# Effect of Non-Holomorphic Soft Interactions on Supersymmetry Phenomenology

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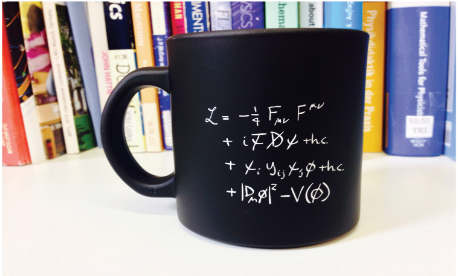
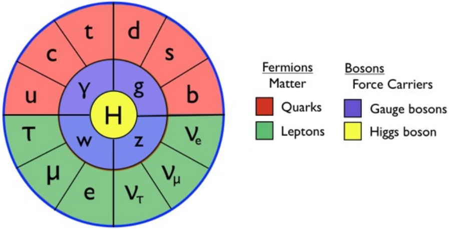
Based on **JHEP10(2018)202** & **JHEP01(2018)158**

**Kavli IPMU, Kashiwanoha, Japan**

# Outline

# Cheers to Standard Model ☺!

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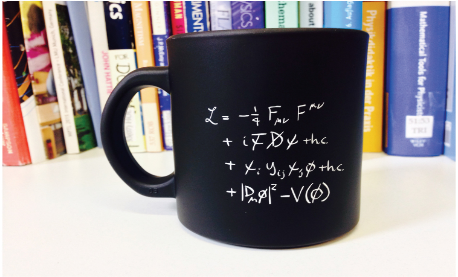


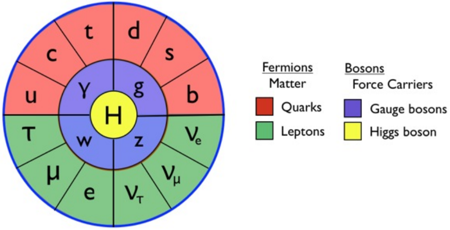


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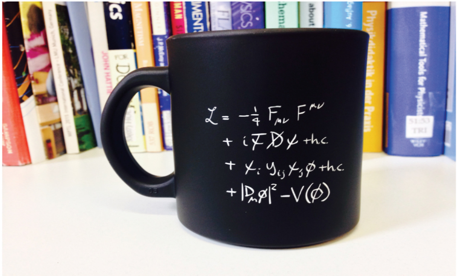
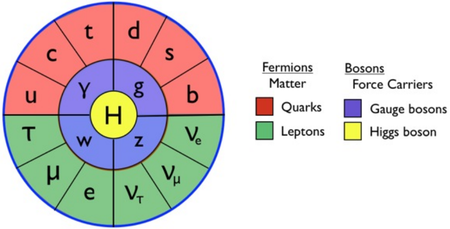
- ✓ **Higgs boson**
- ✓ **W & Z bosons**
  - ✓ **Various decay channels of Z bosons.**
- ✓ **charm & top quark**
- ✓ **gluon**

# Cheers to Standard Model 🙂!

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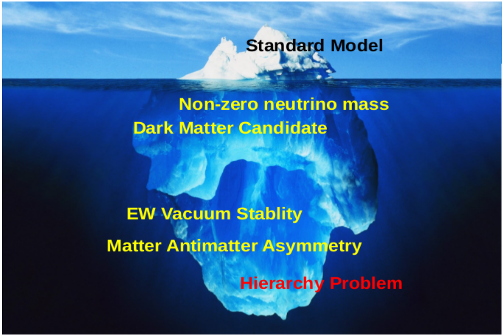
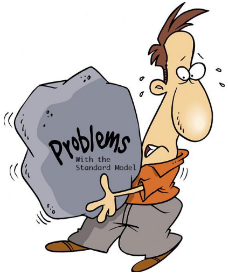
But, Beyond Standard Model Particle Physics is going a long way to explain many more "why"!!

# Still there are some concerns :




- ✗ Interactions between Higgs & SM particles tend to make the Higgs very heavy.
- ✗ Neutrinos are massless.
- ✗ No viable dark matter particle candidate.
- ✗ Matter-Antimatter asymmetry.
- ✗ EW vacuum stability and criticality.

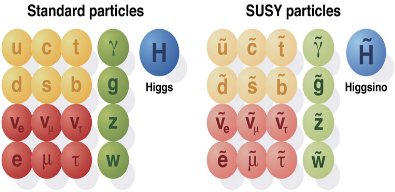
# Overview

# 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** :

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

$$\begin{aligned}
-\mathcal{L}_{soft}^{MSSM} = {} & \frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + c.c) \\
& + (\tilde{q}_{iL} \cdot h_u \mathbf{A_u}_{ij} \tilde{u}_{jR}^* + \tilde{q}_{iL} \cdot h_d \mathbf{A_d}_{ij} \tilde{d}_{jR}^* + \tilde{\ell}_{iL} \cdot h_d \mathbf{A_e}_{ij} \tilde{e}_{jR}^* + h.c.) \\
& + \tilde{q}_{iL}^\dagger \mathbf{m_q^2}_{ij} \tilde{q}_{jL} + \tilde{\ell}_{iL}^\dagger \mathbf{m_l^2}_{ij} \tilde{\ell}_{jL} + \tilde{u}_{iR} \mathbf{m_u^2}_{ij} \tilde{u}_{jR}^\dagger + \tilde{d}_{iR} \mathbf{m_d^2}_{ij} \tilde{d}_{jR}^\dagger \\
& + \tilde{e}_{iR} \mathbf{m_e^2}_{ij} \tilde{e}_{jR}^\dagger + m_{h_u}^2 h_u^* h_u + m_{h_d}^2 h_d^* h_d + (B_\mu h_u . h_d + c.c)
\end{aligned}$$

# Possible origin & type of "soft" terms

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.

| Nature | Term | order of magnitude | origin |
|---|---|---|---|
| | $\lambda\lambda$ | $\frac{F}{M} \sim m_w$ | $\frac{1}{M}[XW^{\alpha}W_{\alpha}]_F$ |
| soft | $\phi^*\phi$ | $\frac{\lvert F\rvert^2}{M^2} \sim m_w^2$ | $\frac{1}{M^2}[XX^*\Phi\Phi^*]_D$ |
| | $\phi^2$ | $\frac{\mu F}{M} \sim m_w$ | $\frac{\mu}{M}[X\Phi^2]_F$ |
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**Are there any more possible soft terms?** **[Ref : S. Martin, Phys. Rev D., 2000; Possible non-holomorphic soft SUSY breaking terms]**

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

# NH trilinear terms and bilinear Higgsino term:

Taking these terms in account,

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

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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.

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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.

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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.

# Which mass scale to choose for new soft terms?

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  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]

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✓ One can also work in entirely **EW scale input parameters**, in an unbiased approach.
[UC, A Dey : JHEP 1610 (2016) 027 & UC, AD, SM, AKS : JHEP10(2018)202]

- 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.]

