# Sbottoms as probes to MSSM with Nonholomorphic Soft Interactions

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# Outline

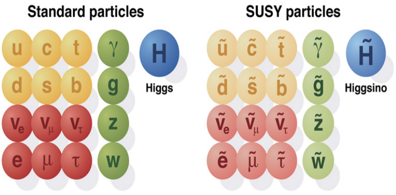
1. Minimal Supersymmetric Standard Model
   - Generalized Soft Breaking Sector
   - Non-Holomorphic soft terms
2. Results
   - Sbottom Sector Phenomenology
   - Corrections to bottom Yukawa coupling
   - Effect of NH terms in parton level yields
3. Discussions

# 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** :

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

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

# Possible origin & type of "soft" terms

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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| | $\phi^2\phi^*$ | $\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_w^2}{M}$ | $\frac{1}{M^3}[XX^*\Phi^2\Phi^*]_D$ |
| "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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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.

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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.

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

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,

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

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

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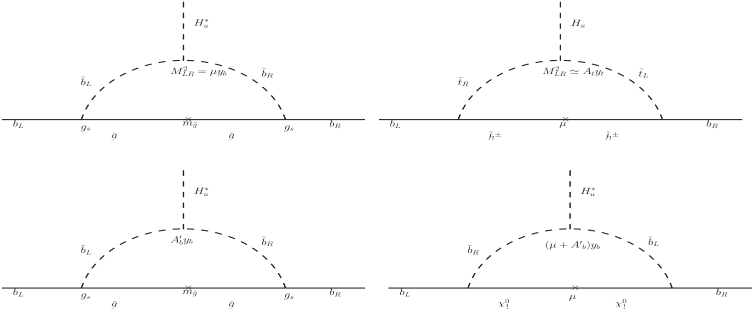
# Non-trivial contributions through $y_b$

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




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

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

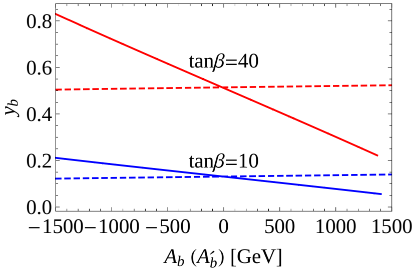
$$\Delta m_b^{\tilde{h}^+}{}_{\rm MSSM} = \frac{y_t y_b}{16\pi^2} \mu A_t y_t \frac{v_u}{\sqrt{2}} I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2);$$

$$\Delta m_b^{\tilde{h}^0}{}_{\rm NHSSM} = \frac{y_b^2}{16\pi^2} \mu(\mu + A'_b) y_b \frac{v_u}{\sqrt{2}} I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, \mu^2).$$

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.

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

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

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

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

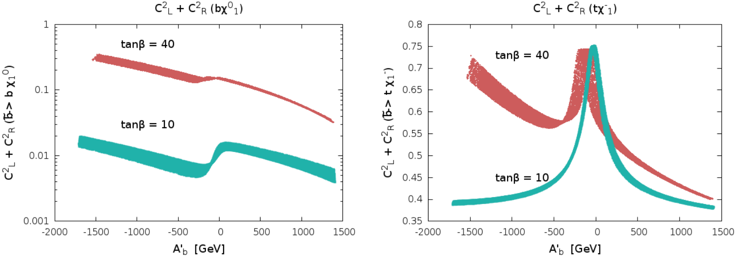
$$C_L = i(y_t Z^d_{i3} V_{j2}),$$

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

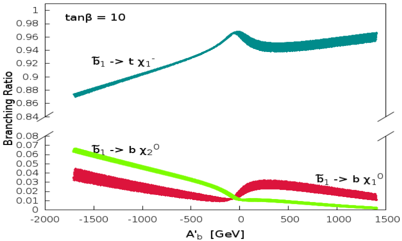
**$N_{ij}, U_{ij}, V_{ij}$ & $Z_{ij}$'s are diagonalizing mass matrices of neutralino, charginos and sbottoms respectively.**

