Exploring Non-Holomorphic Soft Terms in the Framework of GMSB

Samadrita Mukherjee

Department of Theoretical Physics
Indian Association for the Cultivation of Science, Kolkata, India.

(Based on JHEP01(2018)158 by U. Chattopadhyay, D. Das, **SM**)

Planck 2018

Outline

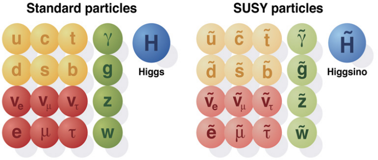
1. Generalized Soft Breaking Sector:
   - Supersymmetry: in its Minimal Model
   - soft terms : where do they come from?
2. The Model : MSSM with Non-Holomorphic soft terms
   - minimal GMSB
   - Non-Holomorphic GMSB
   - Structures of Mass Matrices
3. Numerical Results
   - Impact on Higgs mass and top squark mass
   - Effect of SUSY Breaking Scale
   - Status of low-energy Observables
   - NLSP Decays
4. Summary & Outlook

MSSM : Different parts of Lagrangian

The general form of Lagrangian density :

$$\mathcal{L}_{MSSM} = \mathcal{L}_{SUSY} + \mathcal{L}_{SOFT}$$

$$\mathcal{L}_{SUSY} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_{Higgs-Yukawa}$$



Superpotential (W_{MSSM}) and $\mathcal{L}_{soft}^{MSSM}$ are as follows:

$$W_{MSSM} = \mathbf{y_u} Q \cdot H_u \bar{U} - \mathbf{y_d} Q \cdot H_d \bar{D} - \mathbf{y_e} L \cdot H_d \bar{E} + \mu H_u \cdot H_d$$

$$\begin{aligned}
-\mathcal{L}_{soft}^{MSSM} &= \frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + c.c) \\
&+ (\tilde{q}_{iL} \cdot h_u \mathbf{A_u}_{ij} \tilde{u}^*_{jR} + \tilde{q}_{iL} \cdot h_d \mathbf{A_d}_{ij} \tilde{d}^*_{jR} + \tilde{\ell}_{iL} \cdot h_d \mathbf{A_e}_{ij} \tilde{e}^*_{jR} + h.c.) \\
&+ \tilde{q}^\dagger_{iL} \mathbf{m^2_q}_{ij} \tilde{q}_{jL} + \tilde{\ell}^\dagger_{iL} \mathbf{m^2_l}_{ij} \tilde{\ell}_{jL} + \tilde{u}_{iR} \mathbf{m^2_u}_{ij} \tilde{u}^\dagger_{jR} + \tilde{d}_{iR} \mathbf{m^2_d}_{ij} \tilde{d}^\dagger_{jR} \\
&+ \tilde{e}_{iR} \mathbf{m^2_e}_{ij} \tilde{e}^\dagger_{jR} + m^2_{h_u} h^*_u h_u + m^2_{h_d} h^*_d h_d + (B_\mu h_u . h_d + c.c)
\end{aligned}$$

Possible origin & type of "soft" terms

Nature	Term	order of magnitude	origin
	$\lambda\lambda$	$\frac{F}{M} \sim m_w$	$\frac{1}{M}[XW^{\alpha}W_{\alpha}]_F$
soft	$\phi^*\phi$	$\frac{\|F\|^2}{M^2} \sim m_w^2$	$\frac{1}{M^2}[XX^*\Phi\Phi^*]_D$
	ϕ^2	$\frac{\mu F}{M} \sim m_w$	$\frac{\mu}{M}[X\Phi^2]_F$
	ϕ^3	$\frac{F}{M} \sim m_w$	$\frac{1}{M}[X\Phi^3]_F$

The MSSM Lagrangian is usually claimed to include all possible "soft supersymmetry breaking" terms, i.e. terms which split the masses of the particles and their superpartners, but which do not remove the supersymmetric protection against large radiative corrections to scalar masses.

Possible origin & type of “soft” terms

Nature	Term	order of magnitude	origin
	$\lambda\lambda$	$\frac{F}{M} \sim m_w$	$\frac{1}{M}[XW^{\alpha}W_{\alpha}]_F$
soft	$\phi^*\phi$	$\frac{\|F\|^2}{M^2} \sim m_w^2$	$\frac{1}{M^2}[XX^*\Phi\Phi^*]_D$
	ϕ^2	$\frac{\mu F}{M} \sim m_w$	$\frac{\mu}{M}[X\Phi^2]_F$
	ϕ^3	$\frac{F}{M} \sim m_w$	$\frac{1}{M}[X\Phi^3]_F$

The MSSM Lagrangian is usually claimed to include all possible “soft supersymmetry breaking” terms, i.e. terms which split the masses of the particles and their superpartners, but which do not remove the supersymmetric protection against large radiative corrections to scalar masses.

Are there any more possible soft terms?