## 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, $-m_d(A_d - (\mu + A'_d)\tan\beta)$
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, $X'_t = A_t - (\mu + A'_t)\cot\beta$.
The Neutralino & Chargino mass matrices are,

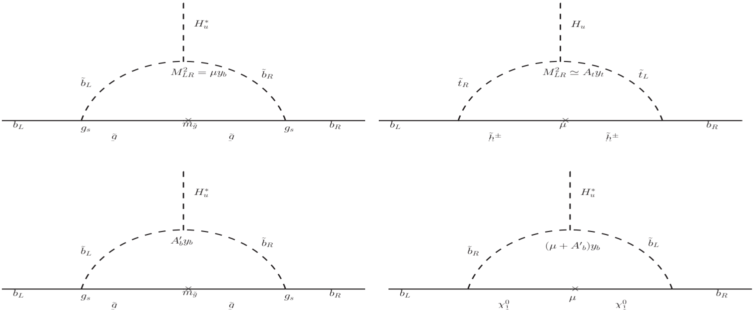
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -(\mu+\mu') \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -(\mu+\mu')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

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

# Overview

# Non-trivial contributions through $y_b$

✓ $y_b$ has the usual dependence on $\tan\beta$ as in the MSSM case.



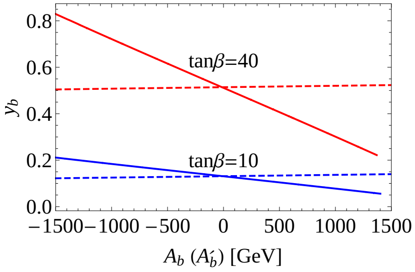

$$\Delta m_b^{(\tilde{g})}{}_{\mathrm{MSSM}} = \frac{2\alpha_3}{3\pi} m_{\tilde{g}} \mu y_b \frac{v_u}{\sqrt{2}} I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{g}}^2); \qquad \Delta m_b^{(\tilde{g})}{}_{\mathrm{NHSSM}} = \frac{2\alpha_3}{3\pi} m_{\tilde{g}} A'_b y_b \frac{v_u}{\sqrt{2}} I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, m_{\tilde{g}}^2),$$

$$\Delta m_b^{\tilde{h}^+}{}_{\mathrm{MSSM}} = \frac{y_t y_b}{16\pi^2} \mu A_t y_t \frac{v_u}{\sqrt{2}} I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2); \qquad \Delta m_b^{\tilde{h}^0}{}_{\mathrm{NHSSM}} = \frac{y_b^2}{16\pi^2} \mu(\mu + A'_b) y_b \frac{v_u}{\sqrt{2}} I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, \mu^2).$$

where, $I(a,b,c) = -\frac{ab\ \ln(a/b) + bc\ \ln(b/c) + ca\ \ln(c/a)}{(a-b)(b-c)(c-a)}$.

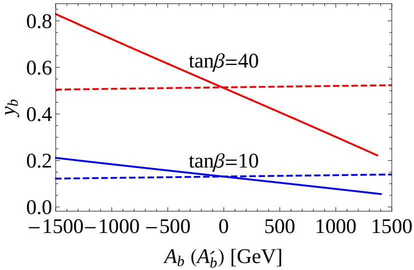
**In NHSSM, $y_b$ becomes a function of $A'_b$ quite similar to** $\tan\beta$ **reliance. Neutralino loop and gluino loop has $A'_b$ dependence.**

# Non-trivial contributions through $y_b$




Variation of $y_b$ as a function of $A_b'$ (NHSSM with $A_b = 0$; bold lines) and $A_b$ (MSSM; broken lines) for $\tan\beta = 10$ (in blue) and for $\tan\beta = 40$ (in red). Some of the fixed input parameters are $\mu = 200$ GeV, $\mu' = 0$, $M_1 = 500$ GeV and $M_2 = 1.1$ TeV.

## Non-trivial contributions through $y_b$

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### $\tilde{b}_i$-$b$-$\tilde{\chi}^0_j$ coupling:

$$C_L = -\frac{i}{6}(-3\sqrt{2}g_2 N^*_{j2} Z^d_{i3} + 6 N_{j3} y_b Z^d_{i6} + \sqrt{2} g_1 N_{j1} Z^d_{i3}$$

$$C_R = -\frac{i}{3}(3 y_b Z^d_{i3} N_{j3} + \sqrt{2} g_1 Z^d_{i6} N_{j1})$$

### $\tilde{b}_i$-$t$-$\tilde{\chi}^-_j$ coupling:

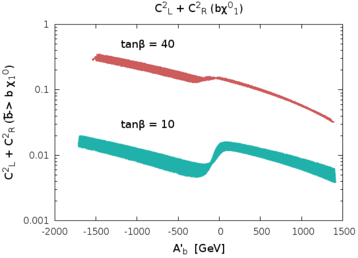
$$C_L = i(y_t Z^d_{i3} V_{j2}),$$

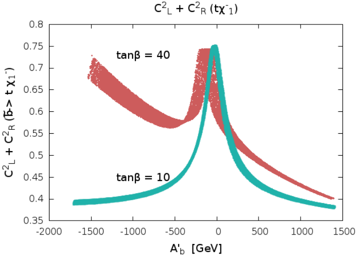
$$C_R = i(-g_2 U^*_{j1} Z^d_{i3} + U^*_{j2} y_b Z^d_{i6})$$

**$N_{ij}, U_{ij}, V_{ij}$ & $Z_{ij}$'s are diagonalizing mass matrices of neutralino, charginos and sbottoms respectively.**

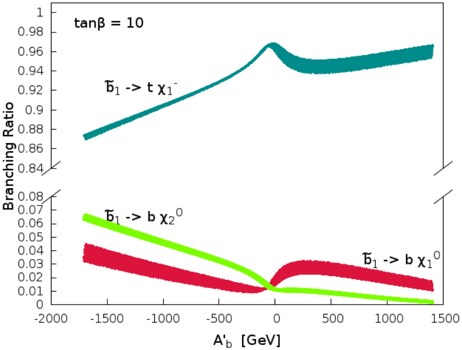
# Features of the couplings:

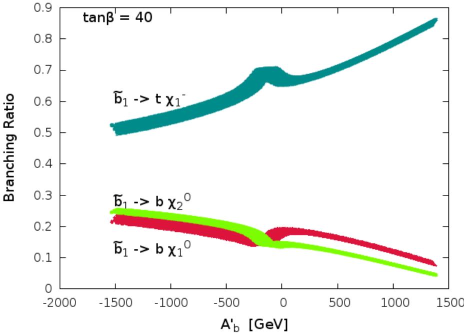
- ✓ Strength of sbottom state to a higgsino-like neutralino is always $\propto y_b$.
- ✓ For top quark and a higgsino-like chargino, it depends on the chiral admixture it possesses. Such a coupling for a left-like sbottom $\propto y_t$ while that for a right-like sbottom $\propto y_b$.
- ✓ A left-like sbottom dominantly decays to $t\tilde{\chi}_1^-$ $\Longrightarrow$ small branching fraction for the $b\tilde{\chi}^0_{1,2}$ final state when $\tilde{\chi}^0_{1,2}$ are both higgsino-dominated and light.
- ★ NHSSM $\Rightarrow$ the presence of a non-vanishing $A'_b$ alters the composition of the sbottom states in a nontrivial way.
- ✗ Another competing decay mode of $\tilde{b}_1$ : $\tilde{b}_1 \to \tilde{t}_1 W^-$ is taken to be kinematically forbidden.
  i.e. $m_{\tilde{b}_1} < m_{\tilde{t}_1} + m_{W^-}$.