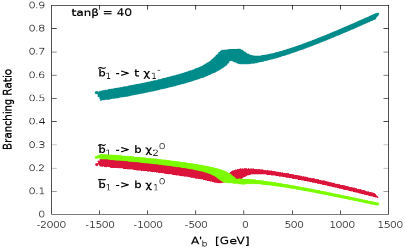
# Features of the couplings:

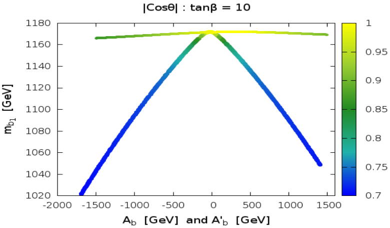
- ✓ Strength of sbottom state to a higgsino-like neutralino is always $\propto y_b$.
- ✓ For top quark and a higgsino-like chargino, it depends on the chiral admixture it possesses. Such a coupling for a left-like sbottom $\propto y_t$ while that for a right-like sbottom $\propto y_b$.
- ✓ A left-like sbottom dominantly decays to $t\tilde{\chi}_1^-$ $\Longrightarrow$ small branching fraction for the $b\tilde{\chi}_{1,2}^0$ final state when $\tilde{\chi}_{1,2}^0$ 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 $\tilde{b}_1$ : $\tilde{b}_1 \rightarrow \tilde{t}_1 W^-$ is taken to be kinematically forbidden.
  i.e. $m_{\tilde{b}_1} < m_{\tilde{t}_1} + m_{W^-}$.

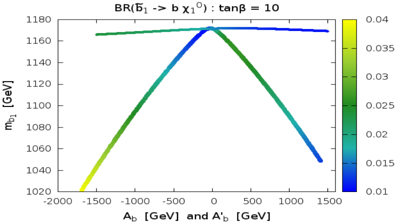


# Behaviour of Branching fractions: follow the same profile of vertex strengths



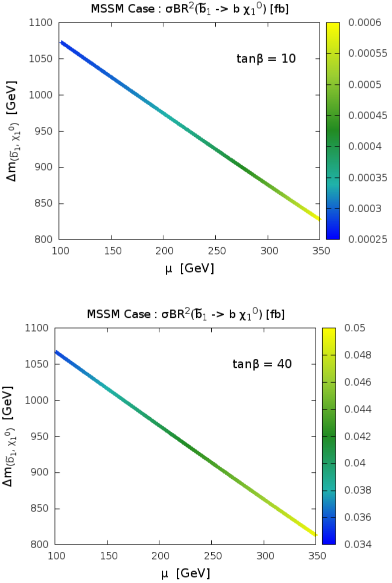



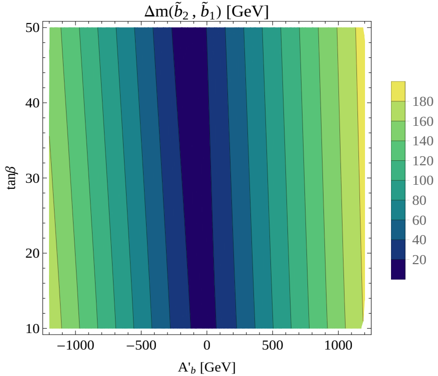

**Common Backdrop : The variation of $m_{\tilde{b}_1}$ as a function of $A'_b$ ($A_b$ ) in the NHSSM (MSSM). Flatter lines at the top of these plots illustrate the MSSM. $m_{\tilde{b}_L} = m_{\tilde{b}_R} = 1.2$ TeV. $\cos\theta_{\tilde{b}}$ ranges between $\frac{1}{\sqrt{2}} \approx 0.7$ (maximal mixing)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

**Signal Strengths** $\Rightarrow$ Parton level yields: $pp \to \tilde{b}_1 \tilde{b}_1^*$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$. The major effect, in NHSSM, rather comes from a significant variation of $y_b$ with $A'_b$, induces such a big change in $m_{\tilde{b}_1}$.



