Probing non-holomorphic MSSM via precision constraints, dark matter and LHC data

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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	$\phi\phi^*$	$\frac{\lvert F\rvert^2}{M^2} \sim m_W^2$	$\frac{1}{M^2}[XX^*\Phi\Phi^*]_D$
	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 singlet scalar of the gauge group* 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.
- Nonholomorphic (NH) model (MSSM + terms like $\phi^2\phi^*$ and $\psi\psi$):

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

- Why are these terms not included usually ? [suppression by a high scale M.]

Higgsino mass soft term: reparametrization

- While the trilinear terms are genuinely non-standard interactions, the specific need of keeping a bilinear higgsino soft term is debatable.
- A reparametrization invariance exists between μ, $m^2_{H_D}$ and $m^2_{H_U}$ such as the following: $\mu \to \mu + \delta$, $\mu' \to \mu' + \delta$, and $m^2_{H_{U,D}} \to m^2_{H_{U,D}} - 2\mu\delta - \delta^2$. Thus the additional higgsino mass soft term $\mu' \tilde{h}_u.\tilde{h}_d$ is redundant. A reparametrization would however involve *ad-hoc* correlations between unrelated parameters [Jack and Jones 1999, Hetherington 2001 etc.].
- This is not desired at least in view of fine-tuning. In particular, there may be scenarios where definite SUSY breaking mechanisms generate bilinear higgsino mass terms whereas it may keep the scalar sector sequestered. [Ross *et. al.* 2016, 2017, Antoniadis *et. al.* 2008, Perez *et. al.* 2008 etc].
- Hence, the μ' term has been used by authors as an additional contribution and this isolates a fine-tuning measure (typically $\sim \text{factor} \times \mu^2/M_Z^2$) from the higgsino mass $(\mu - \mu')$. $\Rightarrow$ Tuning higgsino mass with μ' while not affecting small fine-tuning.
- In a general standpoint we acknowledge the importance of NH terms, irrespective of a suppression predicted by a *given* model. Unlike other analyses, we will entirely use low scale input parameters for phenomenological studies.

NHSSM: scalars and electroweakinos

- $$\mathit{Squarks}: \quad M^2_{\tilde{u}} = \begin{bmatrix} m^2_{\tilde{Q}} + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) M_Z^2 \cos 2\beta + m_u^2 & -m_u(A_u - (\mu + A'_u)\cot\beta) \\ -m_u(A_u - (\mu + A'_u)\cot\beta) & m^2_{\tilde{u}} + \frac{2}{3}\sin^2\theta_W M_Z^2\cos 2\beta + m_u^2 \end{bmatrix},$$

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

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

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

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

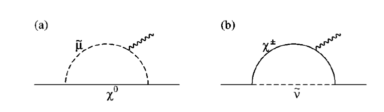
  $m_{\widetilde{\chi}^\pm_1} \gtrsim 100$ GeV $\Rightarrow |\mu - \mu'| \gtrsim 100$ GeV. Muon $g-2$ may be affected via a higgsino like lighter chargino if it becomes light.

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

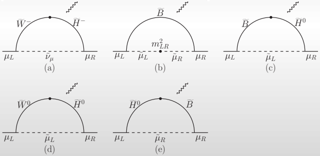
- If $|(\mu - \mu')| << M_1, M_2 \Rightarrow \widetilde{\chi}^0_1$ is higgsino-like. It is possible to have an acceptable higgsino-like LSP with small μ ($\sim$ i.e. small electroweak fine-tuning.)

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.

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

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

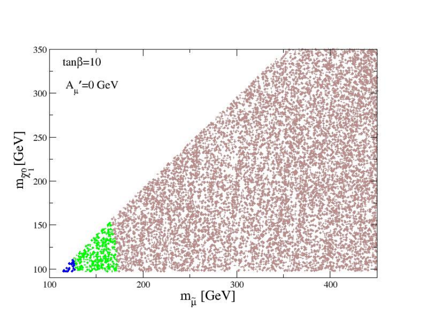
$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_L) \simeq \quad 0.76 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\ \mathrm{GeV})^2}{M_1 \mu}\right) \left(\frac{f_N}{1/6}\right),$$

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

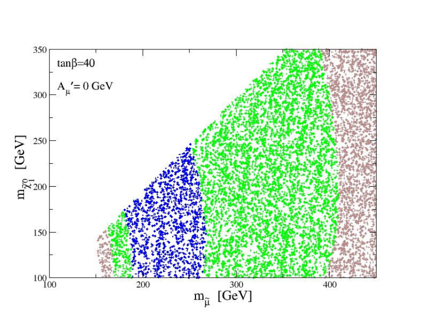
$$\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \simeq \quad 1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right) \left(\frac{(100\ \mathrm{GeV})^2}{m_{\tilde{\mu}_L}^2 m_{\tilde{\mu}_R}^2 / M_1 \mu}\right) \left(\frac{f_N}{1/6}\right).$$