# Behaviour of Branching Fractions :



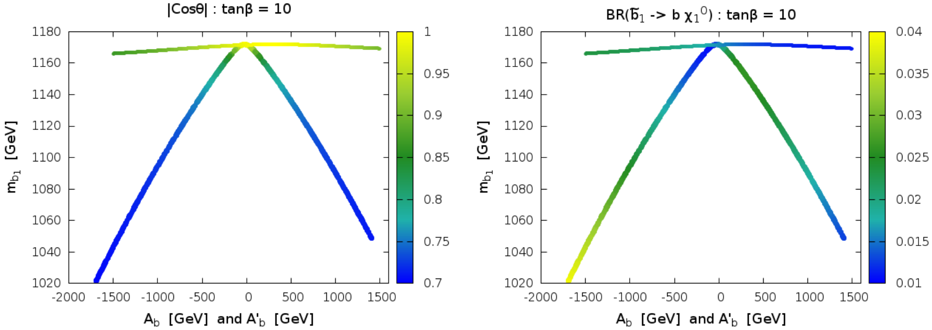

($100 < \mu < 350$ GeV, $M_1 = 500$ GeV, $M_2 = 1000$ GeV.)

Branching fractions of $\tilde{b}_1$ as a function of $A'_b$ follow the same profile of vertex strengths.

# Masses, Mixings and Mass-splittings :

**Higgsino Like LSP**

($\mu = 200$ GeV, $M_1 = 500$ GeV, $M_2 = 1000$ GeV.)

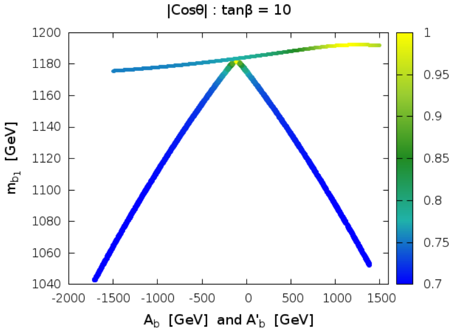


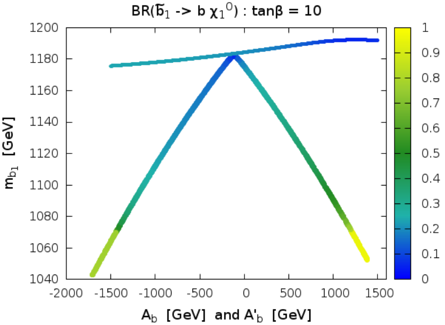

Common Backdrop : The variation of $m_{\tilde{b}_1}$ as a function of $A'_b$ ($A_b$ ) in the NHSSM (MSSM). Flatter lines at the top of these plots illustrate the MSSM. $m_{\tilde{b}_L} = m_{\tilde{b}_R} = 1.2$ TeV. $\cos\theta_{\tilde{b}}$ ranges between $\frac{1}{\sqrt{2}} \approx 0.7$ (maximal mixing) and 1 signifying $\tilde{b}_1$ to be $\tilde{b}_L$ dominated.

# Masses, Mixings and Mass-splittings :

**Gaugino Like LSP**

($\mu = 900$ GeV, $M_1 = 500$ GeV, $M_2 = 1000$ GeV.)




The specific choice of '$\mu$' also ensures that the decay mode $\tilde{b}_1 \to t\tilde{\chi}_1^-$ could be opened or closed depending upon varying $m_{\tilde{b}_1}$ as a function of $A'_b$.

## Masses, mixings and Mass-splittings :

✓ Over the range of variation of $A_b'$, $m_{\tilde{b}_1}$ could vary by $\leq 160$ GeV.

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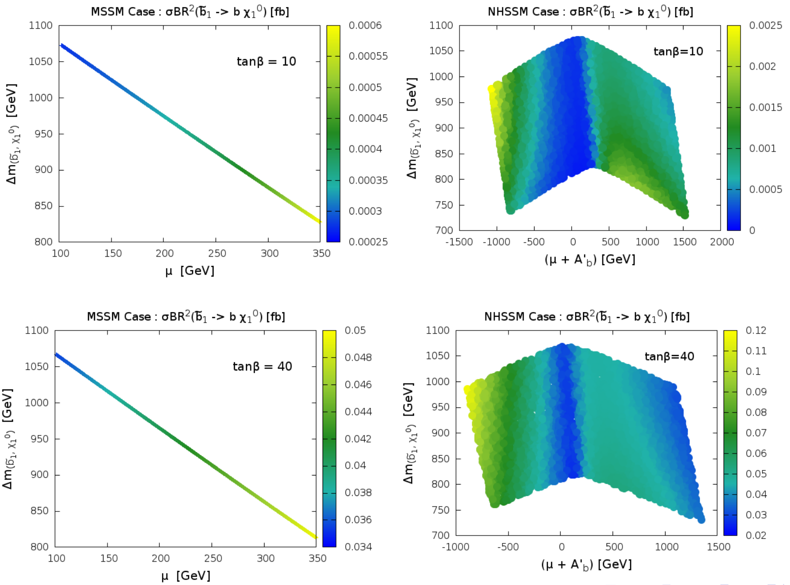
- ✓ Over the range of variation of $A_b'$, $m_{\tilde{b}_1}$ could vary by $\leq 160$ GeV.
- ✓ It is a significant variation : Corresponding number in the MSSM as a $f(A_b)$, reaches at most 20 GeV.
- ★ It may appear that a comparable range of variation in $m_{\tilde{b}_1}$, in the MSSM, could be found just by allowing '$\mu$' to vary over a larger range thereby compensating for the missing $A_b'$. However, this is not correct.

$$
\begin{aligned}
M^2_{\tilde{d}12} &= -m_b(A_b - (\mu + A_b') \tan\beta) \\
&= -m_b(A_b - (\mu_{eff} - \mu' + A_b') \tan\beta) \\
&= -m_b(A_b - (\mu_{eff} - (\mu' - A_b')) \tan\beta)
\end{aligned}
$$

