Phenomenological Implication of Non-holomorphic Soft SUSY Breaking Interactions

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

[Ref.: UC, **Abhishek Dey**, JHEP 1610 (2016) 027, arXiv:1604.06367], UC, **Debottam Das, Samadrita Mukherjee** arXiv:1710.10120]

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MSSM

- MSSM Superpotential and soft SUSY breaking terms::

$$\mathcal{W} = \mu H_D.H_U - Y^e_{ij} H_D.L_i \bar{E}_j - Y^d_{ij} H_D.Q_i \bar{D}_j - Y^u_{ij} Q_i.H_U \bar{U}_j$$

$$A.B = \epsilon_{\alpha\beta} A^\alpha B^\beta$$

$$\begin{aligned}
-\mathcal{L}_{soft} &= [\tilde{q}_{iL}.hu(A_u)_{ij}\tilde{u}^*_{jR} + h_d.\tilde{q}_{iL}(A_d)_{ij}\tilde{d}^*_{jR} + h_d.\tilde{l}_{iL}(A_e)_{ij}\tilde{e}^*_{jR} + h.c.] \\
&+ (B\mu h_d.h_u + h.c.) + m_d^2|h_d|^2 + m_u^2|h_u|^2 \\
&+ \tilde{q}^*_{iL}(M^2_{\tilde{q}})_{ij} + \tilde{u}^*_{iR}(M^2_{\tilde{u}})_{ij}\tilde{u}_{jR} + \tilde{d}^*_{iR}(M^2_{\tilde{d}})_{ij}\tilde{d}_{jR} + \tilde{l}^*_{iL}(M^2_{\tilde{l}})_{ij}\tilde{l}_{jL} \\
&+ \text{gaugino mass terms}
\end{aligned}$$

- Possible origin of soft terms: SUSY breaking parametrized by vev of F-term of a chiral superfield X, so that $< X >= \theta\theta < F >\equiv \theta\theta F$. X couples to Φ and a gauge strength superfield W^a_α.

Type	Term	Naive Suppression	Origin
soft	$\phi\phi^*$	$\frac{\|F\|^2}{M^2} \sim m_W^2$	$\frac{1}{M^2}[XX^*\Phi\Phi^*]_D$
	ϕ^2	$\frac{\mu F}{M} \sim \mu m_W$	$\frac{\mu}{M}[X\Phi^2]_F$
	ϕ^3	$\frac{F}{M} \sim m_W$	$\frac{1}{M}[X\Phi^3]_F$
	$\lambda\lambda$	$\frac{F}{M} \sim m_W$	$\frac{1}{M}[XW^\alpha W_\alpha]_F$

- Are there any more possible soft terms ?

Nonholomorphic soft SUSY breaking terms

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

Type	Term	Naive Suppression	Origin
"maybe soft"	$\phi^2\phi^*$	$\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_W^2}{M}$	$\frac{1}{M^3}[XX^*\Phi^2\Phi^*]_D$
	$\psi\psi$	$\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_W^2}{M}$	$\frac{1}{M^3}[XX^*D^\alpha\Phi D_\alpha\Phi]_D$
	$\psi\lambda$	$\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_W^2}{M}$	$\frac{1}{M^3}[XX^*D^\alpha\Phi W_\alpha]_D$

- "maybe soft": *In the absence of any gauge singlet scalar* the above non-holomorphic terms are of soft SUSY breaking in nature.
- A gauge singlet scalar field would have tadpole contributions causing hard SUSY breaking.
- NHSSM: MSSM + NH terms like $\phi^2\phi^*$ and $\psi\psi$:

$$-\mathcal{L}'_{soft} = h_d^c.\tilde{q}_{iL}(A'_u)_{ij}\tilde{u}^*_{jR} + \tilde{q}_{iL}.h_u^c(A'_d)_{ij}\tilde{d}^*_{jR} + \tilde{l}_{iL}.h_u^c(A'_e)_{ij}\tilde{e}^*_{jR} + \mu'\tilde{h}_u.\tilde{h}_d + h.c.$$

  Higgs fields are replaced with their conjugates: h_d going with up-type of squarks etc.
- V_{Higgs} is unaffected. But, the potential involving charged and colored scalar fields needs a separate study for CCB (Next talk by Abhishek Dey).

Bilinear Higgsino soft term

- The following reparametrization of μ, μ' and Higgs scalar mass parameters may evade the need of a bilinear higgsino soft term. $\mu \to \mu + \delta$, $\mu' \to \mu' + \delta$, and $m^2_{H_{U,D}} \to m^2_{H_{U,D}} - 2\mu\delta - \delta^2$
- A reparametrization would however involve *ad-hoc* correlations between unrelated parameters [Jack and Jones 1999, Hetherington 2001 etc.].
- Such correlations are arbitrary, at least in view of fine-tuning. In particular, there may be a scenario where definite SUSY breaking mechanisms generate bilinear higgsino soft terms whereas it may keep the scalar sector unaffected. [Ross *et. al.* 2016, 2017, Antoniadis *et. al.* 2008, Perez *et. al.* 2008 etc].
- The μ' term that is traditionally retained, isolates a fine-tuning measure (typically $\sim \mathrm{factor} \times \mu^2/M_Z^2$) from the higgsino mass $(\mu - \mu')$. $\Rightarrow$ Possibility of a large higgsino mass for a small fine-tuning.

In a general standpoint we acknowledge the importance of trilinear and bilinear NH soft terms, irrespective of a suppression predicted by a *given* model. Unlike other analyses, we will use a
i) pMSSM type of analysis (NHSSM),
ii) explore in a framework of mGMSB (NHmGMSB).

NHSSM: scalars and electroweakinos

- $$\textit{Squarks}: \quad M_{\tilde{u}}^2 = \begin{bmatrix} m_{\tilde{Q}}^2 + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)M_Z^2\cos 2\beta + m_u^2 & -m_u(A_u - (\mu + A_u')\cot\beta) \\ -m_u(A_u - (\mu + A_u')\cot\beta) & m_{\tilde{u}}^2 + \frac{2}{3}\sin^2\theta_W M_Z^2\cos 2\beta + m_u^2 \end{bmatrix},$$

  Sleptons (off-diagonal): $-m_\mu[A_\mu - (\mu + A_\mu')\tan\beta] \Rightarrow A_\mu'\tan\beta$ **potentially enhances** $(g-2)_\mu^{\mathrm{SUSY}}$**, particularly affecting the** $\widetilde{\chi}_1^0 - \tilde{\mu}$ **loop contributions.**

- $$\text{Higgs mass corrections}: \Delta m_{h,top}^2 = \frac{3g_2^2\bar{m}_t^4}{8\pi^2 M_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{\bar{m}_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1}m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12m_{\tilde{t}_1}m_{\tilde{t}_2}}\right)\right],$$

  Here, $X_t = A_t - (\mu + A_t')\cot\beta \Rightarrow$ influence on m_h.