## 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.

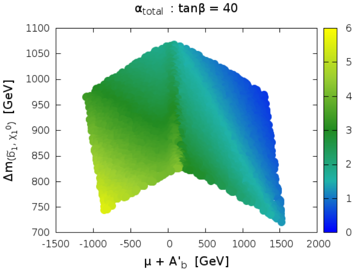



Contours of constant mass-split ($\Delta m_{\tilde{b}_1-\tilde{b}_2}$) between $\tilde{b}_1$ and $\tilde{b}_2$ in the $A'_b$–$\tan\beta$ plane.

## Total Relative Rates:

We now summarize our findings by undertaking a simple-minded comparison of the $2b + \not{E}_T$ rates obtained in the MSSM and in the NHSSM, as $A'_b$ varies for the same values of $\mu$.

$$\alpha_i(A'_b) = \frac{\left[(\sigma_{\tilde{b}_i\tilde{b}_i} \times \mathrm{BR}[\tilde{b}_i \to b\tilde{\chi}_1^0]^2)\right]^{\mathrm{NHSSM}}}{\left[(\sigma_{\tilde{b}_i\tilde{b}_i} \times \mathrm{BR}[\tilde{b}_i \to b\tilde{\chi}_1^0]^2)\right]^{\mathrm{MSSM}}}$$




- Up to a six-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.

$$\alpha_{\mathrm{total}}(A'_b) = \frac{\sum_{i=1,2} \left[(\sigma_{\tilde{b}_i\tilde{b}_i} \times \mathrm{BR}[\tilde{b}_i \to b\tilde{\chi}_1^0]^2)\right]^{\mathrm{NHSSM}}}{\sum_{i=1,2} \left[(\sigma_{\tilde{b}_i\tilde{b}_i} \times \mathrm{BR}[\tilde{b}_i \to b\tilde{\chi}_1^0]^2)\right]^{\mathrm{MSSM}}}$$

# Overview

# Summary :-

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

# THANK YOU!

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: $\mathcal{L} \supset (\mu + \mu')\tilde{h_1}\tilde{h_2} + (\mu^2 + m_{h_1}^2)|h_1|^2 + (\mu^2 + m_{h_2}^2)|h_2|^2$

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

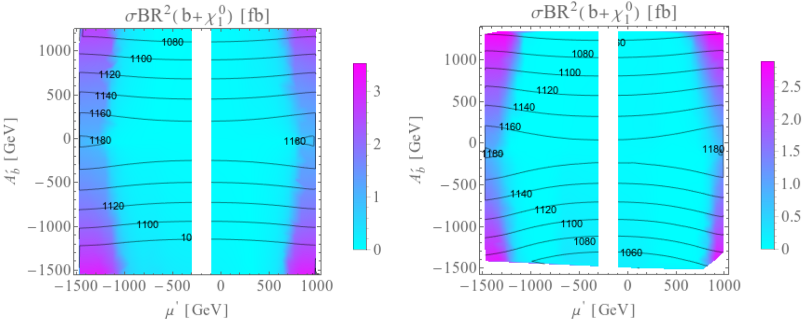
A reparametrization would however involve ad-hoc correlations between unrelated parameters. [Jack and Jones 1999, Hetherington 2001 etc.]

✓ **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 $\mu'$ :

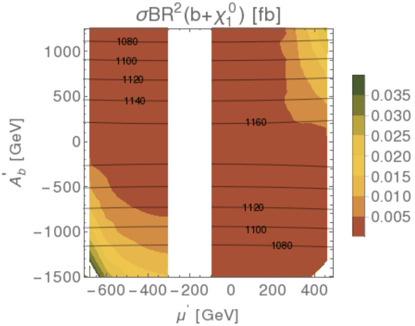
Gives rise to a relatively heavier higgsino-like neutralino ($\sim$ 1 TeV) LSP without requiring '$\mu$' to be large. This would then help avoid an imminent tension with the notion of 'naturalness'.