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

Results of muon g-2 in MSSM



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

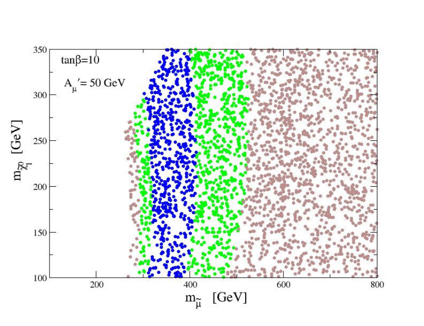


Same for $\tan\beta = 40$.

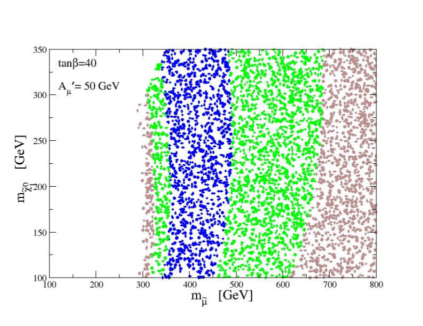
$\mu = 500$ GeV and $M_2 = 1500$ GeV. Blue, green and brown regions satisfy the muon g-2 constraint at 1σ, 2σ and 3σ levels respectively. All the squark and stau masses are set at 1 TeV. All trilinear parameters are zero except $A_t = -1.5$ TeV that is favorable to satisfy the Higgs mass data. Only very 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

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



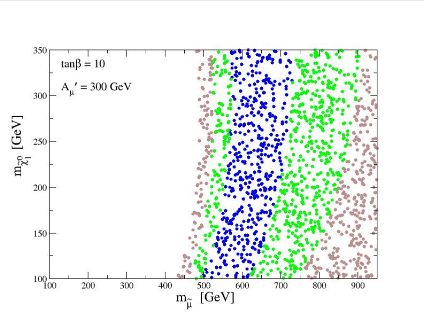
$m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{\mu}_1}$ plane for $\tan\beta = 10$.
Upper limit of $m_{\tilde{\mu}_1}$:400 GeV at 1σ.



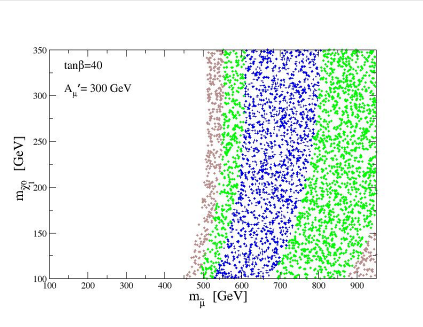
Same for $\tan\beta = 40$.
Upper limit of $m_{\tilde{\mu}_1}$:500 GeV at 1σ

Results of muon g-2 in NHSSM

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

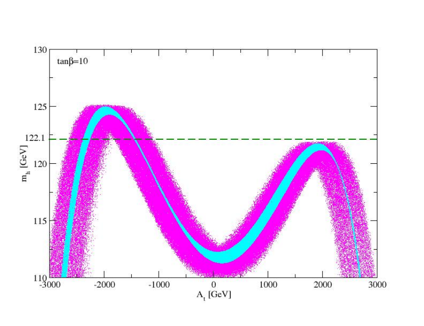


$m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{\mu}_1}$ plane for $\tan\beta = 10$.
Upper limit of $m_{\tilde{\mu}_1}$: 700 GeV at 1σ.



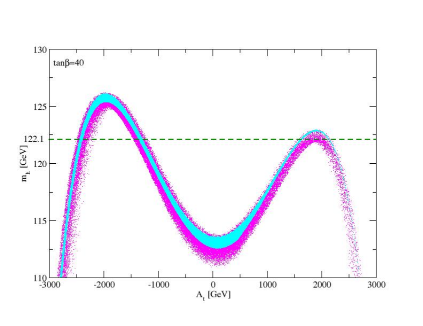
Same for $\tan\beta = 40$. Upper limit of $m_{\tilde{\mu}_1}$: 800 GeV at 1σ.

Impact of non-holomorphic soft parameters on m_h



m_h against A_t for $\tan\beta = 10$.

- magenta (NHSSM) and cyan (MSSM, i.e. with $A_t' = \mu' = 0$). m_h is enhanced/decreased by 2-3 GeV due to non-holomorphic terms.
- Correct m_h possible for significantly smaller $|A_t|$.



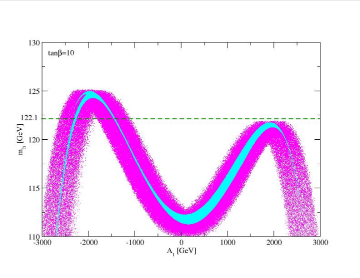
m_h against A_t for $\tan\beta = 40$.