- $$\textit{Charginos}: M_{\widetilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2}M_W\sin\beta \\ \sqrt{2}M_W\cos\beta & -(\mu - \mu') \end{pmatrix},$$

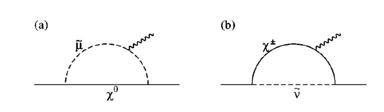
  $m_{\widetilde{\chi}_1^\pm} \gtrsim 100$ GeV $\Rightarrow |\mu - \mu'| \gtrsim 100$ GeV. Muon $g-2$ may be enhanced via a light higgsino.

- $$\textit{Neutralinos}: M_{\widetilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -(\mu - \mu') \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -(\mu - \mu') & 0 \end{pmatrix}$$

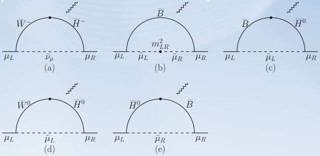
- If $|(\mu - \mu')| << M_1, M_2 \Rightarrow \widetilde{\chi}_1^0$ is higgsino-like. It is possible to have an acceptable higgsino-like LSP with small μ ($\sim$ i.e. small electroweak fine-tuning.)

Muon anomalous magnetic moment: $(g-2)_\mu$ in MSSM

- Large discrepancy from the SM (more than 3σ): $a_\mu^{exp} - a_\mu^{SM} = (29.3 \pm 8) \times 10^{-10}$
- MSSM contributions to muon (g-2): Diagrams involving charginos and neutralinos



Gauge Eigenstate basis:



- Slepton L-R mixing in MSSM: $m_\mu(A_\mu - \mu \tan\beta)$
- The mixing influences the last item of Δa_μ shown in blue. Typically the SUSY breaking mechanisms do not lead to large values of A_μ comparable to $\mu \tan\beta$.
- In NHSSM: $m_\mu[(A_\mu - A'_\mu \tan\beta) - \mu\tan\beta]$
  A'_μ **effect is enhanced by** $\tan\beta$ causing a significant change in Δa_μ.

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\nu}_\mu) \simeq 15 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_C}{1/2}\right),$$

$$\Delta a_\mu(\tilde{W}, \tilde{H}, \tilde{\mu}_L) \simeq -2.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_2\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) \simeq 0.76 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

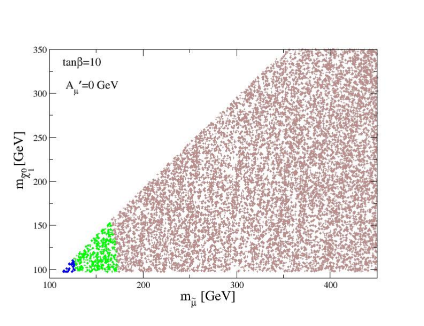
$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_R) \simeq -1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

$$\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \simeq 1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\,\mathrm{GeV})^2}{m^2_{\tilde{\mu}_L} m^2_{\tilde{\mu}_R}/M_1\mu}\right)\left(\frac{f_N}{1/6}\right).$$

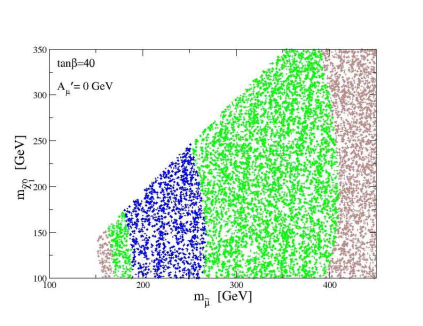
[Ref. arXiv 1303.4256 by Endo, Hamaguchi, Iwamoto, Yoshinaga]

Results of muon g-2 in MSSM

For a parameter point enhancing muon $g-2$ upto 1σ level via smuon L-R mixing effect, the smuon mass is quite small ($\sim$ 125 GeV or 200 GeV for $\tan\beta = 10$ and 40 respectively.)



Plot in $m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{\mu}_1}$ plane for $\tan\beta = 10$



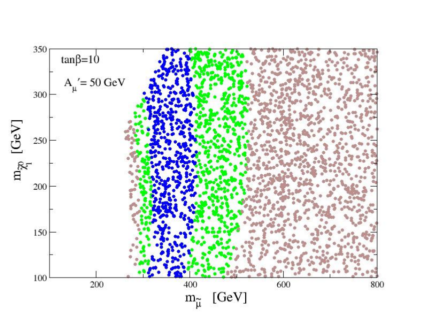
Same for $\tan\beta = 40$.

$\mu = 500$ GeV and $M_2 = 1500$ GeV. Blue, green and brown regions satisfy the muon g-2 constraint at 1σ, 2σ and 3σ levels respectively. All the squark and stau masses are set at 1 TeV. All trilinear parameters are zero except $A_t = -1.5$ TeV that is favorable to satisfy the Higgs mass data. Only very light smuon can satisfy the muon $g-2$ constraint at 1σ for $\tan\beta = 10$. The upper limit of $m_{\tilde{\mu}_1}$ is about 250 GeV for $\tan\beta = 40$.

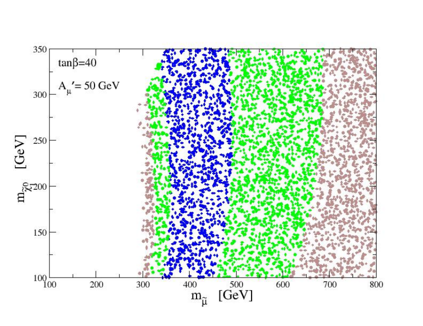
Results of muon g-2 in NHSSM

$$\mathbf{A}'_\mu = \mathbf{50}\ \text{GeV}.$$

A large increase of SUSY contribution to muon $g-2$ due to enhancement effect via A'_μ that is multiplied by $\tan\beta$.