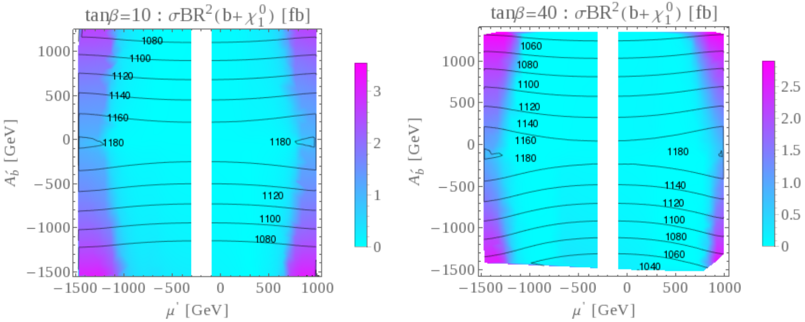
- ✓ The major effect, in the NHSSM, does not come directly from $A_b'$, per se, in the off-diagonal element of the mass-squared matrix. Rather, a significant variation of $y_b$ with $A_b'$, induces such a big change in $m_{\tilde{b}_1}$.

**Signal Strengths** $\Rightarrow$ Parton level yields: $pp \to \tilde{b}_1\tilde{b}_1^*$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$, bottom squarks produced in pairs at the LHC and each decaying to a bottom quark and an LSP.



# Effect of $\mu'$ :

Gives rise to a relatively heavier higgsino-like neutralino ($\sim$ 1 TeV) LSP without requiring '$\mu$' to be large.

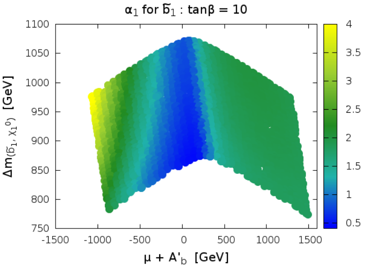


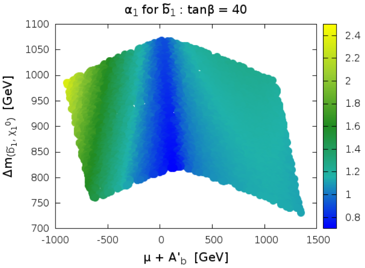

$[\mu = 200$ GeV, $A_b = 0$ with $\tan\beta = 10$ (left) and 40 (right)].

$(\sigma \times \mathrm{BR}^2)$ as a function of $\mu'$ and $A'_b$.

The blank vertical bands in the middle are roughly excluded by searches of the lighter chargino at LEP.

$$\alpha_{\tilde{b}_1} = \frac{(\sigma_{\tilde{b}_1\tilde{b}_1} \times \mathrm{BR}[\tilde{b}_1 \to b\tilde{\chi}_1^0]^2)_{NHSSM}}{(\sigma_{\tilde{b}_1\tilde{b}_1} \times \mathrm{BR}[\tilde{b}_1 \to b\tilde{\chi}_1^0]^2)_{MSSM}}$$

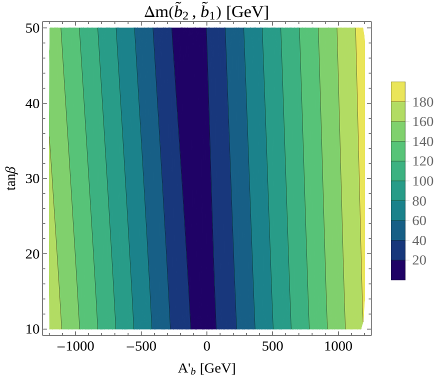



- Up to a four-fold increased rates could be possible over the expected MSSM rates in the final state under consideration.
- The largest deviation is expected for $-A_b'$ for which $y_b$ is much enhanced.
- Variations of $\alpha$ closely mimic that of $\sigma \times \mathrm{BR}^2$ figure
- Finds similar explanations in terms of how the effective interaction strengths vary.

# Role of $\tilde{b}_2$ production:

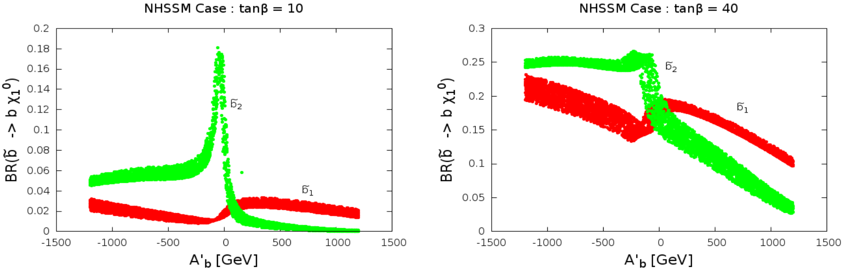
- We consider $m_{\tilde{b}_L}$ & $m_{\tilde{b}_R}$ to be degenerate ($=$ 1200 GeV).
- To check what role could $\tilde{b}_2$ possibly play in the analysis.
- For the ranges of various parameters (like $A'_b$ and $\tan\beta$), $m_{\tilde{b}_1}$ and $m_{\tilde{b}_2}$ may not be too different.
- The mass-split is largely independent of $\tan\beta$.
- For extreme value of $|A'_b|$ (=1200 GeV) in the present analysis, the split between $m_{\tilde{b}_1}$ and $m_{\tilde{b}_2}$ cannot be more than around 170 GeV.




Contours of constant mass-split ($\Delta m_{\tilde{b}_1-\tilde{b}_2}$) between $\tilde{b}_1$ and $\tilde{b}_2$ in the $A'_b$–$\tan\beta$ plane.

# Comparison between BR's of $\tilde{b}_{1,2}$ :

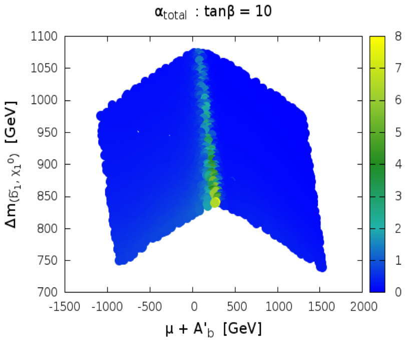
The largest difference - around vanishing $A'_b$ where BR[$\tilde{b}_2 \to b\chi_1^0$] peaks while BR[$\tilde{b}_2 \to b\chi_1^0$] touches the minimum. The phenomenon could be understood in terms of the sharply increasing dominance of $\tilde{b}_R$ in $\tilde{b}_2$ as $|A'_b| \rightsquigarrow 0$. This suppresses BR[$\tilde{b}_2 \to t\chi_1^-$] in favour of BR[$\tilde{b}_2 \to b\chi_1^0$].