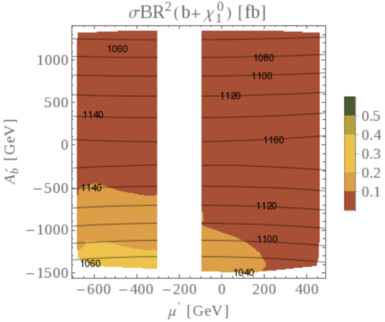



[$\mu = 200$ GeV, $A_b = 0$ with $\tan\beta = 10$ (left) and 40 (right)].
($\sigma \times \mathrm{BR}^2$) as a function of $\mu'$ and $A_b'$.
The blank vertical bands in the middle are roughly excluded by searches of the lighter chargino at LEP.

# Effect of $\mu'$ :

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

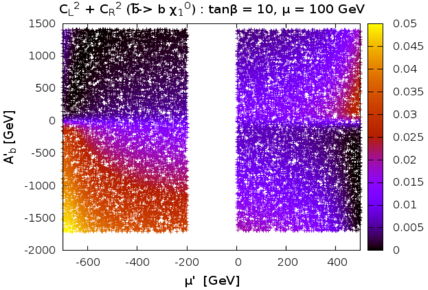



- This can be traced back to similar profile in $C_L^2 + C_R^2$.
- 5 to 7 fold variation in the yield is possible over the indicated range.
- The blank vertical bands in the middle are roughly excluded by searches of the lighter chargino at LEP.

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

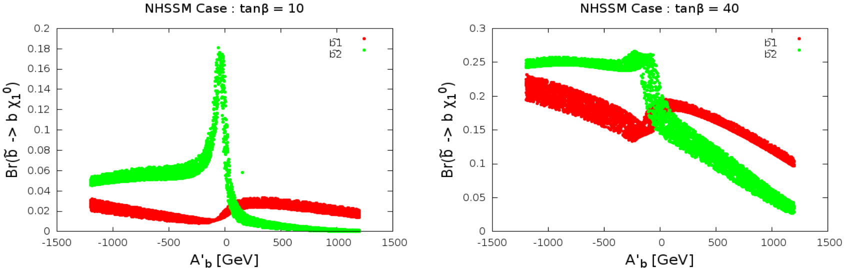
Zoomed-in on the higgsino-like LSP region ⇔ altering nature of the yield and its extent across the region.




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

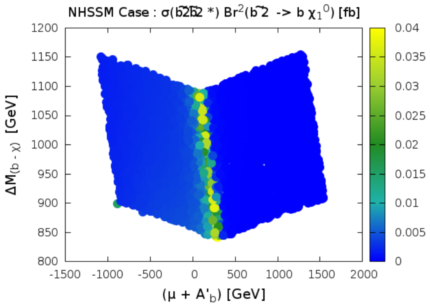
# Comparison between BR's of $\tilde{b}_{1,2}$ :

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$[\tilde{b}_2 \to b\chi_1^0]$.




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

# Parton level yield of $\sigma_{\tilde{b}_2\tilde{b}_2} \times \mathrm{BR}[\tilde{b}_2 \to b\tilde{\chi}_1^0]^2$ :




$\tan\beta = 10$ : Small values of $|A_b'|$, yield from $\tilde{b}_2$ pair production dominates and this simply inherits its trend from the BR profile.
However, with small $|A_b'|$ the scenario tends to become MSSM-like over this region. large $\tan\beta$ : relatively large negative $A_b'$ the combined contribution from $\tilde{b}_1$ and $\tilde{b}_2$ pair production could exceed the MSSM expectation significantly.

# 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:

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

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