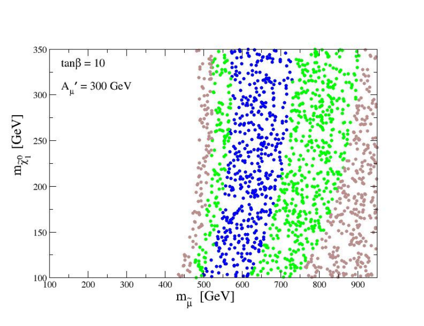
$m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{\mu}_1}$ plane for $\tan\beta = 10$.
Upper limit of $m_{\tilde{\mu}_1}$:400 GeV at 1σ.



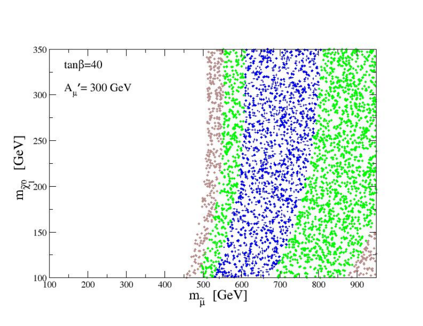
Same for $\tan\beta = 40$.
Upper limit of $m_{\tilde{\mu}_1}$:500 GeV at 1σ

Results of muon g-2 in NHSSM

$\mathbf{A}'_\mu = \mathbf{300}$ GeV



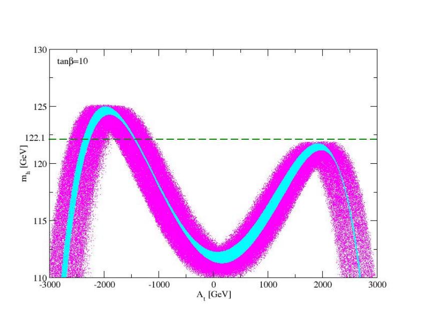
$m_{\widetilde{\chi}_1^0}$ vs $m_{\tilde{\mu}_1}$ plane for $\tan\beta = 10$.
Upper limit of $m_{\tilde{\mu}_1}$: 700 GeV at 1σ.

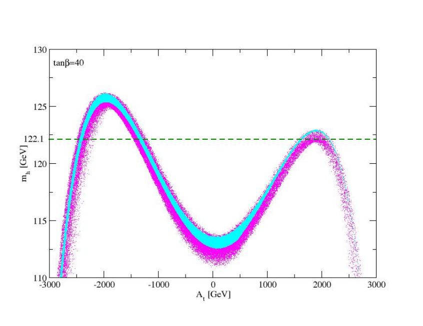


Same for $\tan\beta = 40$. Upper limit of $m_{\tilde{\mu}_1}$: 800 GeV at 1σ.

Impact of non-holomorphic soft parameters on m_h

A 2 to 3 GeV change in m_h can be possible via A'_t. The effect is larger for a smaller $\tan\beta$.
Cyan:MSSM, Magenta:NHSSM





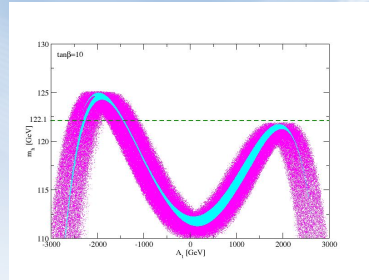
m_h is enhanced/decreased by 2-3 GeV due to non-holomorphic terms.
• **Correct m_h possible for significantly smaller $|A_t|$.**

•Since A'_t is associated with a suppression by $\tan\beta$ [off-diag term in stop sector: $X_t = A_t - (\mu + A'_t)\cot\beta$], m_h is affected only marginally.

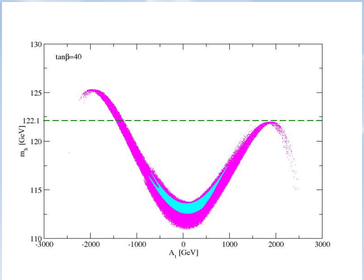
•$0 \leqslant \mu \leqslant 1$ TeV, $-2 \leqslant \mu' \leqslant 2$ TeV, $-3 \leqslant A'_t \leqslant 3$ TeV.
• A 3 GeV uncertainty in computation of m_h in SUSY is assumed.

Imposing $\mathrm{Br}(B \to X_s + \gamma)$ and $\mathrm{Br}(B_s \to \mu^+\mu^-)$ constraints

$2.77 \times 10^{-4} \leqslant \mathrm{Br}(B \to X_s + \gamma) \leqslant 4.09 \times 10^{-4}$, $0.8 \times 10^{-9} \leqslant \mathrm{Br}(\mathbf{B_s} \to \mu^+\mu^-) \leqslant 5 \times 10^{-9}$ [both at 3σ]



m_h vs A_t for $\tan\beta = 10$ with the above constraints.
$\Rightarrow$ Essentially unaltered results for a low $\tan\beta$ like 10.



m_h vs A_t for $\tan\beta = 40$.
$\Rightarrow$ $\mathrm{Br}(B \to X_s + \gamma)$ that increases with $\tan\beta$ takes away large $|A_t|$ zones of MSSM (cyan). Large $|A_t|$ with $\mu A_t < 0$ is discarded via the lower bound and vice versa. Thus m_h does not reach the desired limit beyond $|A_t| \sim 1$ TeV in MSSM.
NHSSM: The effect of A_t' is via L-R mixing:
$[A_t \to A_t - (\mu + A_t')\cot\beta]$. Thus large $|A_t|$ regions are valid via $\mathrm{Br}(B \to X_s + \gamma)$ and m_h may stay above the desired limit.
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ limits are not important once $\mathrm{Br}(B \to X_s + \gamma)$ constraint is imposed.

Electroweak fine-tuning in MSSM

EWSB conditions out of minimization of V_{Higgs} :

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2, \qquad \sin 2\beta = \frac{2b}{m_{H_d}^2 + m_{H_u}^2 + 2|\mu|^2} \tag{1}$$

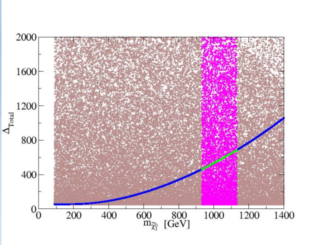
Electroweak Fine-tuning:

$$\Delta_{p_i} = \left|\frac{\partial \ln m_Z^2(p_i)}{\partial \ln p_i}\right|, \qquad \Delta_{Total} = \sqrt{\sum_i \Delta_{p_i}^2}, \text{where } p_i \equiv \{\mu^2, b, m_{H_u}, m_{H_d}\}$$

Δ_{p_i} details.