- 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.

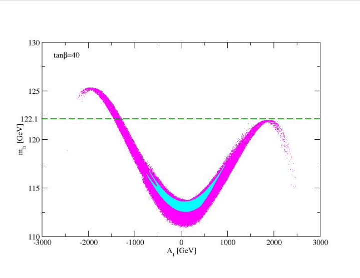
- $0 \leqslant \mu \leqslant 1$ TeV, $-2 \leqslant \mu' \leqslant 2$ TeV, $-3 \leqslant A_t' \leqslant 3$ TeV.
- A 3 GeV uncertainty in computation of m_h in SUSY is assumed.

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 $V_{\rm Higgs}$:

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

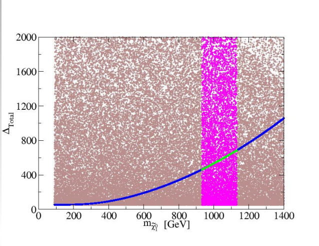
Electroweak Fine-tuning:

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

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 $V_{\rm Higgs}$ 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 $m_{\tilde{\chi}_1^\pm} \sim 100$ 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 $\tan\beta$.

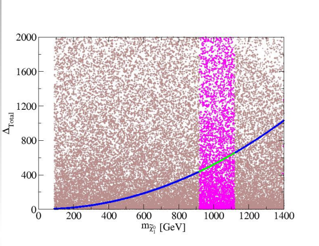
Electroweak fine-tuning and higgsino dark matter



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.

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

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

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
$\sigma^{\mathrm{SI}}_{\tilde{\chi}_1^0 \mathrm{p}}$ in pb	4.01×10^{-9}	3.47×10^{-10}	6.79×10^{-9}	3.15×10^{-12}

Conclusion

- Keeping aside any suppression related issues arising out of model dependent conclusions, it would be interesting to explore nonholomorphic soft SUSY breaking terms in the context of various beyond the MSSM scenarios.
- Studying flavor physics with NH terms can be interesting in general.
- As we have seen yesterday (P. Paradisi's plenary talk) new physics contribution to leptonic $g-2$ is intimately connected with several observables like leptonic EDMs, decays like $l \to l' + \gamma$ etc. One can explore the effect of NH terms on such observables.

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 *et. al.* 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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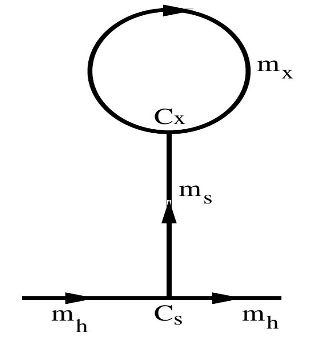
Tadpole correction



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

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

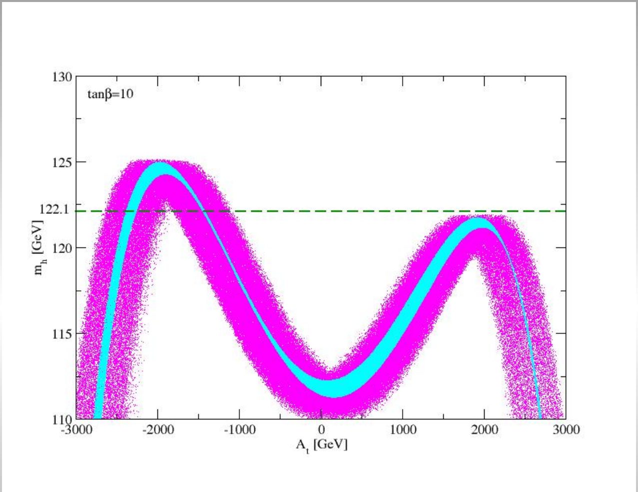
If $m_S << m_X$ the tadpole contribution becomes very large.

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	$\frac{F}{M^2} \sim \frac{m_W}{M}$	$\frac{1}{M^2}[X\Phi^4]_F$
	$\phi^3\phi^*$	$\frac{\|F\|^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\Phi^3\Phi^*]_D$
	$\phi^2\phi^{*2}$	$\frac{\|F\|^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\Phi^2\Phi^{*2}]_D$
	$\phi\psi\psi$	$\frac{\|F\|^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi D^\alpha\Phi D_\alpha\Phi]_D$
	$\phi^*\psi\psi$	$\frac{\|F\|^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi^* D^\alpha\Phi D_\alpha\Phi]_D$
	$\phi\psi\lambda$	$\frac{\|F\|^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi D^\alpha\Phi W_\alpha]_D$
	$\phi^*\psi\lambda$	$\frac{\|F\|^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi^* D^\alpha\Phi W_\alpha]_D$
	$\phi\lambda\lambda$	$\frac{F}{M^2} \sim \frac{m_W}{M}$	$\frac{1}{M^2}[X\Phi W^\alpha W_\alpha]_F$
	$\phi^*\lambda\lambda$	$\frac{\|F\|^2}{M^4} \sim \frac{m_W^2}{M^2}$	$\frac{1}{M^4}[XX^*\,\Phi^* W^\alpha W_\alpha]_D$



