Gauge mediation and the light Higgs mass

V Suryanarayana
C H E P, IISc
Bangalore

Work done in collaboration with
Sudhir K Vempati

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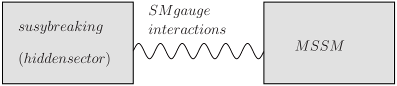
Outline

1. Gauge mediated Supersymmetry Breaking(GMSB) (see lectures by Dedes in Presusy)
2. Model:U(1) extension of Standard Model
3. Summary

Features of Gauge Mediation

- GMSB models assume that SUSY is broken in a secluded sector
- Messenger fields communicate susy breaking from hidden sector to MSSM sector



- Messenger fields transform vectorially under SM gauge group

Gauge mediation continued..

$$W = y_i X \bar{\Phi}_i \Phi_i$$

- Φ_i, $\bar{\Phi}_i$ are messenger fields
- X Goldstino multiplet

$$\langle X \rangle = M + \theta^2 \mathcal{F}$$

$\Rightarrow$ messenger fermion mass $=\ y_i\, M$
$\Rightarrow$ messenger scalars mass^2 $=\ y_i^2\, M^2 \pm y_i\, \mathcal{F}$

- Breaking effects from hidden sector are communicated to SM via gauge interactions

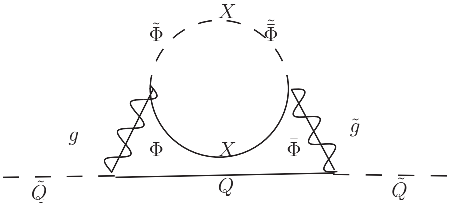


Figure : two loop- squark mass

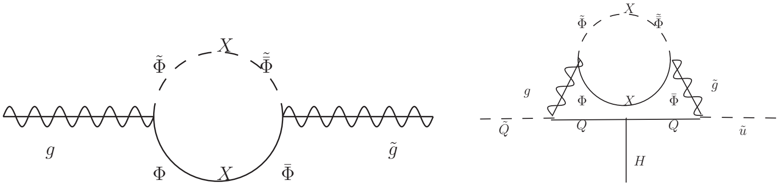


Figure : one loop-gaugino mass and A terms

Boundary conditions

$$
\begin{aligned}
M_a &= \frac{\alpha_a}{4\pi}\Lambda\, n_a(i) \qquad (a = 1-3),\\
\tilde{m}^2 &= 2\Lambda^2 \sum_{a=1}^{3}\left(\frac{\alpha_a}{4\pi}\right)^2 C_a n_a(i)\\
A_f &= 0\\
B &= 0.
\end{aligned}
$$

$\Lambda = \frac{\mathcal{F}}{M}$, $\quad n_a(i)$ *is Dynkin index* and C_a is the casimir invariant

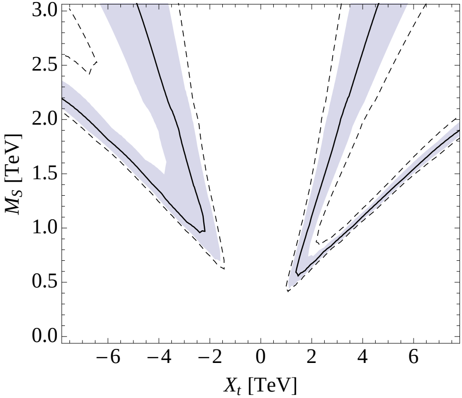
squark masses are universal $\Longrightarrow$ SUSY flavor problem

GMSB is highly predictable Complete spectrum is constrained by only 5 parameters

Can we realise 125 Gev Higgs in mGMSB?