- For $\tan\beta$ and μ both not too small the most important terms are $\Delta(\mu) \simeq \frac{4\mu^2}{m_Z^2}$ and $\Delta(b) \simeq \frac{4M_A^2}{m_Z^2 \tan\beta}$. For a moderately large $\tan\beta$, a small μ means a small Δ_{Total}.
- NH soft terms do not contribute to V_{Higgs} at the tree level. Possibility of small μ with a larger higgsino LSP mass $\sim |\mu - \mu'|$ satisfying the DM data. This is unlike MSSM.
- For small $\tan\beta$ and very small μ (much less than $m_{\widetilde{\chi}_1^\pm} \sim 100$ GeV) $\Delta(m_{H_u})$ and $\Delta(m_{H_d})$ may become larger than $\Delta(\mu)$. Thus Δ_{Total} may not be negligibly small for a small $\tan\beta$.

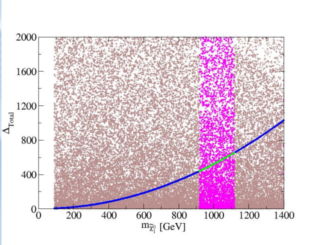
Electroweak fine-tuning and higgsino dark matter



Δ_{Total} vs $m_{\tilde{\chi}_1^0}$ for $\tan\beta = 10$

MSSM (i.e. with $\mu' = A_t' = 0$): Thin blue line and partly green line in the middle. Δ_{Total} is little above 400.

NHSSM: brown and magenta. Consistent region satisfying a 3σ level of WMAP/PLANCK constraints are shown. EWFT in NHSSM ranges from too high to too low (~ 50).



Δ_{Total} vs $m_{\tilde{\chi}_1^0}$ for $\tan\beta = 40$

EWFT in NHSSM can be vanishingly small.

$-3\ \mathrm{TeV} < \mu, \mu' < 3\ \mathrm{TeV}$

$-3\ \mathrm{TeV} < \mathrm{A_t}, \mathrm{A_t'} < 3\ \mathrm{TeV}$

EW fine-tuning differs from FT estimate in UV complete scenario like CMSSM with NH terms. There, an FT expression would depend on NH parameters. The FT related low scale parameters p_i are no longer independent. NH+CMSSM still has FT estimate dominantly controlled by μ^2 (Ross *et. al.* 2016, 2017).

NH terms affecting or not affecting muon g-2 in two benchmark points where $\widetilde{\chi}_1^0$ is bino-like

Table 1. *Benchmark points for NHSSM. Masses are shown in GeV. Only the two NHSSM benchmark points shown satisfy the phenomenological constraint of Higgs mass, dark matter relic density along with direct detection cross section, muon anomaly, $\mathrm{Br}(B \to X_s + \gamma)$ and $\mathrm{Br}(B_s \to \mu^+\mu^-)$. The associated MSSM points are only given for comparison and do not necessarily satisfy all the above constraints.*

Parameters	MSSM	NHSSM	MSSM	NHSSM
$m_{1,2,3}$	472, 1500, 1450	472, 1500, 1450	243, 250, 1450	243, 250, 1450
$m_{\tilde{Q}_3}/m_{\tilde{U}_3}/m_{\tilde{D}_3}$	1000	1000	1000	1000
$m_{\tilde{Q}_2}/m_{\tilde{U}_2}/m_{\tilde{D}_2}$	1000	1000	1000	1000
$m_{\tilde{Q}_1}/m_{\tilde{U}_1}/m_{\tilde{D}_1}$	1000	1000	1000	1000
$m_{\tilde{L}_3}/m_{\tilde{E}_3}$	2236	2236	1000	1000
$m_{\tilde{L}_2}/m_{\tilde{E}_2}$	592	592	500	500
$m_{\tilde{L}_1}/m_{\tilde{E}_1}$	592	592	500	500
A_t, A_b, A_τ	-1500, 0, 0	-1500, 0, 0	-1368.1, 0, 0	-1368.1, 0, 0
A'_t, A'_μ, A'_τ	0, 0, 0	2234, 169, 0	0, 0, 0	3000, 200, 0
$\tan\beta$	**10**	**10**	**40**	**40**
μ	500	500	390.8	390.8
μ'	0	-175	0	1655.5
m_A	1000	1000	1000	1000
$m_{\tilde{g}}$	1438.9	1439.1	1438.9	1438.9
$m_{\tilde{t}_1}, m_{\tilde{t}_2}$	894.4, 1151.2	865.5, 1154.9	907.8, 1137.5	903.4, 1141.4
$m_{\tilde{b}_1}, m_{\tilde{b}_2}$	1032.4, 1046.2	1026.3, 1045.1	1013.8, 1051.2	1017.7, 1056.5
$m_{\tilde{\mu}_L}, m_{\tilde{\nu}_\mu}$	596.4, 596.3	573.5, 595.9	502.0, 497.1	465.8, 496.3
$m_{\tilde{\tau}_1}, m_{\tilde{\nu}_\tau}$	2237.1, 2238.5	2237.1, 2238.5	985.4, 997.2	988.5, 998.8
$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm}$	504.2, 1483.6	677.6, 1484.7	244.6, 421.0	262.3, 1255.2
$m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$	448.6, 509.0	464.0, 680.6	231.3, 249.9	240.9, 262.1
$m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}$	522.6, 1483.5	683.2, 1484.7	400.7, 421.0	1253.3, 1253.7
$m_{H^\pm}$	1011.9	1005.8	955.7	1011.6
m_H, m_h	1008.1, 121.4	984.8, 122.8	948.0, 122.4	990.2, 122.8
$\mathrm{Br}(B \to X_s + \gamma)$	3.00×10^{-4}	3.01×10^{-4}	2.01×10^{-4}	4.05×10^{-4}
$\mathrm{Br}(B_s \to \mu^+\mu^-)$	3.40×10^{-9}	3.45×10^{-9}	5.06×10^{-9}	1.65×10^{-9}
a_μ	1.94×10^{-10}	22.3×10^{-10}	34.8×10^{-10}	35.8×10^{-10}
$\Omega_{\tilde{\chi}_1^0} h^2$	0.035	0.095	0.0114	0.122
$\sigma^{\mathrm{SI}}_{\tilde{\chi}_1^0 p}$ in pb	4.01×10^{-9}	3.47×10^{-10}	6.79×10^{-9}	3.15×10^{-12}