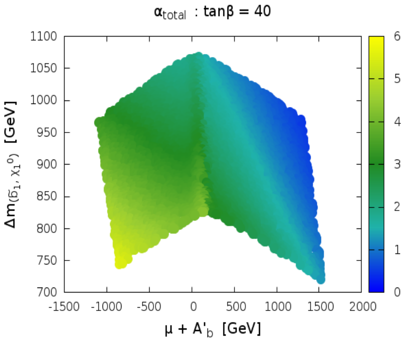



$(100 < \mu < 350$ GeV, $M_1 = 500$ GeV, $M_2 = 1000$ GeV.)

# The Total Relative Rate : $\alpha_{total}$

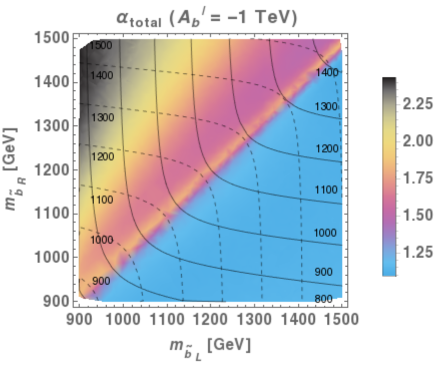
$$\alpha_{total} = \frac{((\sigma_{\tilde{b}_1\tilde{b}_1} \times \mathrm{BR}[\tilde{b}_1 \to b\tilde{\chi}_1^0]^2) + (\sigma_{\tilde{b}_2\tilde{b}_2} \times \mathrm{BR}[\tilde{b}_2 \to b\tilde{\chi}_1^0]^2))_{NHSSM}}{((\sigma_{\tilde{b}_1\tilde{b}_1} \times \mathrm{BR}[\tilde{b}_1 \to b\tilde{\chi}_1^0]^2) + (\sigma_{\tilde{b}_2\tilde{b}_2} \times \mathrm{BR}[\tilde{b}_2 \to b\tilde{\chi}_1^0]^2))_{MSSM}}$$

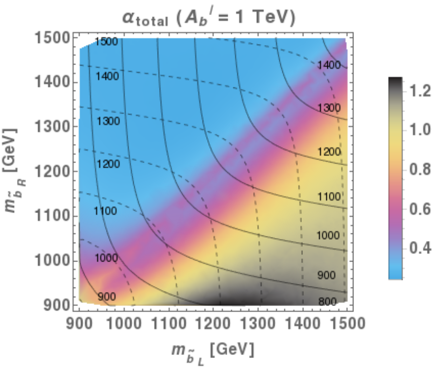



The plots reveal that up to a eight-fold (six-fold) increased rates could be possible for $\tan\beta = 10\,(40)$ over the expected MSSM rates in the final state under consideration.

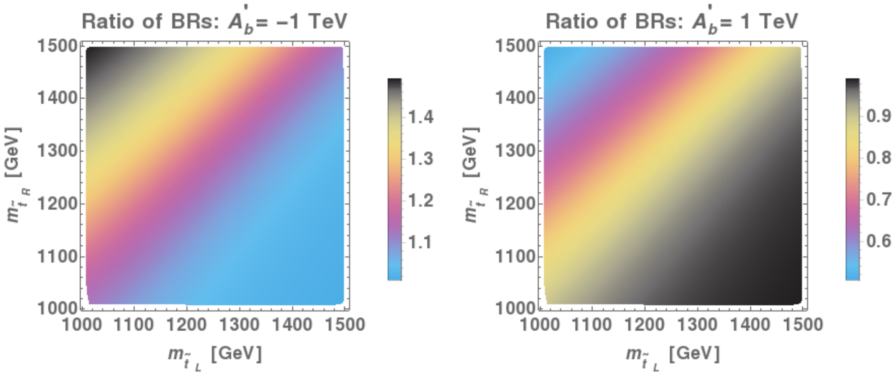
## how the rates would compare when the masses of the sbottoms vary:




$\Rightarrow$ $\alpha_{\rm total}$ in the NHSSM and in the MSSM in the $m_{\tilde{b}_L}$ - $m_{\tilde{b}_R}$ plane for two fixed values of $A'_b$ and for $\tan\beta = 40$. Contours of constant $m_{\tilde{b}_1}$ ($m_{\tilde{b}_2}$) are overlaid with solid (dashed) lines along the right (left) edges of the plots.

# Implication for stop searches:



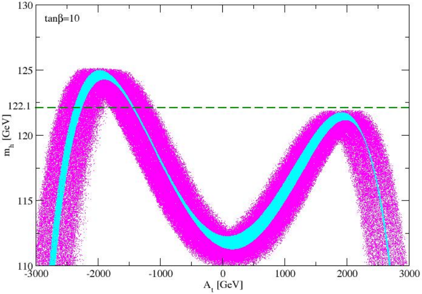

Variations of the ratio of branching fractions for the decay $\tilde{t}_1 \to b\chi_1^+$ in the NHSSM and the MSSM in the $\tilde{t}_L$-$\tilde{t}_R$ plane for $A'_b = \pm 1$ and for fixed values of $\tan\beta$ (=40) and $\mu$ (=200 GeV).

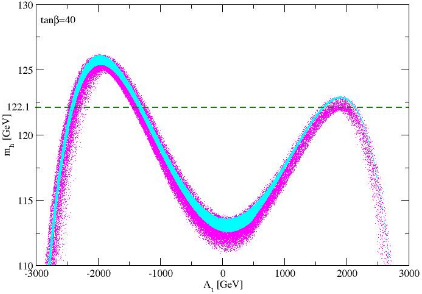
## Impact on Higgs Sector:

**Magenta** points are of **NHSSM** and **Cyan** points are of **MSSM**.

- Off-diagonal term in stop sector : $A_t - (\mu + A'_t) \cot\beta$
- Correct Higgs mass obtained for reasonably smaller $A_t$ for $\tan\beta = 10$.
- Higgs mass affected marginally for $\tan\beta = 40$.
- $10 \leq \mu$ [GeV] $\leq 500$, $-2 \leq \mu'$ [TeV] $\leq 2$, $-3 \leq A'_t$ [TeV] $\leq 3$

Figure courtesy : **JHEP 1610(2016) 027** by UC, A. Dey

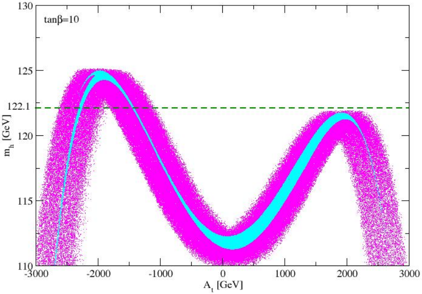


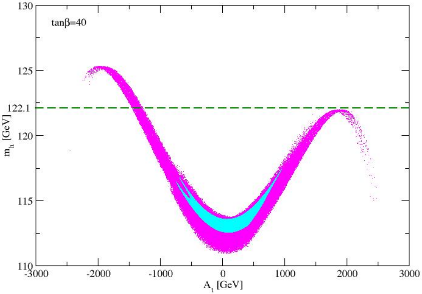



# Imposing $Br(B \to X_s + \gamma)$ constraints after Higgs mass:

- 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.
  - $2.99 \leqslant Br(B \to X_s + \gamma) \times 10^4 \leqslant 3.87$ ($2\sigma$).