Non-Standard symmetry breaking terms

Nature	Term	order of magnitude	origin
	$\phi^2\phi^*$	$\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_w^2}{M}$	$\frac{1}{M^3}[XX^*\Phi^2\Phi^*]_D$
"may be" soft	$\psi\psi$	$\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_w^2}{M}$	$\frac{1}{M^3}[XX^*D^\alpha\Phi D_\alpha\Phi]_D$
	$\lambda\psi$	$\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_w^2}{M}$	$\frac{1}{M^3}[XX^*D^\alpha\Phi W_\alpha]_D$
	ϕ^4	$\frac{F}{M^2} \sim \frac{m_w}{M}$	$\frac{1}{M^2}[X\Phi^4]_F$
"hard"	$\phi^3\phi^*$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_w^2}{M^2}$	$\frac{1}{M^4}[XX^*\Phi^3\Phi^*]_D$
	$\phi^2\phi^{*2}$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_w^2}{M^2}$	$\frac{1}{M^4}[XX^*\Phi^2\Phi^{*2}]_D$
	$\phi\psi\psi$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_w^2}{M^2}$	$\frac{1}{M^4}[XX^*\Phi D^\alpha\Phi D_\alpha\Phi]_D$

[Ref : S. Martin, Phys. Rev D., 2000; Possible non-holomorphic soft SUSY breaking terms]

NH trilinear terms and bilinear Higgsino term:

Nature	Term	order of magnitude	origin
"may be" soft	$\phi^2\phi^*$	$\frac{\|F\|^2}{M^3} \sim \frac{m_w^2}{M}$	$\frac{1}{M^3}[XX^*\Phi^2\Phi^*]_D$
	$\psi\psi$	$\frac{\|F\|^2}{M^3} \sim \frac{m_w^2}{M}$	$\frac{1}{M^3}[XX^*D^\alpha\Phi D_\alpha\Phi]_D$

Taking these terms in account,

$$-\mathcal{L}'^{\phi^2\phi^*}_{soft} \supset \tilde{q}\cdot h_d^*\mathbf{A'_u}\tilde{u}^* + \tilde{q}\cdot h_u^*\mathbf{A'_d}\tilde{d}^* + \tilde{\ell}\cdot h_u^*\mathbf{A'_e}\tilde{e}^* + h.c$$

$$-\mathcal{L}'^{\psi\psi}_{soft} = \mu'\tilde{h_u}\cdot\tilde{h_d}$$

But these interactions are not considered generally....

Let us see why?

High Scale Suppression:

In a hidden sector based SUSY breaking, Non-Holomorphic trilinear terms and bare higgsino mass term go as $\sim \frac{m_W^2}{M}$. M is a high scale, can be as large as Planck Scale.

Reappearance of divergences:

If any of the chiral supermultiplets are singlets under the entire gauge group, these terms may lead to large radiative corrections.

$$\sim \frac{m_X^2}{m_s^2} ln(\frac{m_X^2}{m_s^2})$$

m_s : mass of the singlet field, m_X : mass of some heavy field.

If $m_s << m_X$, then the correction becomes very large. However if $m_s \sim m_X$, then there is no problem.

Let us see why?

High Scale Suppression:

In a hidden sector based SUSY breaking, Non-Holomorphic trilinear terms and bare higgsino mass term go as $\sim \frac{m_W^2}{M}$. M is a high scale, can be as large as Planck Scale.

Reappearance of divergences:

If any of the chiral supermultiplets are singlets under the entire gauge group, these terms may lead to large radiative corrections.

$$\sim \frac{m_X^2}{m_s^2} ln(\frac{m_X^2}{m_s^2})$$

m_s : mass of the singlet field, m_X : mass of some heavy field.

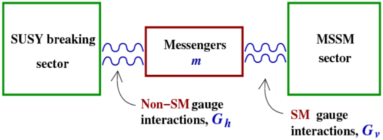
If $m_s << m_X$, then the correction becomes very large. However if $m_s \sim m_X$, then there is no problem.

MSSM contains no singlet under the entire gauge group, so we can always include $\mathcal{L}^{NH}$ & $\mathcal{L}^{\psi\psi}$ with the usual soft terms.

Overview

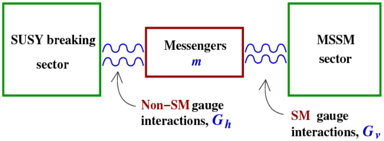
1. Generalized Soft Breaking Sector:
   - Supersymmetry: in its Minimal Model
   - soft terms : where do they come from?
2. The Model : MSSM with Non-Holomorphic soft terms
   - minimal GMSB
   - Non-Holomorphic GMSB
   - Structures of Mass Matrices
3. Numerical Results
   - Impact on Higgs mass and top squark mass
   - Effect of SUSY Breaking Scale
   - Status of low-energy Observables
   - NLSP Decays
4. Summary & Outlook

: Features of GMSB :



$$M_\alpha = \frac{g_\alpha^2}{16\pi^2}\Lambda N_5 \; [1 + O(x^2)]$$
$$m_{\tilde{f}}^2 = 2\Lambda^2 N_5 \sum_\alpha \left(\frac{g_\alpha^2}{16\pi^2}\right)^2 C_\alpha \; [1 + O(x^2)]$$
$$\alpha = 1, 2, 3$$

: Features of GMSB :



$$M_\alpha = \frac{g_\alpha^2}{16\pi^2}\Lambda N_5\ [1 + O(x^2)]$$
$$m_{\tilde{f}}^2 = 2\Lambda^2 N_5 \sum_\alpha \left(\frac{g_\alpha^2}{16\pi^2}\right)^2 C_\alpha\ [1 + O(x^2)]$$
$$\alpha = 1, 2, 3$$

- Flavor blind gauge interactions through Messengers.
- $W_{mess} = \sum \lambda_i S \overline{\Phi}_i \Phi_i,\ i = 1 ... N_m$.
  $S = \langle S \rangle + \theta\theta\langle F \rangle \rightarrow$ creating a mass splitting between scalars and fermions of Φ_i in the Messenger sector. This breaking of SUSY is then communicated to the observable sector via loops.
- The gauginos and sfermions acquire their masses at one loop and two loop order respectively. The loops involve messenger scalar & fermions, gauginos & SM gauge bosons.
- $x_i = |F/\lambda_i S^2|$ for each messenger coupling λ_i and $x_i < 1$ implied. $\Lambda = |\frac{\langle F \rangle}{\langle S \rangle}|$ sets the scale for soft SUSY breaking felt by the low-energy sector. The messenger mass scale $M_{mess} = |\lambda_i \langle S \rangle| \equiv \frac{\Lambda}{x_i}$.