Gauge Mediated SUSY breaking (GMSB)

[Ref. UC, Debottam Das, Samadrita Mukherjee, arxiv: 1710.10120]

- The fact that NH soft terms may be suppressed by the scale of mediation motivates us toward exploring a GMSB type of setup.
- For minimal GMSB (mGMSB) the set of free parameters are:

$$\Lambda, M_{\rm mess}, \tan\beta, N_5, \text{and } {\rm sgn}(\mu).$$

  Here $\Lambda = \frac{\langle F \rangle}{M_{\rm mess}}$ is the SUSY breaking scale in MSSM and N_5 is the number of flavor of messenger copies Φ and $\bar{\Phi}$ transforming as 5 and $\bar{5}$ representations of SU(5).
- We include the trilinear NH soft terms and the bilinear higgsino NH soft term with coupling μ_0' (at $M_{\rm mess}$). The latter assumed to have a SUSY breaking origin different from GMSB is introduced with a phenomenological motivation. This will also allow us exploring a higgsino type of NLSP, a feature typically unavailable in mGMSB.

  Similar to A_0, A_0' also vanishes at the messenger scale.
- As usual,

$$M_\alpha = \frac{g_\alpha^2}{16\pi^2}\Lambda N_5 \text{ and } m_{\tilde{f}}^2 = 2\Lambda^2 N_5 \sum_\alpha \left(\frac{g_\alpha^2}{16\pi^2}\right)^2 C_\alpha,$$

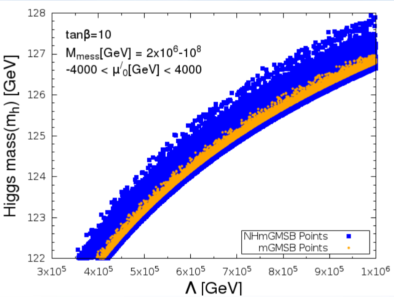
  where the Casimirs C_α are: $C_{U(1)} = (3/5)Y^2$ and $C_{SU(n)} = \frac{n^2-1}{2n}$. Further

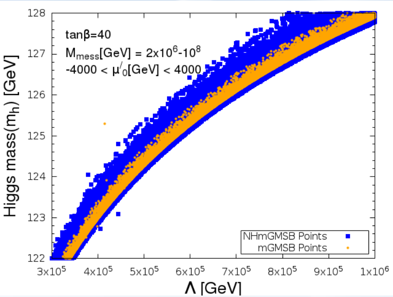
Scanned Regions and Constraints

$$3.0\times10^5\ \mathrm{GeV}\leqslant\Lambda\leqslant1.0\times10^6\ \mathrm{GeV}$$
$$2\times10^6\ \mathrm{GeV}\leqslant M_{\mathrm{mess}}\leqslant10^8\ \mathrm{GeV}$$
$$\tan\beta=10\ \text{and}\ 40$$
$$-4000\ \mathrm{GeV}\leqslant\mu_0'\leqslant4000\ \mathrm{GeV}$$

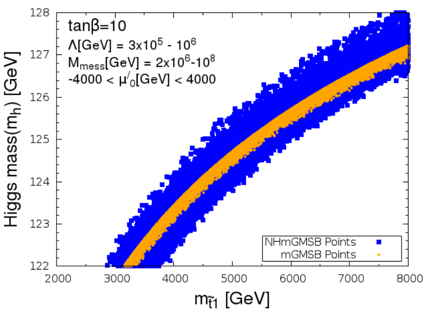
$$122.1\ \mathrm{GeV}\leqslant m_h\leqslant128.1\ \mathrm{GeV}$$
$$2.99\times10^{-4}\leqslant Br(B\to X_s+\gamma)\leqslant3.87\times10^{-4}\ (2\sigma)$$
$$1.5\times10^{-9}\leqslant Br(B_s\to\mu^+\mu^-)\leqslant4.3\times10^{-9}\ (2\sigma)$$

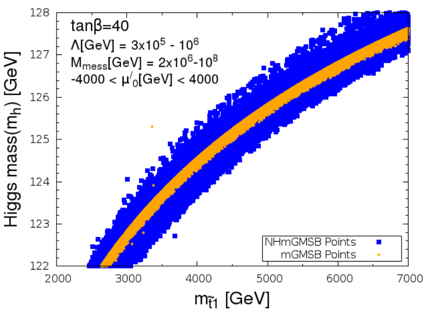
Codes: SARAH-4.9.1 and SPheno-3.3.8.
Higgs mass vs Λ: Yellow: MSSM; Blue: NHmGMSB
The m_h spread is reduced to below 1 GeV.

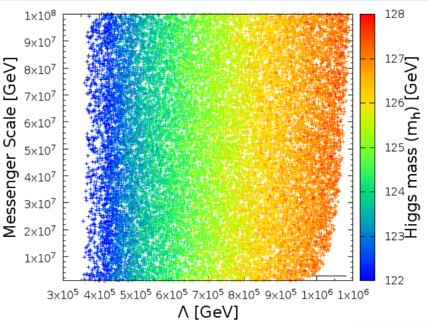


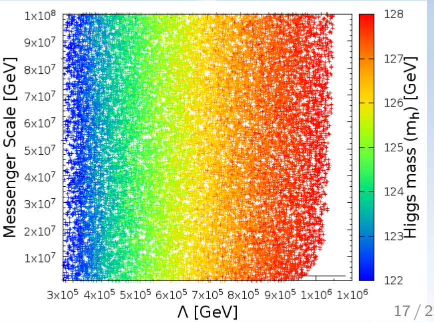


Scalars; Dependence on Λ and M_{mess}

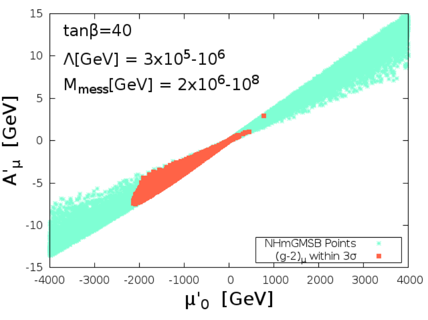








Muon $g-2$



Dependence on $a_\mu^{\rm susy}$ on μ' with $\mu > 0$. Orange region: 3σ level satisfied zone. Unlike NHSSM, here $a_\mu^{\rm susy}$ becomes large only when higgsino masses $[\sim (\mu + \mu')]$ are small.