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

D.Shih,2011



solid $-$ $m_h = 125 GeV$ *with* $m_t = 173$
violet band-$m_h = 123 - 127 Gev$
dashed lines- $m_t = 172 - 174$
$X_t = A_t - \mu \cot\beta$
$Ms = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$

No

Messenger matter mixing

K.S Babu, Albaid, Iftah gallon, Shadmi, Abdullah, Bhyakti, Ray, Pawelczyk, David Shih, Drapper, Brynt, Ruby,........

$$W_{5+\bar{5}} \;=\; f_d \overline{d^c}_m d^c_m X + f_e \overline{L}_m L_m X + \lambda'_b Q_3 d^c_m H_d + \lambda'_{\tau^c} L_m e^c_3 H_d$$

$$\begin{aligned}
\delta \tilde{m}^2_{Q_3} &= \frac{\alpha'_b \Lambda^2}{8\pi^2}\left(3\alpha'_b + \frac{1}{2}\alpha'_{\tau^c} - \frac{8}{3}\alpha_3 - \frac{3}{2}\alpha_2 - \frac{7}{30}\alpha_1\right) \\
\delta \tilde{m}^2_{\tau^c} &= \frac{2\alpha'_{\tau^c}\Lambda^2}{8\pi^2}\left(2\alpha'_{\tau^c} + \frac{3}{2}\alpha'_b - \frac{3}{2}\alpha_2 - \frac{9}{10}\alpha_1\right) \\
\delta \tilde{m}^2_{H_d} &= \frac{\delta \tilde{m}^2_{\tau^c}}{2} + 3\delta \tilde{m}^2_{Q_3} + \frac{3\Lambda^2 \alpha'_b \alpha_t}{16\pi^2}
\end{aligned}$$

$$\boxed{\begin{aligned}
\delta A_t &= -\frac{1}{4\pi}\alpha'_b \Lambda \\
\delta A_b &= -\left(\frac{4\alpha'_b + \alpha'_{\tau^c}}{4\pi}\right)\Lambda \\
\delta A_\tau &= -\left(\frac{3\alpha'_b + 3\alpha'_{\tau^c}}{4\pi}\right)\Lambda
\end{aligned}}$$

- No FCNCs
- No conflict with Higgs mass
- Testable at LHC

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U(1) extension of Standard Model

NMSSM with GMSB A. Delgado, F Giudice 2007

$$W = \lambda N H_d H_u - \frac{k}{3} N^3$$

$$\begin{aligned}
\mu^2 &= \frac{\tilde{m}^2_{H_d} - \tilde{m}^2_{H_u} \tan^2\beta}{\tan^2\beta - 1} - \frac{g^2 + g'^2}{4} v^2 \\
\sin 2\beta &= \frac{2\, B_\mu}{\tilde{m}^2_{H_d} + \tilde{m}^2_{H_u} + 2\mu^2} \\
2\, \frac{k^2}{\lambda^2}\, \mu^2 - \frac{k}{\lambda} A_k\, \mu + \tilde{m}^2_N &= \lambda^2 v^2 \left[-1 + \left(\frac{B_\mu}{\mu^2} + \frac{k}{\lambda} \right) \frac{\sin 2\beta}{2} \right. \\
&\quad \left. + \frac{\lambda^2\, v^2\, \sin^2 2\beta}{4\, \mu^2} \right]
\end{aligned}$$

Where $\mu = \lambda < N >$

In GMSB $\tilde{m}_N^2$, B_μ *and* A_k at the low scale are very small and can be neglected

$$< N >\approx \frac{v}{\sqrt{2}}\frac{\lambda}{k}\sqrt{-1+\frac{k}{\lambda}\sin 2\beta} \; < v$$

- Electro weak symmetry breaking is not viable

$G_{SM} \times U(1)_X$

$$
\begin{array}{llllll}
L: & (1,2,-\frac{1}{2},l) & \bar{E}: & (1,1,1,e) & Q: & (3,2,\frac{1}{6},q) \\
\bar{U}: & (\bar{3},1,-\frac{2}{3},u) & \bar{D}: & (\bar{3},1,\frac{1}{3},d) & H_1: & (1,2,-\frac{1}{2},h_1) \\
H_2: & (1,\bar{2},\frac{1}{2},h_2) & S: & (1,1,0,s) & &
\end{array}
$$

$$W = Y_E L E^c H_1 + Y_D Q D^c H_1 + Y_U Q U^c H_2 + \lambda S H_1 H_2$$

where $Y_E,\ Y_D,\ Y_U, \lambda$ are Yukawa couplings

Anomaly Cancellation

$(SU(3)_C)^2\, X$ anomaly

$$\begin{aligned}
3(2q+u+d)+A_1(exotics) &= 0 \\
l+e+h_1 &= 0 \\
q+d+h_1 &= 0 \\
q+u+h_2 &= 0 \\
s+h_1+h_2 &= 0
\end{aligned}$$

$$\implies A_1(exotics) = -3\, s$$

- We assume that they are triplets and anti triplets of $SU(3)_c$ with equal and opposite $U(1)_Y$ hypercharges $\pm y_i$

N.B :$U(1)_X$ charges are family independent.