Non-Holomorphic mGMSB (NHmGMSB)

- The trilinear soft SUSY breaking couplings - A terms tend to rise at two loop order. Hence, $A_0 = 0$ at messenger scale.
- For mGMSB the set of free parameters are: $\{\ \Lambda, M_{mess}, \tan\beta, N_5, sgn(\mu)\}$

The mGMSB scenario is augmented with Non-Holomorphic soft breaking terms and a higgsino mass term at messenger scale, i.e. $\tilde{q} \cdot h_d^* A'_u \tilde{u}^*,\ \tilde{q} \cdot h_u^* A'_d \tilde{d}^*,\ \tilde{\ell} \cdot h_u^* A'_e \tilde{e}^*$ and $\mu' \tilde{h}_u . \tilde{h}_d$

- Like holomorphic trilinear ones, the NH trilinear couplings $A'_{t,b,\tau}$ also arise at two loop level. Hence, $A'_0 = 0$ at the messenger scale.
- With an additional free parameter at M_{mess}, NHmGMSB can be realized with the following set of free parameters: $\{\ \Lambda, M_{mess}, \tan\beta, N_5, sgn(\mu), \mu'\}$.
- We are considering μ' from a phenomenological standpoint. μ' can take both positive and negative values.

Structures of Mass Matrices: Scalars & Electroweakinos

$$squarks = M^2_{\tilde{u}} = \begin{pmatrix} m^2_{\tilde{Q}_L} + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)M_Z^2\cos 2\beta + m_u^2 & -m_u(A_u - (\mu + A'_u)\cot\beta) \\ -(A_u - (\mu + A'_u)\cot\beta)m_u & m^2_{\tilde{u}} + \frac{2}{3}\sin^2\theta_W M_Z^2 \cos 2\beta + m_u^2 \end{pmatrix}.$$

Similarly for down-type squark and sleptons we have in off-diagonal, $-m_e(A_e - (\mu + A'_e)\tan\beta)$
The Higgs mass up to one loop :

$$m^2_{h,top} = m_Z^2\cos^2 2\beta + \frac{3g_2^2\bar{m}_t^4}{8\pi^2 M_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{\bar{m}_t^2}\right) + \frac{{X'_t}^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{{X'_t}^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right].$$

Here, $X'_t = A_t - (\mu + A'_t)\cot\beta$.

Structures of Mass Matrices: Scalars & Electroweakinos

$$squarks = M_{\tilde{u}}^2 = \begin{pmatrix} m_{\tilde{Q}_L}^2 + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)M_Z^2\cos 2\beta + m_u^2 & -m_u(A_u - (\mu + A_u')\cot\beta) \\ -(A_u - (\mu + A_u')\cot\beta)m_u & m_{\tilde{u}}^2 + \frac{2}{3}\sin^2\theta_W M_Z^2\cos 2\beta + m_u^2 \end{pmatrix}.$$

Similarly for down-type squark and sleptons we have in off-diagonal, $-m_e(A_e - (\mu + A_e')\tan\beta)$
The Higgs mass up to one loop :

$$m_{h,top}^2 = m_Z^2\cos^2 2\beta + \frac{3g_2^2\bar{m}_t^4}{8\pi^2 M_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{\bar{m}_t^2}\right) + \frac{X_t'^2}{m_{\tilde{t}_1}m_{\tilde{t}_2}}\left(1 - \frac{X_t'^2}{12m_{\tilde{t}_1}m_{\tilde{t}_2}}\right)\right].$$

Here, $X_t' = A_t - (\mu + A_t')\cot\beta$.
The Neutralino & Chargino mass matrices are,

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -(\mu+\mu') \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -(\mu+\mu') & 0 \end{pmatrix}.$$

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2}M_W\sin\beta \\ \sqrt{2}M_W\cos\beta & (\mu+\mu') \end{pmatrix}.$$

Overview

Interplay between Higgs boson and top squark:

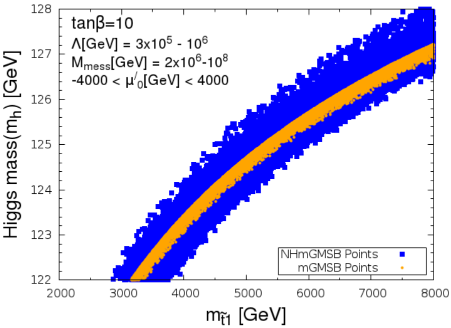
Uniform random scan over : $\{\Lambda, M_{mess}, \mu'\}$ for two fixed values of $\tan\beta$.

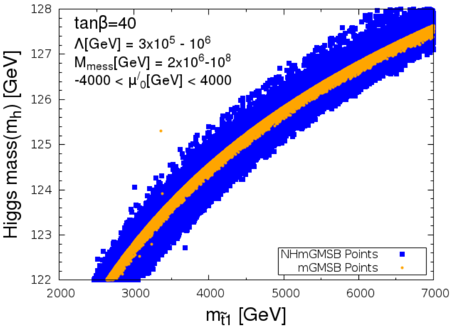
$$3.0 \times 10^5 \text{ GeV} \leqslant \Lambda \leqslant 1.2 \times 10^6 \text{ GeV}, \quad 2 \times 10^6 \text{ GeV} \leqslant M_{mess} \leqslant 10^8 \text{ GeV}$$

$$N_5 = 1, \quad \tan\beta = 10 \text{ and } 40, \quad A_0' = 0$$

$$\mu > 0, \quad -4000 \text{ GeV} \leqslant \mu' \leqslant 4000 \text{ GeV}$$

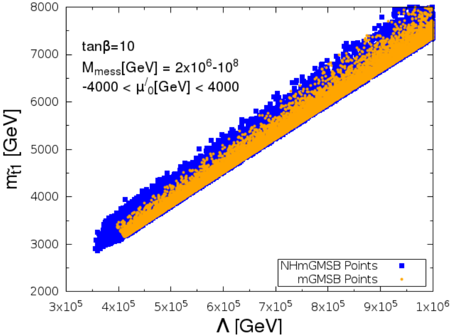
The **blue** and **orange** coloured regions correspond to NHSSM and MSSM spectra respectively.