- Unlike NHSSM, the pMSSM kind of analysis, a vanishing trilinear coupling A_0' at $M_{\rm mess}$ restricts top-squark mixing. Thus one has a limited increase of the radiative corrections to m_h. The same is attributed to the limited increase of $a_\mu^{\rm susy}$.
- Non-minimal GMSB cases with messenger-matter interactions where non-vanishing trilinear couplings originate at one-loop level would enhance both the above effects.

Higgsino NLSP decaying into gravitino LSP

Gravitino ψ_μ interacting with NLSP, higgs and gauge bosons: $\mathcal{L} = \sum_{\alpha=1}^{3} \mathcal{L}^{(\alpha)}$ where α stands for a given gauge group out of $SU(3)_C \times SU(2)_L \times U(1)_Y$.

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

$\mathcal{D}_\mu^{(\alpha)}$ and $F_{\rho\sigma}^{(\alpha)a}$ depend on α and the generator index a.

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

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

$$m_{\tilde{G}} = \frac{\Lambda M_{mess}}{\sqrt{3}M_P}$$

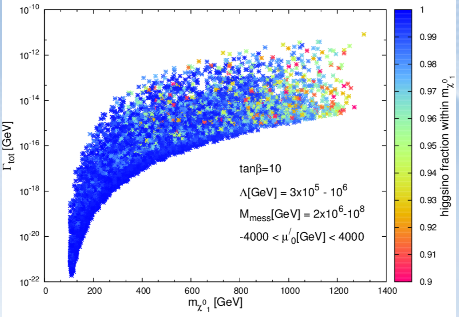
We only consider pure higgsino NLSP in the work.

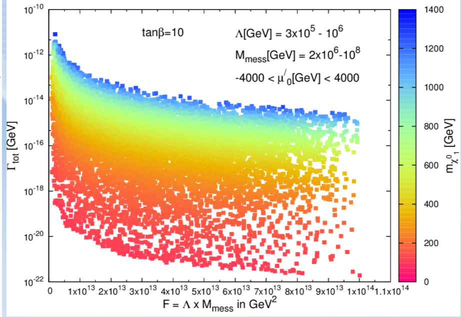
$$\Gamma^{\rm tot} \equiv \Gamma^{\rm tot}_{\rm NLSP} \simeq \Gamma(\widetilde{\chi}_1^0 \to \widetilde{G}\,Z) + \Gamma(\widetilde{\chi}_1^0 \to \widetilde{G}\,h).$$

Mean decay length of χ_1^0 as NLSP with energy E in the laboratory frame:

$$d \;\simeq\; (E^2/m_{\chi_1^0}^2 - 1)^{1/2}/\Gamma^{\rm tot}. \qquad (1)$$

NLSP Decays to Gravitino and Z or h





$1/\Gamma^{\text{tot}}$ varies between $\simeq 10^{-3}$ sec to $\simeq 10^{-13}$ sec or $\simeq 1000$ km to 0.1 mm respectively. The decay lengths when computed in the laboratory frame would point out a long range of values indicating decays occurring both within and outside the detector.

Representative parameter points

Representative Points for NHmGMSB: All the dimensional parameters are in GeV

Parameters	A	B
Λ	3.65×10^5	3.16×10^5
M_{mess}	9.742×10^6	8.073×10^6
$\tan\beta$	10	40
A'_0	0	0
μ'_0	-1898	-1144
A_t	-787	-686
A_b	-136	-430
A_τ	-14	-38
A'_t	-210	-147
A'_b	-55	-121
A'_τ	-23	-57
A'_μ	-1.4	-3.4
m_h	122.1	122.3
$m_H, m_{H^\pm}, m_A$	2047,2047,2047	1425,1425,1425
$m_{\tilde{t}_{1,2}}$	3090,3458	2651,2949
$m_{\tilde{b}_{1,2}}$	3357,3453	2841,2946
$m_{\tilde{\tau}_{1,2}}$	695,1315	566,594
$m_{\tilde{\chi}^0_{1,2}}$	432,451	202,212
$m_{\tilde{\chi}^\pm_{1,2}}$	446,981	210,846
$m_{\tilde{g}}$	2636	2311
NLSP Composition	$\tilde{\chi}^0_1 \approx 86\% \tilde{H}$ like	$\chi^0_1 \approx 98\% \tilde{H}$ like
$BR(B \to X_s + \gamma)$	3.22×10^{-4}	3.21×10^{-4}
$BR(B_s \to \mu^+\mu^-)$	3.27×10^{-9}	3.28×10^{-9}
a_μ^{SUSY}	1.027×10^{-10}	7.88×10^{-10}

Conclusion

- It may be interesting to explore nonholomorphic soft SUSY breaking terms in the context of various beyond the MSSM scenarios, especially in processes involving L-R mixing.
- Studying flavor physics with NH soft terms can be interesting in general.
- New physics contribution to leptonic $g-2$ is intimately connected with several observables like leptonic EDMs, decays like $l \to l' + \gamma$ etc.
- NH soft terms may be justified in models like mGMSB having a low mediation scale. This however shows a limited amount of effects on scalar mixing. However, non-minimal GMSB scenarios with messenger-matter interactions can significantly enhance such effects.

Thank you !

Backup pages

Nonholomorphic terms: A partial list of related analyses and our present work

- **Hall and Randall** PRL 1990, **Jack and Jones**, PRD 2000: Quasi IF fixed points and RG invariant trajectories; **Jack and Jones** PLB 2004: General analyses with NH terms involving RG evolutions.
- Works performed under Constrained MSSM (CMSSM)/minimal supergravity(mSUGRA) setup for studying the Higgs mass and observables like $\mathrm{Br}(B \to X_s + \gamma)$ etc.: **Hetherington** JHEP 2001, **Solmaz et. al.** PRD 2005, PLB 2008, PRD 2015. The analyses involve mixed type of inputs given at the unification and electroweak scales.
- **Ross, Schmidt-Hoberg, Staub** PLB 2016, JHEP 2017. Focused on fine-tuning and higgsino DM, stressed the importance of the bilinear higgsino term identifying various scenarios.
- **Our work: No specific mechanism for SUSY breaking: all the parameters are given at the low scale.**
  (i) Possible strong $\tan\beta$ enhancement of muon g-2 by NH terms.
  (ii) Electroweak fine-tuning in a higgsino DM scenario.
  (iii) Impact on Higgs mass, $\mathrm{Br}(B \to X_s + \gamma)$ constraints for large $\tan\beta$.