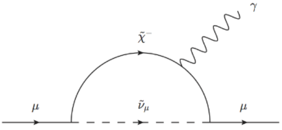
Figure courtesy : **JHEP 1610(2016) 027** by UC, A. Dey

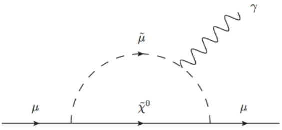


# Results of $(g-2)_\mu$:

Long standing deviation ($\sim 3\sigma$) from SM : $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (29.3 \pm 8) \times 10^{-10}$.
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.

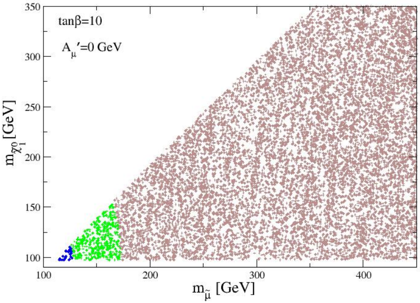
- smuon left-right mixing in MSSM
  $-m_\mu(A_\mu - \mu \tan\beta)$
- ✓ smuon left-right mixing in NHSSM
  $-m_\mu(A_\mu - (\mu + A'_\mu) \tan\beta)$

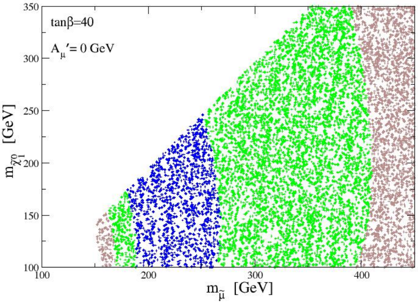
- $\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \propto \tan\beta \, \frac{M_1 \mu}{m^2_{\mu_L} m^2_{\mu_R}}$
  [Ref : 1303.4256 by Endo, Hamaguchi et al.]
- ✓ So, large $\tan\beta$, $\mu$ and sizeable smuon left-right mixing can help in enhancing $(g-2)_\mu$.

# $(g-2)_\mu$ in pMSSM :

Blue points are at $1\sigma$, Green points are at $2\sigma$, Brown points are at $3\sigma$. Only very light smuon can satisfy the muon $g-2$ constraint at $1\sigma$ for $\tan\beta = 10$. The upper limit of smuon mass is about 250 GeV for $\tan\beta = 40$.

$$\underline{A'_\mu = 0 \text{ GeV}}$$



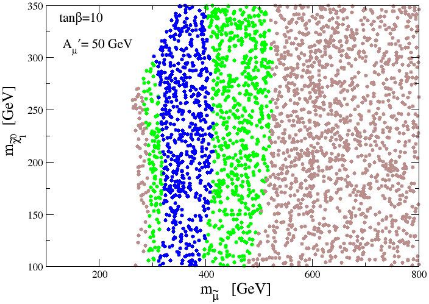
# $(g-2)_\mu$ in NHSSM :

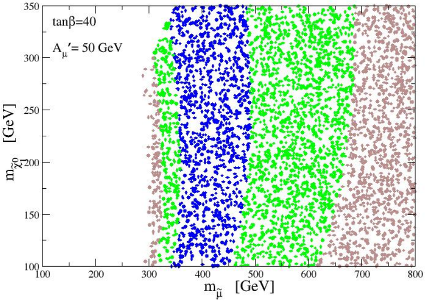
$A'_\mu = 50$ GeV

Upper limit of $m_{\tilde{\mu}_1}$ reaches 400 GeV at $1\sigma$ at $\tan\beta = 10$

and

500 GeV at $1\sigma$ at $\tan\beta = 40$.

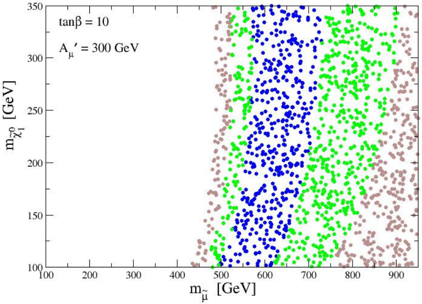


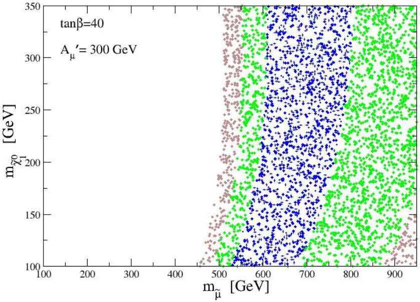



# $(g-2)_\mu$ in NHSSM :

$\underline{A'_\mu = 300 \text{ GeV}}$

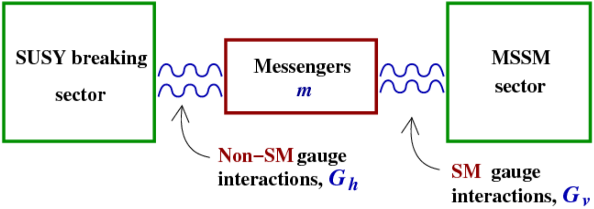
Upper limit of $m_{\tilde{\mu}_1}$ reaches 700 GeV at $1\sigma$ at $\tan\beta = 10$
and
800 GeV at $1\sigma$ at $\tan\beta = 40$.



# Overview

# : Features of GMSB :

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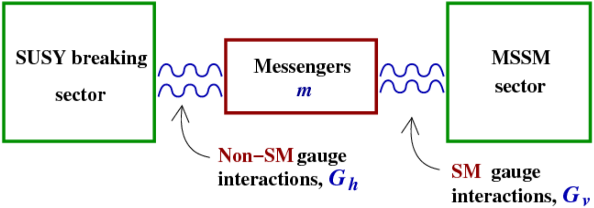


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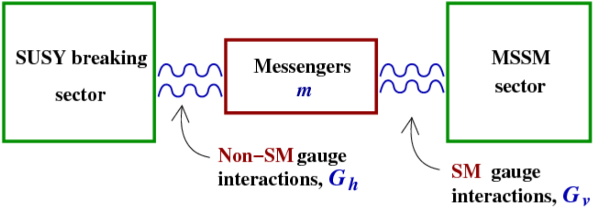



- SUSY breaking effects are communicated to observable sector via usual gauge interactions through Messengers.
- Interactions are flavor-blind.
- $W_{mess} = \sum \lambda_i S \overline{\Phi}_i \Phi_i$, $i = 1 ... N_m$, The scalar and auxiliary components of the chiral superfield S will acquire VEVs, $S = \langle S \rangle + \theta\theta \langle F \rangle \rightarrow$ thereby creating a mass splitting between scalars and fermions of $\Phi_i$ in the Messenger sector. This breaking of SUSY is then communicated to the observable sector via loops.