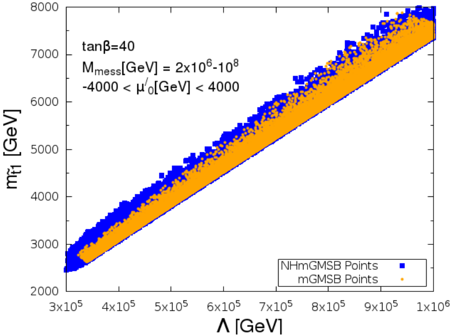




Λ dependence

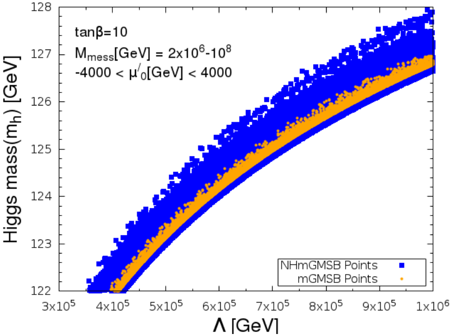
Scatter plot of the lighter Stop mass with Λ for $\tan\beta = 10$ & 40. All the scalar mass parameters as well as gaugino mass parameters are proportional to Λ in this model. A_t' can be obtained at the EWSB scale. With RGE running we get,
$-550\ (-600)$ GeV $\leqslant A_t' \leqslant 550\ (600)$ GeV for $\tan\beta = 10\ (40)$.
Color coding is same of the previous figure.

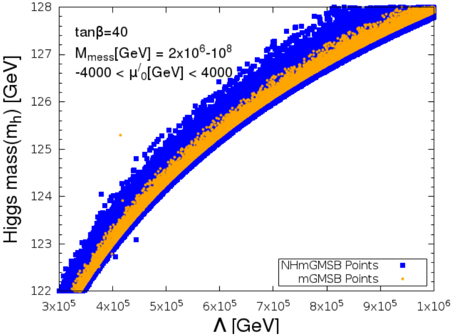




Λ dependence

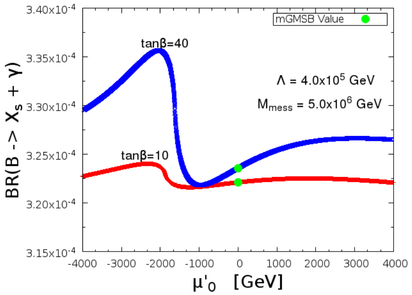
Figures represent the dependence of Higgs mass with the SUSY breaking scale Λ. NH terms help to get a rise $\sim 0.7 - 1.0$ GeV in Higgs mass for a particular value of Λ over mGMSB spectrum for $\tan\beta = 10$. For $\tan\beta = 40$ we obtain a 0.5 GeV lift in Higgs Mass for any given Λ.





Parametric variation of Br($B \to X_s + \gamma$):

In SM : dominant contribution is from t-W loops. For MSSM : $t - H^{\pm}$ and $\tilde{t} - \tilde{\chi}^{\pm}$ loops contribute significantly.
Analytical dependence is like - $Br(B \to X_s + \gamma) \sim \mu A_t \tan\beta f(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, m^2_{\tilde{\chi}^{\pm}})$.
Up & down type higgsino mixing involves $\mu + \mu'$,
stop left-right mixing $\to (A_t - (\mu + A'_t)\cot\beta)$.



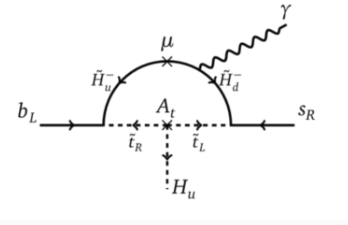
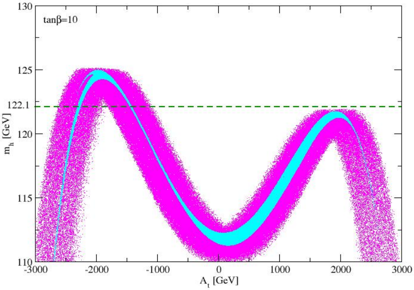


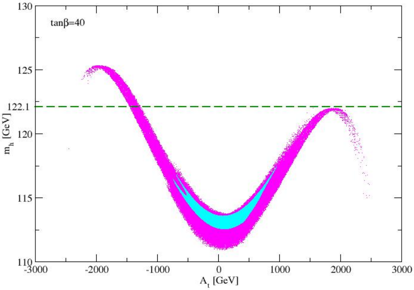
Figure : $b \to s + \gamma$ loop relevant to this discussion

Imposing $Br(B \to X_s + \gamma)$ constraints after Higgs mass in pMSSM:

- Essentially unaltered scenario for $\tan\beta = 10$.
- for $\tan\beta = 40$, $Br(B \to X_s + \gamma)$ constraints always take away large A_t zones of **MSSM**.
- A'_t recovers the discarded area via L-R mixing of top squarks in **NHSSM**.
- $Br(B_s \to \mu^+\mu^-)$ constraints are not so important once $Br(B \to X_s + \gamma)$ is considered.
  - $2.99 \leqslant Br(B \to X_s + \gamma) \times 10^4 \leqslant 3.87$ (2σ).