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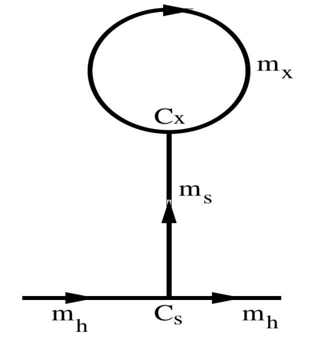
Tadpole correction



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S: a singlet field. m_X: a very heavy scalar mass

Tadpole contribution: $\sim C_S C_X \frac{m_X^2}{m_S^2} ln(\frac{m_X^2}{m_h^2})$

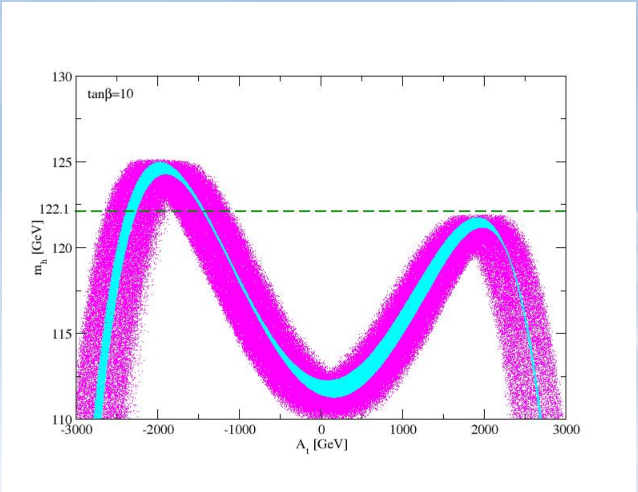
If $m_S << m_X$ the tadpole contribution becomes very large.

For discussions: Ref. Hetherington, JHEP 2001

Hard SUSY breaking terms

Back **S. Martin, Phys. Rev D., 2000; Possible non-holomorphic hard SUSY breaking terms:**

Type	Term	Naive Suppression	Origin
hard	ϕ^4	$\frac{F}{M^2} \sim \frac{m_W}{M}$	$\frac{1}{M^2}[X\Phi^4]_F$
	$\phi^3\phi^*$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\Phi^3\Phi^*]_D$
	$\phi^2\phi^{*2}$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\Phi^2\Phi^{*2}]_D$
	$\phi\psi\psi$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi D^\alpha\Phi D_\alpha\Phi]_D$
	$\phi^*\psi\psi$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi^* D^\alpha\Phi D_\alpha\Phi]_D$
	$\phi\psi\lambda$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi D^\alpha\Phi W_\alpha]_D$
	$\phi^*\psi\lambda$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi^* D^\alpha\Phi W_\alpha]_D$
	$\phi\lambda\lambda$	$\frac{F}{M^2} \sim \frac{m_W}{M}$	$\frac{1}{M^2}[X\Phi W^\alpha W_\alpha]_F$
	$\phi^*\lambda\lambda$	$\frac{\lvert F\rvert^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi^* W^\alpha W_\alpha]_D$



magenta (NHSSM) and cyan (MSSM), $M_3 = 1.5$ TeV, $M_{Q_3} = 1$ TeV. All other trilinear couplings are zero. Fixed gaugino masses: $(M_1, M_2) = (150, 250)$ GeV. m_h near $A_t = 0$ can be increased via a larger M_{Q_3}.

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Electroweak Fine-tuning Components

$$
\begin{aligned}
\Delta(\mu) &= \frac{4\mu^2}{m_Z^2}\left(1+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right), \\
\Delta(b) &= \left(1+\frac{m_A^2}{m_Z^2}\right)\tan^2 2\beta, \\
\Delta(m_{H_u}^2) &= \left|\frac{1}{2}\cos 2\beta+\frac{m_A^2}{m_Z^2}\cos^2\beta-\frac{\mu^2}{m_Z^2}\right| \times \left(1-\frac{1}{\cos 2\beta}+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right), \\
\Delta(m_{H_u}^2) &= \left|-\frac{1}{2}\cos 2\beta+\frac{m_A^2}{m_Z^2}\sin^2\beta-\frac{\mu^2}{m_Z^2}\right| \times \left|1+\frac{1}{\cos 2\beta}+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right|,
\end{aligned}
$$

$$
\Delta_{Total} = \sqrt{\sum\nolimits_i \Delta_{p_i}^2}, \qquad (2)
$$

Ref. Perelstein, Spethmann: JHEP 2007, hep-ph/0702038

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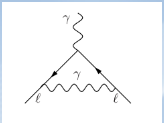
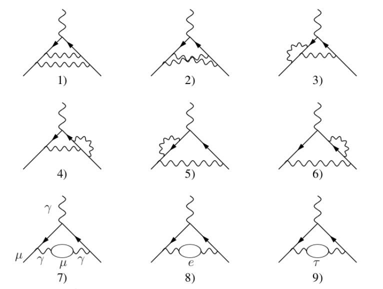
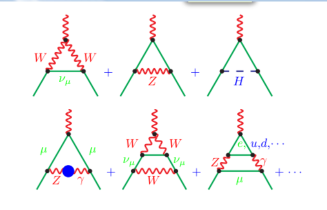
SM contributions: a_μ^{SM}

1 and 2-loop QED:

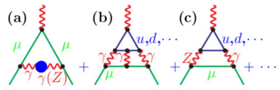




Weak contributions:



hadronic contributions:



(a) Hadronic vacuum polarization $O(\alpha^2), O(\alpha^3)$

(b) Hadronic light-by-light scattering $O(\alpha^3)$

(c) Hadronic effects in 2-loop EWRC $O(\alpha G_F m_\mu^2)$

Light quark loops

↓

Hadronic "blobs"

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$\mathrm{Br}(B \to X_s + \gamma)$ in MSSM