These are anomaly equations of $Y^2X, YX^2, X^3, (SU(2)_L)^2X$, can be solved

q	u	d	l	e	h_1	h_2	s	z_1	z_2	z_3	$\bar{z}_1$	$\bar{z}_2$	$\bar{z}_3$
$\frac{1}{6}$	$\frac{1}{3}$	$\frac{7}{3}$	$\frac{1}{2}$	2	$\frac{-5}{2}$	$\frac{-1}{2}$	3	-3	-1	-1	0	-2	-2

Higgs potential

$$
\begin{aligned}
W =& \lambda \hat{S}\hat{H}_2 \cdot \hat{H}_1 + y_t \hat{U}^c \hat{Q} \cdot \hat{H}_2 \\
V_F =& |\lambda H_2 \cdot H_1|^2 + |\lambda S|^2 \left(|H_1|^2 + |H_2|^2\right) \\
V_D =& \frac{(g_1^2 + g_2^2)}{8} \left(|H_1|^2 - |H_2|^2\right)^2 + \frac{g_2^2}{2} \left(|H_1|^2 |H_2|^2 - |H_2 \cdot H_1|^2\right) \\
& + \frac{{g_4}^2}{2} \left(h_1 |H_1|^2 + h_2 |H_2|^2 + s|S|^2\right)^2 \\
V_{\rm soft} =& m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_s^2 |S|^2 + (A_\lambda S H_2 \cdot H_1 + h.c.)
\end{aligned}
$$

$$\lambda,\ A_\lambda,\ v_s,\ g_4$$

Z- Z' mixing

$\mathcal{L} \supset \chi^T \mathcal{M}^2_{Z'Z} \chi$ where $\chi^T = \{Z', Z\}$ with

$$\mathcal{M}^2_{Z'Z} = \begin{pmatrix} M^2_{Z'Z'} & M^2_{Z'Z} \\ M^2_{Z'Z} & M^2_{ZZ} \end{pmatrix}$$

$$\begin{aligned} M^2_{Z'Z'} &= {g_4}^2 (h_1^2 v_1^2 + h_2^2 v_2^2 + s^2 v_s^2), \\ M^2_{ZZ'} &= g_4 \sqrt{g_1^2 + g_2^2} \left(v_1^2 h_1 - v_2^2 h_2 \right) \\ M^2_{ZZ} &= \frac{\left(g_1^2 + g_2^2\right)\left(v_1^2 + v_2^2\right)}{4} \end{aligned}$$

The mixing of the matrix is given by

$$\Theta_{ZZ'} = \frac{1}{2} \tan^{-1} \left(\frac{2 M^2_{ZZ'}}{M^2_{Z'Z'} - M^2_{ZZ}} \right)$$

- The current limits on $M_{Z'}$ require it to be greater than 1.9 TeV

$$v_s > 1 Tev$$

pdg:2013

- $\Theta_{ZZ'}$ is constrained by electroweak precision data, it should be less than $O(10^{-3})$ Hook:2010.
- For consistent electroweak symmetry breaking