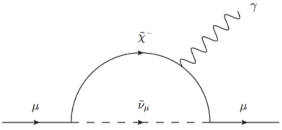
Ref : arXiv [hep-ph] : 1604.06367

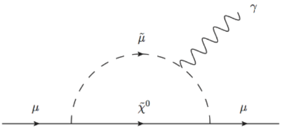




Results of $(g-2)_\mu$:

Long standing deviation ($\sim 3.7\sigma$) from SM : $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (27.0 \pm 7.3) \times 10^{-10}$.
One loop contributions come from :





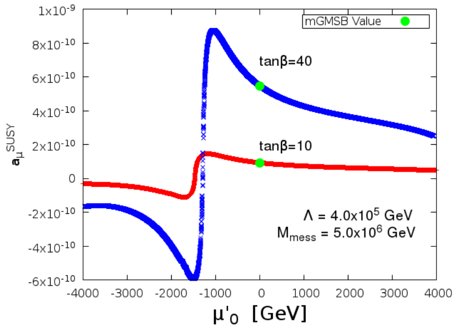
loops involving $(\tilde{\mu}, \tilde{\nu_\mu}, \tilde{\chi}^0, \tilde{\chi}^\pm)$ are important in analyzing the $(g-2)_\mu$ in MSSM.

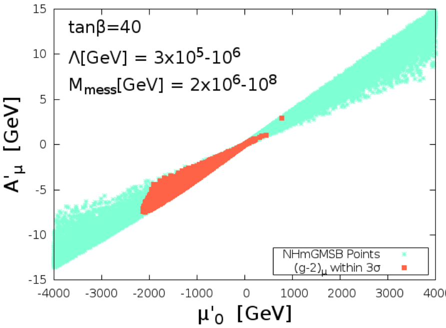
- smuon left-right mixing in MSSM
  $-m_\mu(A_\mu - \mu \tan\beta)$
- ✓ smuon left-right mixing in NHSSM
  $-m_\mu(A_\mu - (\mu + A'_\mu)\tan\beta)$

- $\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \propto \tan\beta \, \frac{M_1 \mu}{m^2_{\mu_L} m^2_{\mu_R}}$
  [Ref : 1303.4256 by Endo, Hamaguchi et al.]
- ✓ So, large $\tan\beta$, μ and sizeable smuon left-right mixing can help in enhancing $(g-2)_\mu$.

Results of $(g-2)_\mu$:

Neutralino & chargino masses involve μ' and the effect is clearly seen.
Lighter electroweakino mass $\downarrow \Rightarrow (g-2)_\mu \uparrow$.
As, $A'_0 = 0$ at messenger scale, A'_μ does not get a large value after RGE running.





On the contrary, in phenomenological study of NHSSM, A'_μ is a free parameter. So, it helps in the enhancement of Δa_μ^{SUSY} significantly. $(g-2)_\mu$ is within 1σ range for A'_μ as low as ~ 100 GeV.

$(g-2)_\mu$ in NHSSM :

Blue points are at 1σ, **Green** points are at 2σ, **Brown** points are at 3σ

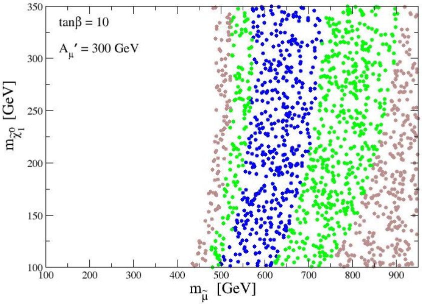
$A'_\mu = 300$ GeV

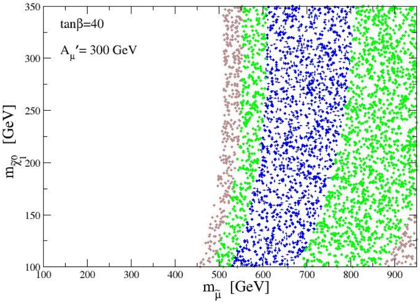
Upper limit of $m_{\tilde{\mu}_1}$ reaches 700 GeV at 1σ at $\tan\beta = 10$

and

800 GeV at 1σ at $\tan\beta = 40$.

(Ref : arXiv [hep-ph] : 1604.06367)





Impact of NH terms on higgsino like NLSP Decays

- **Gravitino** is the lightest supersymmetric particle in GMSB.

The interaction Lagrangian of the gravitino with other sparticles and SM particles:

$$\mathcal{L}_{int} = -\frac{i}{\sqrt{2}M_p}[D_\mu \phi^{*i} \bar{\psi}_\nu \gamma^\mu \gamma^\nu \chi_L^i - D_\mu \phi^i \bar{\chi}_L^i \gamma^\nu \gamma^\mu \psi_\nu] - \frac{i}{8M_p} \bar{\psi}_\mu [\gamma^\rho, \gamma^\sigma] \gamma^\mu \lambda^{(\alpha)a} F_{\rho\sigma}^{(\alpha)a}$$

where,

$$D_\mu \phi^i = \partial_\mu \phi^i + igA_\mu^a T_{aij} \phi^j$$
$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a - gf^{abc} A_\mu^b A_\nu^c$$

Some decay widths of NLSP:

$$\Gamma(\widetilde{\chi}_1^0 \to \widetilde{G}\, Z) \simeq \frac{m_{\widetilde{\chi}_1^0}^5}{96\pi\, m_{\tilde{G}}^2 M_{pl}^2} \left|-N_{13}\cos\beta + N_{14}\sin\beta\right|^2 \left(1 - \frac{m_Z^2}{m_{\widetilde{\chi}_1^0}^2}\right)^4$$