- SM contribution (almost saturates the experimental value) $\to t - W^{\pm}$ loop.
- MSSM contribution:
  1. $\widetilde{\chi}^{\pm} - \tilde{t}$ loop:
  $BR(b \to s\gamma)|_{\widetilde{\chi}^{\pm}} = \mu A_t tan\beta f(m_{\tilde{t}_1}, m_{\tilde{t}_2}, m_{\widetilde{\chi}^{\pm}}) \frac{m_b}{v(1+\Delta m_b)}$
  2. $H^{\pm} - t$ loop:
  $BR(b \to s\gamma)|_{H^{\pm}} = \frac{m_b(y_t cos\beta - \delta y_t sin\beta)}{vcos\beta(1+\Delta m_b)} g(m_{H^{\pm}}, m_t)$
  where,

$$\begin{aligned}\delta y_t &= y_t \frac{2\alpha_s}{3\pi} \mu M_{\tilde{g}} tan\beta[\cos^2\theta_t I(m_{\tilde{s}_L}, m_{\tilde{t}_2}, M_{\tilde{g}}) \\ &+ sin^2\theta_t I(m_{\tilde{s}_L}, m_{\tilde{t}_1}, M_{\tilde{g}})]\end{aligned}$$

- Destructive interference for $A_t\mu < 0 \to$ preferred.
- NLO contributions (from squark-gluino loops: due to the corrections of top and bottom Yukawa couplings) become important at large μ or large $\tan\beta$.

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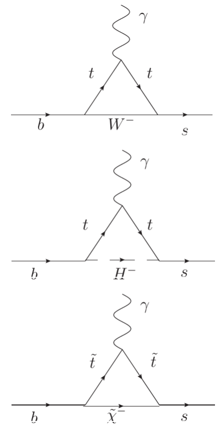
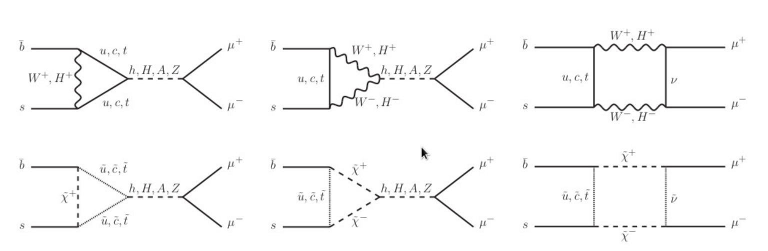


$B_s \to \mu^+\mu^-$ in MSSM



- Dominant SM contribution from : Z penguin top loop & W box diagram.
- SM value : $BR(B_s \to \mu^+\mu^-)$=$3.23 \pm 0.27 \times 10^{-9}$.
- LHCb result : $3.2^{+1.4}_{-1.2}(stat.)^{+0.5}_{-0.3}(syst.) \to$ no room for large deviation.
- $BR(B_s \to \mu^+\mu^-)_{SUSY} \propto \frac{tan^6\beta}{{m_A}^4}$

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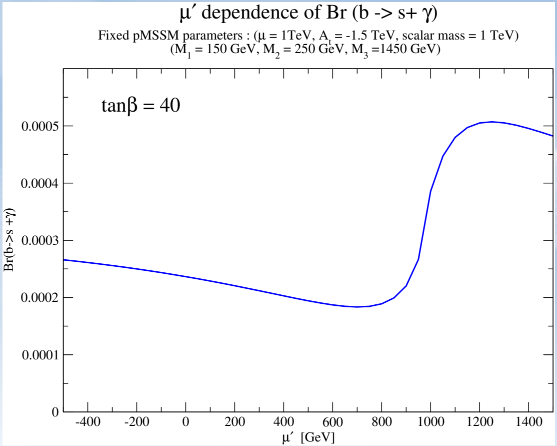

Dependence of $\mathrm{Br}(B \to X_s + \gamma)$ on μ'

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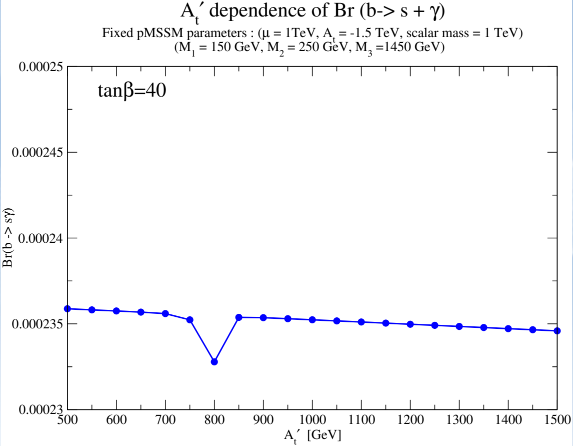

Dependence of $\mathrm{Br}(B \to X_s + \gamma)$ on A_t'

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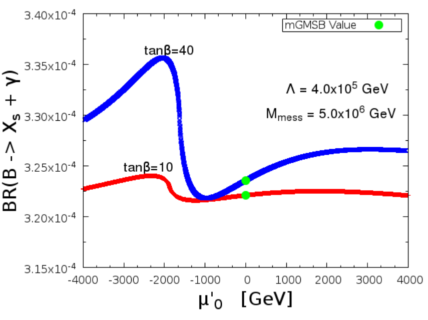
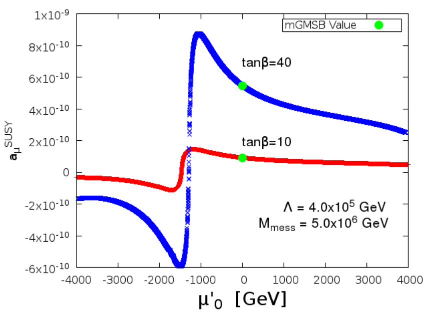
$\mathrm{Br}(B \to X_s + \gamma)$ and muon $g-2$ additional figures





Messenger loop diagrams

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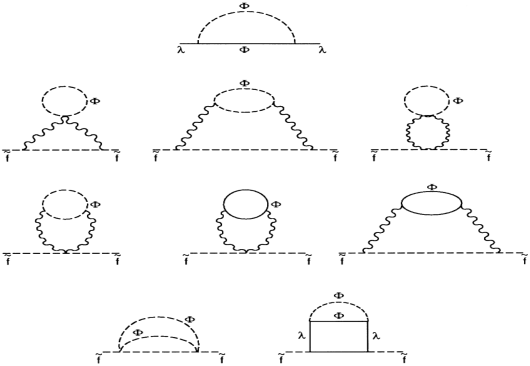

Fig. 1. Feynman diagrams contributing to supersymmetry-breaking gaugino (λ) and sfermion ($\tilde{f}$) masses. The scalar and fermionic components of the messenger fields Φ are denoted by dashed and solid lines, respectively; ordinary gauge bosons are denoted by wavy lines.