# Features of GMSB: Continued...

- 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.
  $M_\alpha = \frac{g_\alpha^2}{16\pi^2}\Lambda N_5\ [1 + O(x^2)]$
  $m_{\tilde{f}}^2 = 2\Lambda^2 N_5 \sum_\alpha (\frac{g_\alpha^2}{16\pi^2})^2 C_\alpha\ [1 + O(x^2)] \qquad \alpha = 1, 2, 3$
- $x_i = |F/\lambda_i S^2|$ for each messenger coupling $\lambda_i$ 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 $M_{mess} = |\lambda_i \langle S\rangle| \equiv \frac{\Lambda}{x_i}$.
- 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:
  $\{\ \Lambda, M_{mess}, \tan\beta, N_5, sgn(\mu)\}$

# Non-Holomorphic mGMSB (NHmGMSB)

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 $\mu'$ from a phenomenological standpoint. $\mu'$ can take both positive and negative values.

# Ranges of Scan and Constraints for NHGMSB:

We perform uniform random scan over the following set of free parameters: $\{\Lambda, M_{mess}, \mu'\}$ for two fixed values of $\tan\beta$.

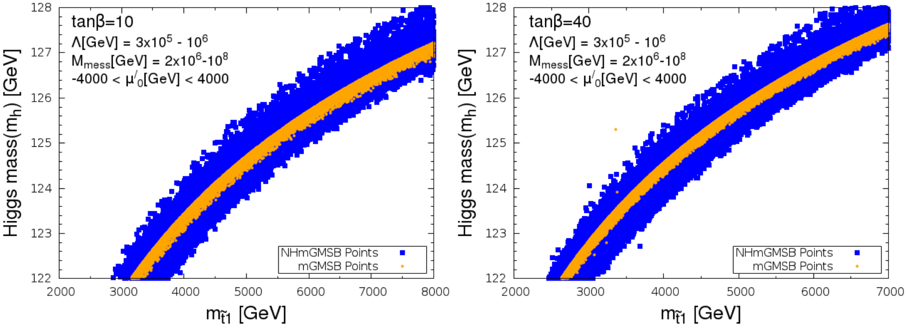
$$3.0 \times 10^5 \text{ GeV} \leqslant \Lambda \leqslant 1.2 \times 10^6 \text{ GeV}$$
$$2 \times 10^6 \text{ GeV} \leqslant M_{mess} \leqslant 10^8 \text{ GeV}$$
$$N_5 = 1$$
$$\tan\beta = 10 \text{ and } 40$$
$$A'_0 = 0$$
$$\mu > 0$$
$$-4000 \text{ GeV} \leqslant \mu' \leqslant 4000 \text{ GeV}$$

Experimental bounds : $122 \text{ GeV} \leqslant m_h \leqslant 128 \text{ GeV}$, $m_{\tilde{\chi}^{\pm}} \geqslant 104 \text{ GeV}$,

$2.99 \leqslant Br(B \to X_s + \gamma) \times 10^4 \leqslant 3.87$ $(2\sigma)$, $1.5 \leqslant Br(B_s \to \mu^+\mu^-) \times 10^9 \leqslant 4.3$ $(2\sigma)$

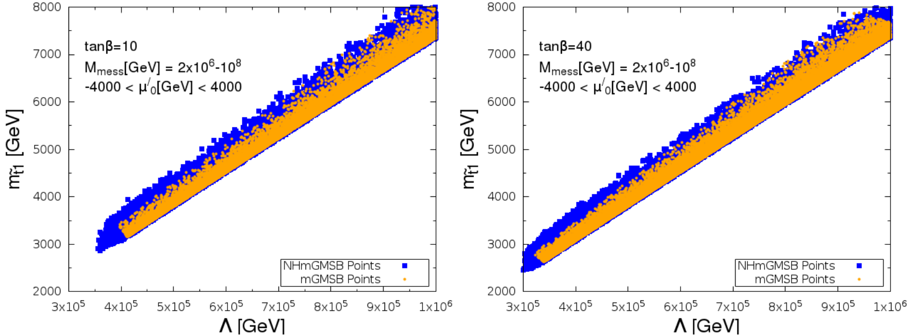
# Interplay between Higgs boson and top squark:

The variation of Higgs mass with stop mass is shown, when $\Lambda$, $M_{mess}$, $\mu'$ are scanned, while $\tan\beta = 10$ & 40. The **blue** and **orange** coloured regions correspond to NHSSM and MSSM spectra respectively.



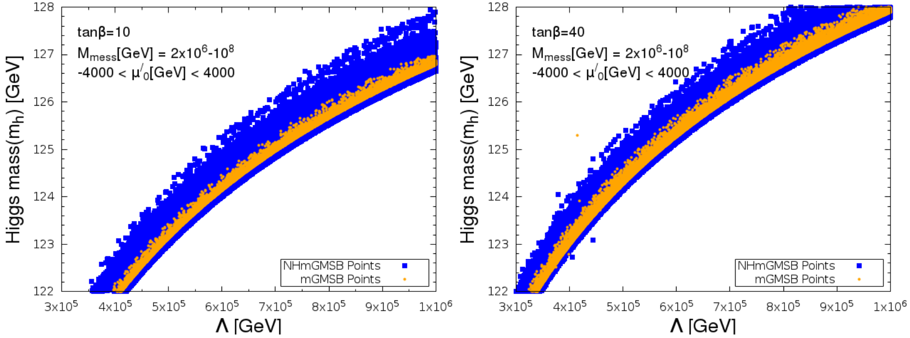
# Λ dependence

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.



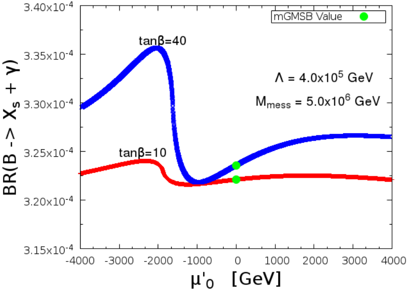
# Λ dependence

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 $\to (A_t - (\mu + A'_t)\cot\beta)$.