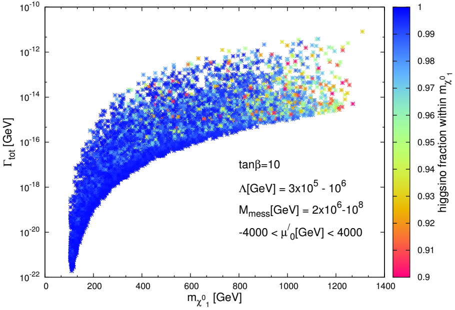
$$\Gamma(\widetilde{\chi}_1^0 \to \widetilde{G}\, h) \simeq \frac{m_{\widetilde{\chi}_1^0}^5}{96\pi\, m_{\tilde{G}}^2 M_{pl}^2} \left|-N_{13}\sin\alpha + N_{14}\cos\alpha\right|^2 \left(1 - \frac{m_h^2}{m_{\widetilde{\chi}_1^0}^2}\right)^4$$

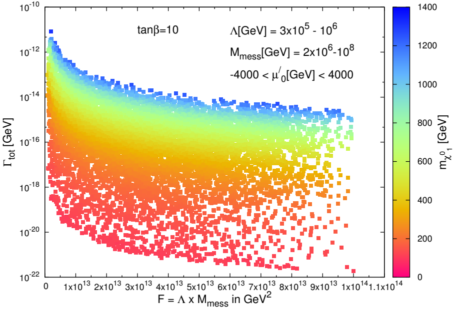
where the gravitino mass is given by, $m_{\tilde{G}} = \frac{\Lambda M_{mess}}{\sqrt{3}M_{Pl}} = \frac{F}{\sqrt{3}M_{pl}}$

Lifetime of NLSP :

$$10^{-22} \leq \Gamma_{tot}\ [\mathrm{GeV}] \leq 10^{-12} \implies 10^{-13} \leq \frac{1}{\Gamma_{tot}}\ [\mathrm{sec}] \leq 10^{-3}$$

$\Gamma_{tot} = \Gamma(\widetilde{\chi}_1^0 \to \widetilde{G} + Z) + \Gamma(\widetilde{\chi}_1^0 \to \widetilde{G} + h)$.





Scatter plot of decay width Γ^{tot} vs. χ_1^0 for a higgsino dominated NLSP over the scanned parameter region. The higgsino fraction is shown in graded color.

Similar scatter plot in the plane of Γ^{tot} vs. $F = \Lambda.M_{mess}$ where the NLSP mass is shown with a reference color bar on the right.

Overview

Final Words

- ✓ We consider most general soft SUSY breaking sector in context of MSSM.
- ✓ Keeping aside any suppression related issues arising out of a given SUSY breaking mechanism,it is interesting to explore non-holomorphic soft SUSY breaking terms in the context of MSSM.
- ✓ In general mGMSB models require large squark masses to radiatively generate Higgs mass from tree level value. Here NH scalar trilinear couplings (mainly A'_t) may relax the requirement.
- ✓ Unlike mGMSB, where NLSP is mostly Bino like, here bilinear higgsino term greatly helps in achieving higgsino like NLSP throughout the canvas.
- ✓ The non-standard soft terms have definite effects on low energy observables (viz : $BR(B \to X_s + \gamma), Br(B_s \to \mu^+\mu^-), (g-2)_\mu$ etc.)

THANK YOU!

Backup Slides : Which mass scale to choose for new soft terms?

Early analyses : Hall and Randall PRL 1990, Jack and Jones PRD 2000; PLB 2004: General analyses with NH terms involving RG evolutions.

- For **Constrained MSSM**, the suppression is of the order of
  $$M_{GUT} = 10^{16}\ \mathrm{GeV}.$$
  So, $\phi^2\phi^*$ and $\psi\psi$ soft terms are suppressed in supergravity scenario. [Graham Ross, K. Schimdt-Hoberg, F. Staub: Phys.Lett. B759 (2016) & JHEP 1703 (2017) 021]

✓ If the SUSY breaking effect is communicated at a lower energy, then such suppression weakens.
  This is the case with **Gauge Mediated Supersymmetry Breaking**.

✓ One can also work in entirely **EW scale input parameters**, in an unbiased approach.
  [U Chattopadhyay, Abhishek Dey : JHEP 1610 (2016) 027]

- Some studies have been done with NH terms in electroweak scale, but otherwise mass spectra was generated under minimal supergravity (mSUGRA). [Solmaz et. al. PRD 2005, PLB 2008, PRD 2015.]

Back up slides : **Mass generation of gauginos and scalars in GMSB**

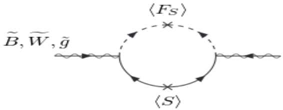


Figure : Contributions to the MSSM gaugino masses in GMSB models come from one loop graphs involving virtual messenger particles

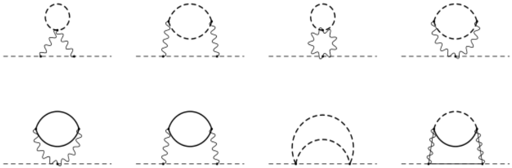


Figure : MSSM scalar squared masses in GMSB models arise in leading order from two loop graphs. The heavy dashed lines are messenger scalars, the solid lines are messenger fermions, the wavy lines are ordinary SM gauge bosons, and the solid lines with wavy lines superimposed are MSSM gaugions.

A separate higgsino mass term !!

- MSSM Superpotential already contains $\mu H_u \cdot H_d$. This term gives masses to both Higgs and higgsinos.