$$\lambda < \frac{\sqrt{2}\mu}{v_s}$$

Electroweak symmetry breaking

$$
\begin{aligned}
m_1^2 &= -\frac{1}{2}\left[\frac{G^2}{4}+h_1^2{g_4}^2\right]v_1^2+\frac{1}{2}\left[\frac{G^2}{4}-\lambda^2-h_1h_2{g_4}^2\right]v_2^2 \\
&\quad -\frac{1}{2}\left[\lambda^2+h_1s{g_4}^2\right]{v_s}^2+\ \frac{A_\lambda}{\sqrt{2}}\frac{v_2v_s}{v_1} \\
m_2^2 &= \frac{1}{2}\left[\frac{G^2}{4}-\lambda^2-h_1h_2{g_4}^2\right]v_1^2-\frac{1}{2}\left[\frac{G^2}{4}+h_2^2{g_4}^2\right]v_2^2 \\
&\quad -\frac{1}{2}\left[\lambda^2+h_2s{g_4}^2\right]{v_s}^2+\ \frac{A_\lambda}{\sqrt{2}}\frac{v_1v_s}{v_2} \\
m_s^2 &= -\frac{1}{2}\left[\lambda^2+h_1s{g_4}^2\right]v_1^2-\frac{1}{2}\left[\lambda^2+h_2s{g_4}^2\right]v_2^2-\frac{1}{2}s^2{g_4}^2v_s^2 \\
&\quad +\frac{A_\lambda}{\sqrt{2}}\frac{v_1v_2}{v_s}
\end{aligned}
$$

$$
v_s \approx -\sqrt{2}\tfrac{m_s}{s\,g_4}
$$

Electroweak symmetry breaking continued...

CP-even Higgs Mass Matrix

in the basis H_1^0, H_2^0, S

$$
\begin{aligned}
\left(\mathcal{M}_+^0\right)_{11} &= \left[\frac{G^2}{4} + h_1^2 {g_4}^2\right] v_1^2 + \frac{A_\lambda}{\sqrt{2}} \frac{v_2 v_s}{v_1} \\
\left(\mathcal{M}_+^0\right)_{12} &= -\left[\frac{G^2}{4} - \lambda^2 - h_1 h_2 {g_4}^2\right] v_1 v_2 - \frac{A_\lambda}{\sqrt{2}} v_s \\
\left(\mathcal{M}_+^0\right)_{13} &= \left[\lambda^2 + h_1 s {g_4}^2\right] v_1 v_s - \frac{A_\lambda}{\sqrt{2}} v_2 \\
\left(\mathcal{M}_+^0\right)_{22} &= \left[\frac{G^2}{4} + h_2^2 {g_4}^2\right] v_2^2 + \frac{A_\lambda}{\sqrt{2}} \frac{v_1 v_s}{v_2} \\
\left(\mathcal{M}_+^0\right)_{23} &= \left[\lambda^2 + h_2 s {g_4}^2\right] v_2 v_s - \frac{A_\lambda}{\sqrt{2}} v_1 \\
\left(\mathcal{M}_+^0\right)_{33} &= s^2 {g_4}^2 v_s^2 + \frac{A_\lambda}{\sqrt{2}} \frac{v_1 v_2}{v_s}
\end{aligned}
$$

where $G^2 = g_1^2 + g_2^2$

Electroweak symmetry breaking continued...

$$\left(\mathcal{M}_{+}^{0}\right)_{11} = \left[\frac{G^2}{4} + h_1^2 {g_4}^2\right] v_1^2 + \frac{A_\lambda}{\sqrt{2}} \frac{v_2 v_s}{v_1}$$

$$Det[M]_{(2\times2)} \approx \frac{A_\lambda v_s}{\sqrt{2} v_1 v_2} [\frac{\lambda^2 \sin 2\beta^2}{2} + \cos 2\beta^2 M_z^2 (v_1^2 + v_2^2) + g_4^2 (h_1 v_1^2 + h_2 v_2^2)^2]$$

$$Det[M]_{(3\times3)} \approx \frac{A_\lambda v_s^3}{4\sqrt{2} v_1 v_2} [g^2\, g_4^2\, s^2\, (v_1^2 - v_2^2)^2 + 4\,(g_4^4\, h_1^2\, s^2\, v_1^4 - (\, l^4 + 2\, g_4^2\, l^2\, (\, h_2 - s\,)\, s + g_4^4\, h_2(-2\, h_1 + h_2\,)\, s^2)\, v_1^2 v_2^2 + g_4^4 h_2^2 s^2 v_2^4)]$$

Electroweak symmetry breaking continued...

