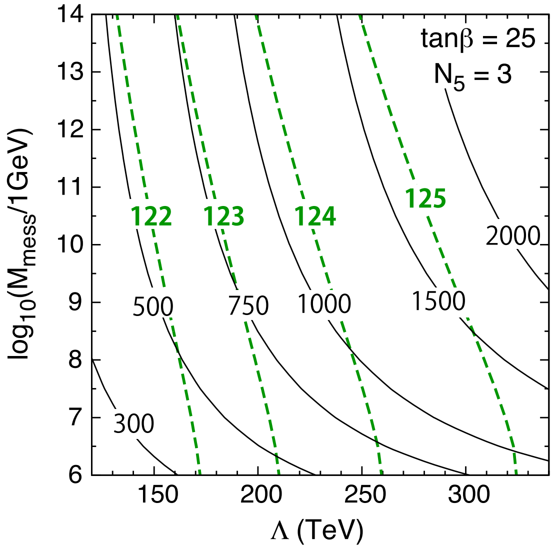
Focus point in AM-GMSB

$$m_{H_u}^2(3\mathrm{TeV}) \simeq [0.16\, r_3^2 - 1.2] M_{\tilde{g}}^2$$

For $r_3 \simeq 2.8, -2.6$ we achieve Focus Point region





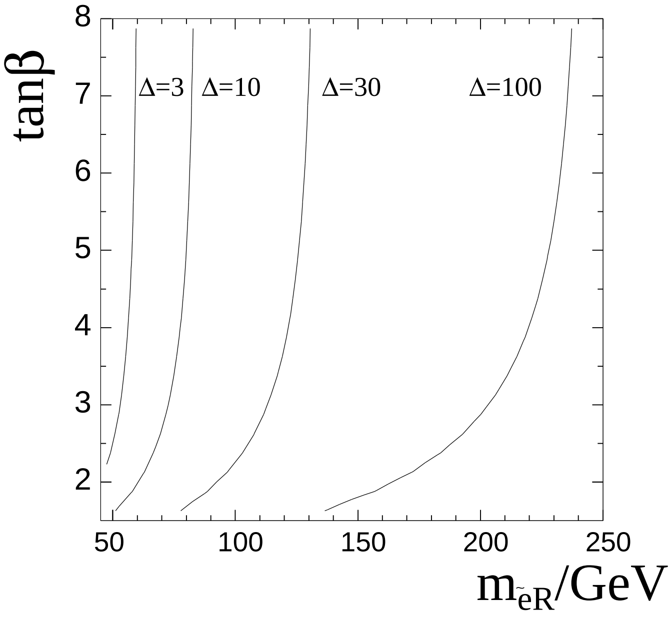


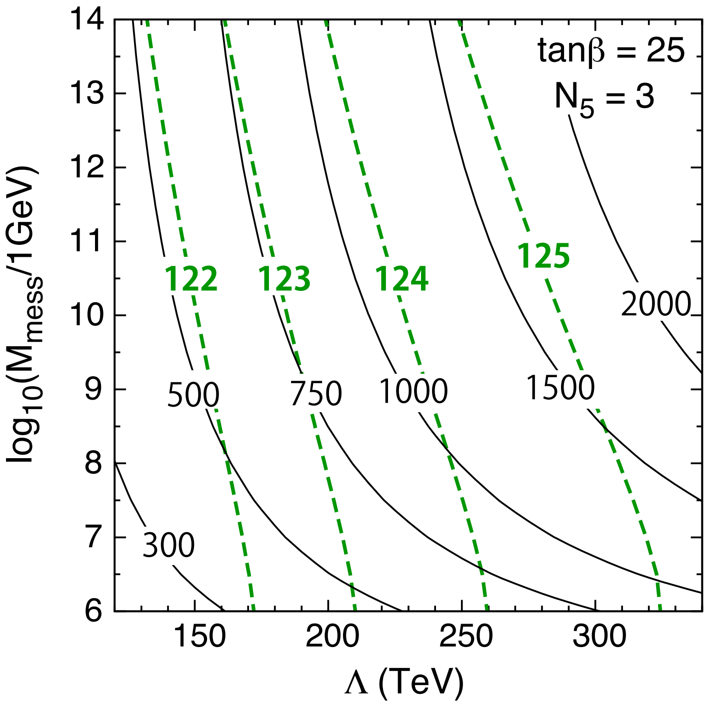
- In the gray region the EWSB does not occur. $M_{\rm mess} = 10^{13}$ GeV.
- $\Delta = 60 - 150$ for $r_3 = 2.8$ to explain the observed m_h.
- For minimal GMSB, $\Delta = 750 - 1000$ to explain $m_h > 125$ GeV for $M_{\rm mess} > 10^9$ GeV.

Sample spectra for Focus Point

P1		**P2**		**P3**	
Λ_8	180 TeV	Λ_8	280 TeV	Λ_8	230 TeV
r_3	2.8	r_3	8/3	r_3	-2.55
$\tan\beta$	15	$\tan\beta$	15	$\tan\beta$	15
m_h	123.1 GeV	m_h	125.1 GeV	m_h	123.0 GeV
Δ	69	Δ	156	Δ	91
μ	538 GeV	μ	850 GeV	μ	652 GeV
$m_{\rm gl}$	3.6 TeV	$m_{\rm gl}$	5.4 TeV	$m_{\rm gl}$	4.5 TeV
$m_{\rm sq}$	3.4 - 4.5 TeV	$m_{\rm sq}$	5.1 - 6.7 TeV	$m_{\rm sq}$	4.2 - 5.5 TeV
$m_{\rm st}$	2.2, 4.1 TeV	$m_{\rm st}$	3.4, 6.2 TeV	$m_{\rm st}$	3.1, 5.1 TeV
$m_{\tilde{e}_L}$	3.1 TeV	$m_{\tilde{e}_L}$	4.5 TeV	$m_{\tilde{e}_L}$	3.6 TeV
$m_{\tilde{e}_R}$	473 GeV	$m_{\tilde{e}_R}$	727 GeV	$m_{\tilde{e}_R}$	618 GeV
$m_{\tilde{\tau}_1}$	221 GeV	$m_{\tilde{\tau}_1}$	399 GeV	$m_{\tilde{\tau}_1}$	394 GeV
$m_{\chi_1^0}$	128 GeV	$m_{\chi_1^0}$	124 GeV	$m_{\chi_1^0}$	131 GeV
$m_{\chi_1^\pm}$	550 GeV	$m_{\chi_1^\pm}$	870 GeV	$m_{\chi_1^\pm}$	670 GeV
$m_{\chi_2^\pm}$	2.6 TeV	$m_{\chi_2^\pm}$	3.8 TeV	$m_{\chi_2^\pm}$	3.1 TeV

F.T. ‘then’ and ‘now’





- Years ago, $\Delta \sim 50$ for $M \sim 10^5$ TeV and it was worse than mSUGRA then (G.B., Romanino 1997).
- In 20 years it has gone up by a factor of ~ 20.

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 messenger 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. *Scenario fine-tuned with* $\mu \sim$ *few TeV*.
  - If we give up $(g-2)$, then with just Σ_3 and Σ_8, Focus Point can be achieved introducing a RG-invariant parameter.
  - Lighter stau is in (100-400) GeV range which can be a target at ILC.

GMSB with Adjoint Messenger multiplets (Σ_3 and Σ_8) is an attractive scenario