Then the presence of $\mu' \tilde{h_u} \cdot \tilde{h_d}$ is questionable. There exists a reparametrization invariance in $\mathcal{L}$ between μ' and other soft terms: $\mathcal{L} \supset (\mu + \mu')\tilde{h_1}\tilde{h_2} + (\mu^2 + m^2_{h_1})|h_1|^2 + (\mu^2 + m^2_{h_2})|h_2|^2$

$$\mu \to \mu + \delta$$
$$\mu' \to \mu' - \delta$$
$$m^2_{h_{1/2}} \to m^2_{h_{1/2}} - 2\mu\delta + \delta^2$$

A reparametrization would however involve ad-hoc correlations between unrelated parameters. [Jack and Jones 1999, Hetherington 2001 etc.]

✓ **Higgs scalar potential depends on μ but is independent of μ'.**
So, the bilinear higgsino mass term is important in light of fine tuning. This term sequesters fine-tuning ($\Delta_\mu = \frac{\mu^2}{M_z^2}$) from higgsino mass term ($\mu + \mu'$).

In particular, there may be scenarios where definite SUSY breaking mechanisms generate bilinear higgsino mass terms whereas it may keep the scalar sector sequestered. [Graham G. Ross et. al. 2016, 2017, Antoniadis et. al. 2008, Perez et. al. 2008 etc] .

Back up Slides : $b \to s + \gamma$ diagrams

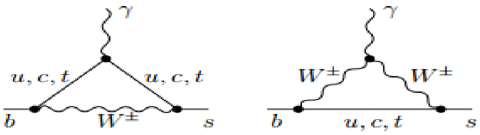


Figure : Leading order Feynman diagram for $b \to s + \gamma$ transition in Standard Model

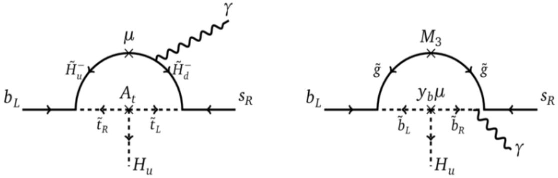
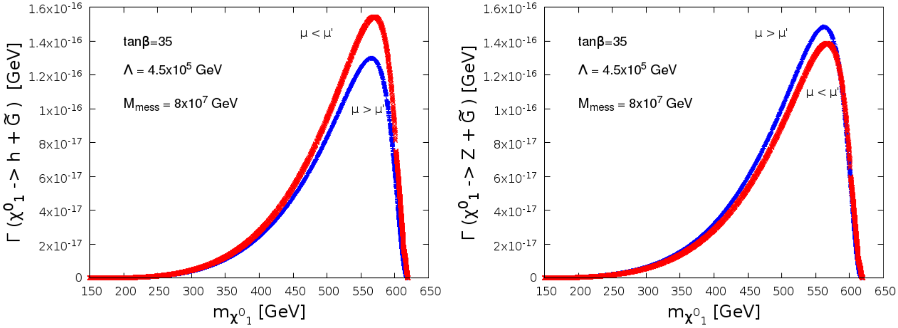


Figure : Diagrams contributing in $b \to s + \gamma$ process in SUSY theories.

Apart from this we also have diagrams with charged Higgs($H^{\pm}$) similar to SM diagrams. But those are not special for our

Decay width vs. neutralino mass

$m_{\tilde{\chi}_1^0}$ is a function of $\mu + \mu'$. Hence decay widths of $m_{\tilde{\chi}_1^0}$ also have a strong effect on that. $M_1 = 630$ GeV. So the neutralino is dominantly higgsino like upto say 500 GeV. Decay width increases rapidly in magnitude compared to the 200-300 GeV mass of the same.



Two peaks at same mass !!

The two peaks appear as a result of $\mu < |\mu'|$ and $\mu > |\mu'|$.
For our analysis, $Sgn(\mu)$ is fixed $\mu \sim 1500 - 1600$ GeV. But $m_{\tilde{\chi}_1^0}$ being $|\mu + \mu'|$ is the same for same $|\mu'|$.

Two peaks at same mass !!

The two peaks appear as a result of $\mu < |\mu'|$ and $\mu > |\mu'|$.
For our analysis, $Sgn(\mu)$ is fixed $\mu \sim 1500 - 1600$ GeV. But $m_{\tilde{\chi}_1^0}$ being $|\mu + \mu'|$ is the same for same $|\mu'|$.

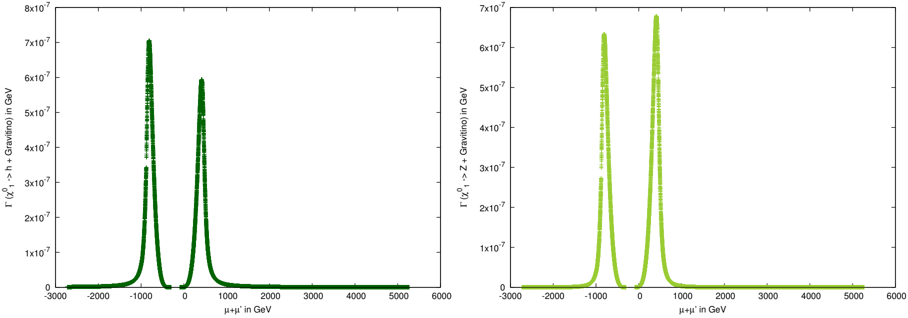


Figure : The decay widths for $\Gamma(\widetilde{\chi}_1^0 \to \widetilde{G} + h)$ and $\Gamma(\widetilde{\chi}_1^0 \to \widetilde{G} + Z)$ as a function of $\mu + \mu'$.

Why two distinct peak? Same mass but different height !!