$$Det[M]_{(2\times 2)} \approx \frac{A_\lambda v_s}{\sqrt{2} v_1 v_2}[\frac{\lambda^2 \sin 2\beta^2}{2} + \cos 2\beta^2 M_z^2 (v_1^2 + v_2^2) + g_4^2 (h_1 v_1^2 + h_2 v_2^2)^2]$$

$$Det[M]_{(3\times 3)} \approx \frac{A_\lambda v_s^3}{4\sqrt{2} v_1 v_2}[g_4^2\, s^2((g^2 + 4\, g_4^2\, h_1^2)\cos\beta^4 - \frac{g^2}{2}\sin 2\beta^2 + (g^2 + 4\, g_4^2\, h_2^2)\sin\beta^4) + g_4^4 (h_1^2 + h_2^2) s^2)\sin 2\,\beta^2 - (4\,\lambda^4 + 2\, s\, g_4^2\,\lambda^2\,(2\,(h_1 + h_2) - s)]$$

- Positive A_λ and smaller λ values favours electroweak symmetry breaking

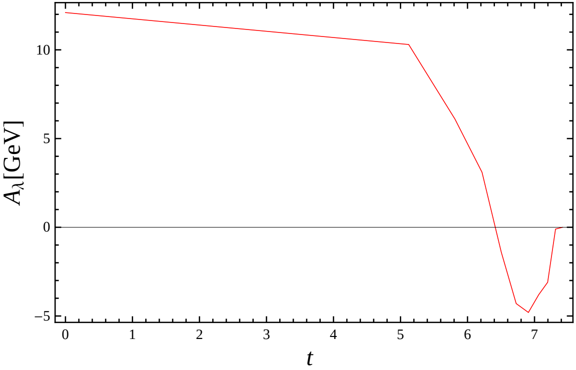

Figure : A_λ is plotted as a function of the energy scale

$$\frac{dA_\lambda}{dt} \approx \frac{\lambda}{16\pi^2}\left[6y_t A_t + 6y_b A_b + 2A_\tau y_\tau + 6(A_{k_1}k_1 + A_{k_2}k_2 + A_{k_3}k_3)\right]$$

$$t = \log\frac{M_X}{M_Z}$$

Results

The particle spectrum :
$v_s = 2261.72$, $tan(\beta) = 4.23$, $\lambda = 0.329309$, $g_4 = 0.1109$, $M_x = 97.147\,TeV$, $\kappa_1 = 0.1754$, $\kappa_2 = 0.9345$, $\kappa_3 = 0.3909$

Parameter	mass(GeV)	Parameter	mass(GeV)
$\widetilde{t}_1$	779.94	χ_1^0	250.74
$\widetilde{t}_2$	881.86	χ_2^0	465.16
$\widetilde{b}_1$	849.9	χ_3^0	841.7
$\widetilde{b}_2$	989.99	χ_4^0	846.02
$\widetilde{\tau}_1$	283.883	χ_5^0	1335.86
$\widetilde{\tau}_2$	434.705	χ_6^0	1344.26
h_1^0	127.67	h_2^0	267.52
h_3^0	755.87	A_1^0	370.99
$\chi_2^\pm$	840	$\chi_1^\pm$	166.

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Summary

- mGMSB is solves the flavour problem and it is highly predictable
- mGMSB fails to accommodate 125 GeV Higgs owing to the fact that A-terms are small
- Extensions of GMSB
  - Matter messenger mixing models can give 125 Gev higgs but reintroduces flavor problem
  - In NMSSM electroweak breaking is not possible
- 125 Gev higgs mass can be realized in $G_{SM} \times U(1)_X$, keeping stop masses within LHC reach

$$m_h^2 = 70507.8 \begin{pmatrix} 1.0 & -0.25619 & 0.00740018 \\ -0.25619 & 0.178602 & 0.69263 \\ 0.00740018 & 0.69263 & 7.91098 \end{pmatrix}$$

For $\tan\beta = 3.9, \lambda = 0.33, g_4 = 0.11, A_\lambda = 11.39$

$$m_{h_0}{}^2 \leq M_Z^2 \left[\cos 2\beta^2 + \frac{\lambda^2}{2g^2}\sin 2\beta^2 + \frac{g_4^2}{g^2}(h_1 + h_2 + (h_1 - h_2)\cos 2\beta)^2\right]$$