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

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

$$
\Delta_{Total} = \sqrt{\sum_i \Delta_{p_i}^2}, \tag{1}
$$

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

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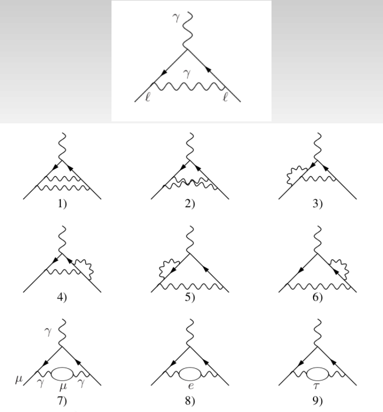
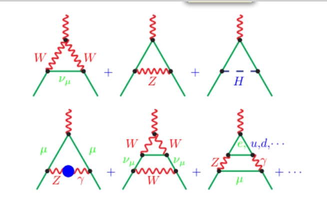
SM contributions: a_μ^{SM}

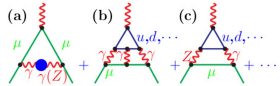
1 and 2-loop QED:



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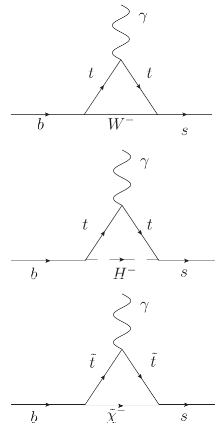
$\mathrm{Br}(B \to X_s + \gamma)$ in MSSM

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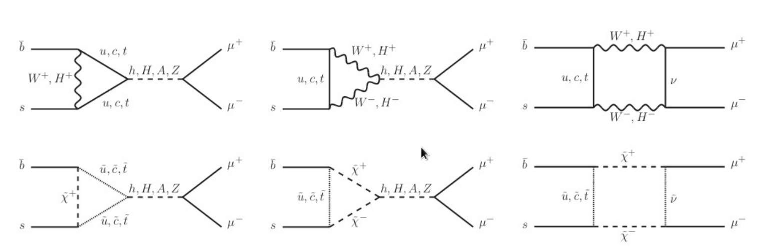
$B_s \to \mu^+\mu^-$ in MSSM



- Dominant SM contribution from : Z penguin top loop & W box diagram.
- SM value : $BR(B_s \to \mu^+\mu^-)$=$3.23 \pm 0.27\times10^{-9}$.
- 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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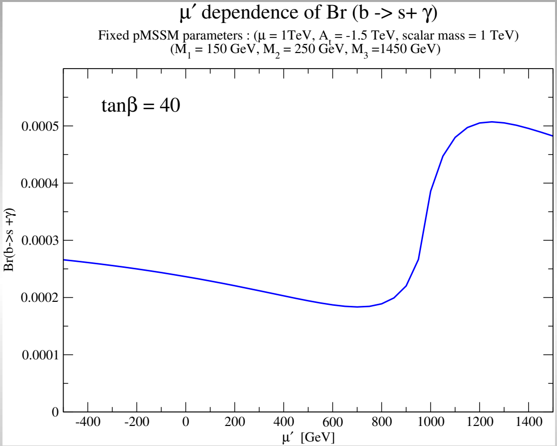

Dependence of $\mathrm{Br}(B \to X_s + \gamma)$ on μ'

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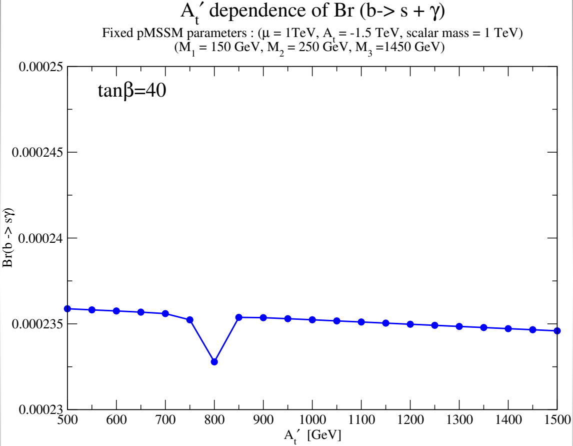

Dependence of $\mathrm{Br}(B \to X_s + \gamma)$ on A_t'

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