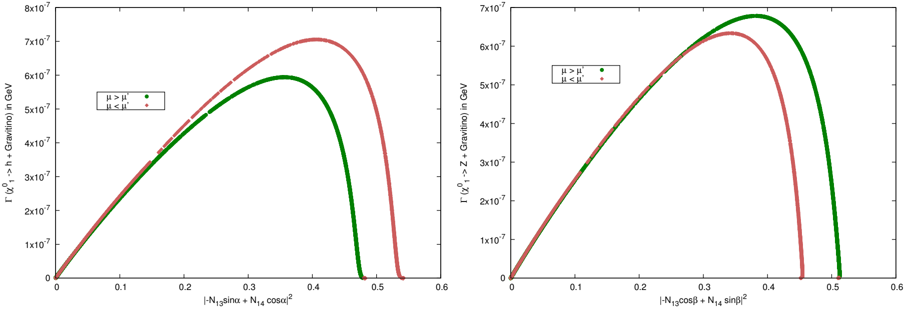


Figure : The decay widths for $\Gamma(\widetilde{\chi}_1^0 \rightarrow \widetilde{G} + h)$ and $\Gamma(\widetilde{\chi}_1^0 \rightarrow \widetilde{G} + Z)$ as a function of the vertex factor. It involves neutralino mixing matrix. Specifically N_{13} plays the role. For the heigher peak N_{13} is positive for $\Gamma(\widetilde{\chi}_1^0 \rightarrow \widetilde{G} + Z)$ & negative for $\Gamma(\widetilde{\chi}_1^0 \rightarrow \widetilde{G} + h)$ decay.

RGE equations for NH trilinear coupling:

$$\beta^{(1)}_{T'_u} = +3T'_u Y_d^\dagger Y_d + T'_u Y_u^\dagger Y_u + 2Y_u Y_d^\dagger T'_d - 4\mu' Y_u Y_d^\dagger Y_d + 2Y_u Y_u^\dagger T'_u$$
$$- \frac{6}{5} Y_u \Big(\big(5g_2^2 + g_1^2\big)\mu' - 5\mathrm{Tr}\big(T'_u Y_u^\dagger\big)\Big)$$
$$+ T'_u \Big(3\mathrm{Tr}\big(Y_d Y_d^\dagger\big) - \frac{4}{15}\big(20g_3^2 + g_1^2\big) + \mathrm{Tr}\big(Y_e Y_e^\dagger\big)\Big) \tag{1}$$

$$\beta^{(2)}_{T'_u} = 0 \tag{2}$$

$$\beta^{(1)}_{T'_d} = +T'_d Y_d^\dagger Y_d + 3T'_d Y_u^\dagger Y_u + 2Y_d Y_d^\dagger T'_d + 2Y_d Y_u^\dagger T'_u - 4\mu' Y_d Y_u^\dagger Y_u$$
$$+ Y_d \Big(2\mathrm{Tr}\big(T'_e Y_e^\dagger\big) + 6\mathrm{Tr}\big(T'_d Y_d^\dagger\big) - \frac{6}{5}\big(5g_2^2 + g_1^2\big)\mu'\Big)$$
$$+ \frac{1}{15} T'_d \Big(2g_1^2 + 45\mathrm{Tr}\big(Y_u Y_u^\dagger\big) - 80g_3^2\Big) \tag{3}$$

$$\beta^{(2)}_{T'_d} = 0 \tag{4}$$

$$\beta^{(1)}_{T'_e} = +T'_e Y_e^\dagger Y_e + 2Y_e Y_e^\dagger T'_e + Y_e \Big(2\mathrm{Tr}\big(T'_e Y_e^\dagger\big) + 6\mathrm{Tr}\big(T'_d Y_d^\dagger\big) - \frac{6}{5}\big(5g_2^2 + g_1^2\big)\mu'\Big)$$
$$+ T'_e \Big(3\mathrm{Tr}\big(Y_u Y_u^\dagger\big) - \frac{6}{5} g_1^2\Big)$$

$$\beta^{(2)}_{T'_e} = 0 \tag{5}$$

RGE equation for Bilinear higgsino term:

$$\beta_{\mu'}^{(1)} = 3\mu'\mathrm{Tr}\Big(Y_d Y_d^\dagger\Big) - \frac{3}{5}\mu'\Big(5g_2^2 - 5\mathrm{Tr}\Big(Y_u Y_u^\dagger\Big) + g_1^2\Big) + \mu'\mathrm{Tr}\Big(Y_e Y_e^\dagger\Big) \tag{6}$$

$$\begin{aligned}\beta_{\mu'}^{(2)} = \frac{1}{50}\mu'\Big(&207g_1^4 + 90g_1^2g_2^2 + 375g_2^4 - 20\Big(-40g_3^2 + g_1^2\Big)\mathrm{Tr}\Big(Y_d Y_d^\dagger\Big)\\ &+ 60g_1^2\mathrm{Tr}\Big(Y_e Y_e^\dagger\Big) + 40g_1^2\mathrm{Tr}\Big(Y_u Y_u^\dagger\Big)\\ &+ 800g_3^2\mathrm{Tr}\Big(Y_u Y_u^\dagger\Big) - 450\mathrm{Tr}\Big(Y_d Y_d^\dagger Y_d Y_d^\dagger\Big) - 300\mathrm{Tr}\Big(Y_d Y_u^\dagger Y_u Y_d^\dagger\Big)\\ &- 150\mathrm{Tr}\Big(Y_e Y_e^\dagger Y_e Y_e^\dagger\Big) - 450\mathrm{Tr}\Big(Y_u Y_u^\dagger Y_u Y_u^\dagger\Big)\Big)\end{aligned} \tag{7}$$