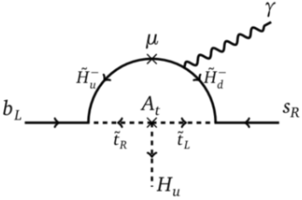
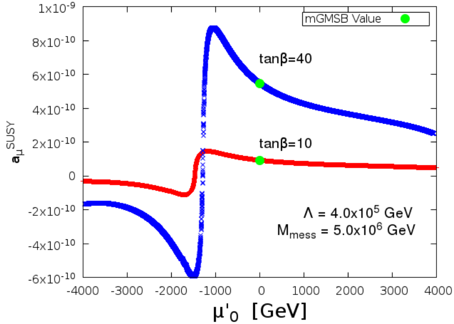
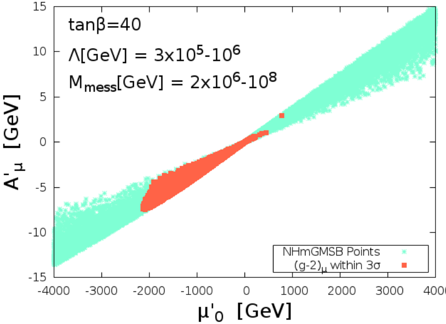




Figure: $b \to s + \gamma$ loop relevant to this discussion

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

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




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

# 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:

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

where,

$$D_\mu \phi^i = \partial_\mu \phi^i + igA^a_\mu T_{aij}\phi^j$$
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - gf^{abc}A^b_\mu A^c_\nu$$

## Some decay widths of NLSP:

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

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

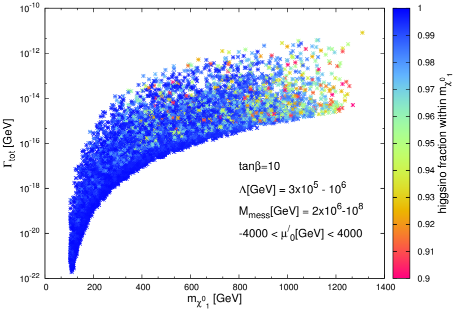
where the gravitino mass is given by, $m_{\tilde{G}} = \frac{\Lambda M_{mess}}{\sqrt{3}M_{Pl}} = \frac{F}{\sqrt{3}M_{pl}}$

# Lifetime of NLSP :

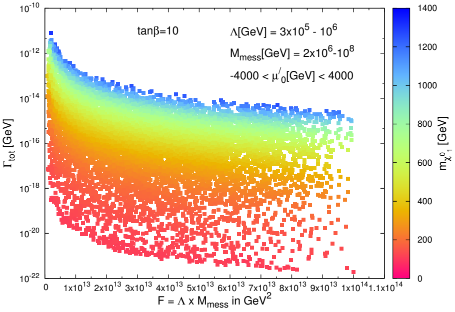
$$10^{-22} \leq \Gamma_{tot}\ [\mathrm{GeV}] \leq 10^{-12} \implies 10^{-13} \leq \frac{1}{\Gamma_{tot}}\ [\mathrm{sec}] \leq 10^{-3}$$

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

(a) Scatter plot of decay width $\Gamma^{\rm tot}$ vs. $\chi_1^0$ for a higgsino dominated NLSP over the scanned parameter region. The higgsino fraction is shown in graded color. (b) Similar scatter plot in the plane of $\Gamma^{\rm tot}$ vs. $F$ where the NLSP mass is shown with a reference color bar on the right.




(c)




(d)

# Overview

# Discussions :-

- In the present work we mostly adopt a scenario in which the SUSY conserving parameter '$\mu$' has a relatively small value ($\leq$ 350 GeV) which help keep the scenario 'natural'.
- The two important classes of non-holomorphic soft terms ($\mu'$ and $A'_i$) appear in the NHSSM Lagrangian
- To extract information about them, one should undertake a precision study of the interactions of the sfermions with the electroweakinos.

✓ An enhanced $y_b$, which is rather characteristic of the NHSSM scenario for large negative $A'_b$ and large $\tan\beta$, could boost the yield in the $2b + \not{E}_T$ final state beyond its MSSM expectation, for similar masses of the lighter sbottom and the LSP.

✓ 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.

✓ A suitably designed multichannel study could turn out to be more efficient in search for a powerful discriminator in the present exercise.

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Back Up 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.]

# 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 $\mu'$ and other soft terms: $\mathcal{L} \supset (\mu + \mu')\tilde{h_1}\tilde{h_2} + (\mu^2 + m^2_{h_1})|h_1|^2 + (\mu^2 + m^2_{h_2})|h_2|^2$

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

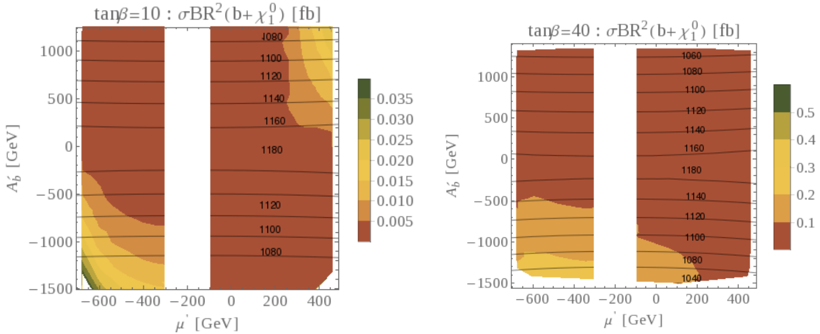
A reparametrization would however involve ad-hoc correlations between unrelated parameters. [Jack and Jones 1999, Hetherington 2001 etc.]

✓ **Higgs scalar potential depends on $\mu$ but is independent of $\mu'$.**
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] .

# Effect of $\mu'$ :

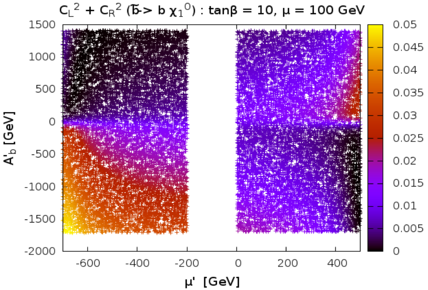
Zoomed-in on the higgsino-like LSP region $\Leftrightarrow$ altering nature of the yield and its extent across the region.

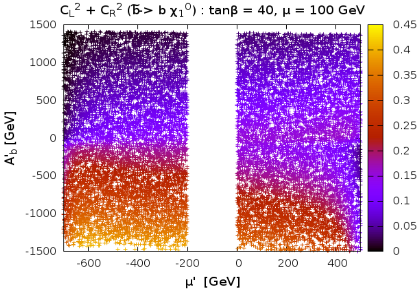



- This can be traced back to similar profile in $C_L^2 + C_R^2$.
- 5 to 7 fold variation in the yield is possible over the indicated range.
- The blank vertical bands in the middle are roughly excluded by searches of the lighter chargino at LEP.

# Effect of $\mu'$ in $C_L^2 + C_R^2$

Zoomed-in on the higgsino-like LSP region ⇔ altering nature of the yield and its extent across the region.




Again the blank vertical bands in the middle are roughly excluded by searches of the lighter chargino at LEP.

# RGE equations for NH trilinear coupling:

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

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

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

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

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

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

# RGE equation for Bilinear higgsino term:

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

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