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

JHEP 1610 (2016) 027,
UC, Abhishek Dey, arXiv:1604.06367

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Based on the work: **JHEP 1610 (2016) 027:**
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- The minimal supersymmetric standard model (MSSM) has several interesting features. This of course includes a candidate for dark matter, typically the lightest neutralino $\widetilde{\chi}_1^0$, a mixture of bino, wino and higgsinos.

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- We would finally focus on the muon anomaly and show how a small amount of appropriate trilinear coupling associated with non-holomorphic soft breaking term may radically change the prediction of muon g-2 in SUSY.
- In MSSM, muon $g-2$ can be accommodated with large values of $\tan\beta$. Large $\tan\beta$ however is strongly disfavoured via the constraint from $\mathrm{Br}(B \to X_s + \gamma)$. We will see how large $\tan\beta$ can be accommodated both in $\mathrm{Br}(B \to X_s + \gamma)$ and muon $g-2$.

MSSM

- The Lagrangian of the Minimal Supersymmetrin Standard Model (MSSM) consists of kinetic and gauge terms, terms derived from the superpotential W, and a softly broken supersymmetry part $\mathcal{L}_{soft}$.
- Superpotential that preserves supersymmetry is a function of superfields that characterise the theory:

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

Notation:$A.B = \epsilon_{DE}A^D B^E$ for SU(2) doublet superfield or field A, B.

- Y^u, Y^d and Y^e are 3×3 Yukawa coupling matrices including all the generations of quarks and leptons.
- Superpotential is dominated by the third generation.
- Both H_U and H_D are required unlike SM.
- We don't see superparticles with small masses $\Rightarrow$ SUSY must be broken $\Rightarrow$ we require $\mathcal{L}_{soft}$ that contains renormalizable terms that would not cause any quadratic divergence.

MSSM contd.

- Exact nature of breaking of SUSY is unknown and this leads to unknown parameters in $\mathcal{L}_{soft}$. Soft SUSY breaking avoids quadratic divergence and refers to mass parameters not too much away from 1 TeV so as to avoid the hierarchy problem.
-

$$
\begin{aligned}
-\mathcal{L}_{soft} &= \frac{1}{2}(M_3\bar{g}g + M_2\bar{W}W + M_1\bar{B}B + h.c.) \boxed{\text{gauginos}} \\
\boxed{\text{Trilinears}} \quad & +(\tilde{Q}.h_u a^u \tilde{\bar{U}} + h_d.\tilde{Q}a^d \tilde{\bar{D}} + h_d.\tilde{L}a^e \tilde{\bar{E}} + h.c.) \\
\boxed{\text{Masses}} \quad & +(\tilde{Q}^\dagger \mathbf{m_Q^2} \tilde{Q} + \tilde{L}^\dagger \mathbf{m_L^2} \tilde{L} + \tilde{\bar{U}} \mathbf{m_U^2} \tilde{\bar{U}}^\dagger + \tilde{\bar{E}} \mathbf{m_E^2} \tilde{\bar{E}}^\dagger) \\
& + m_{h_u}^2 h_u^\dagger h_u + m_{h_d}^2 h_d^\dagger h_d \\
\boxed{\text{Bilinear}} \quad & + B\mu(h_u.h_d + h.c.)
\end{aligned}
$$

- $\mathbf{m^2}$: 3×3 Hermitian matrices in family space. $\mathbf{a}$: 3×3 trilinear coupling matrices: For convenience: $\mathbf{a} = \mathbf{AY}$.
- $\mathcal{L}_{soft}$ has gauginos and scalars and not their super-partners $\Rightarrow$ violates supersymmetry. Large number of parameters for $\mathcal{L}_{soft}$.

CMSSM/mSUGRA

- CMSSM is characterised by the following inputs at the GUT scale ($M_G \sim 2 \times 10^{16}$ GeV). the universal gaugino mass $\mathbf{m_{1/2}}$, the universal scalar mass $\mathbf{m}_0$, the universal trilinear coupling $\mathbf{A}_0$, the universal bilinear coupling $\mathbf{B}_0$ and the Higgsino mixing parameter μ_0.
- Radiative electroweak symmetry breaking (REWSB) is incorporated via minimisation of the Higgs potential.
- The two minimisation conditions at EW scale ($\sim M_Z$) of the Higgs potential give:

$$\mu^2 = -\frac{1}{2}M_Z^2 + \frac{m_{H_D}^2 - m_{H_U}^2 \tan^2\beta}{\tan^2\beta - 1}$$

$$\sin 2\beta = \frac{-2B\mu}{(2\mu^2 + m_{H_U}^2 + m_{H_D}^2)}$$

  where, $\tan\beta = v_u/v_d$, the ratio of the Higgs vacuum expectation values. The second relation provides with B at the EW scale which is RGE evolved to find B_0, the GUT scale value.
- Thus, μ_0 is eliminated via M_Z (except its sign) and B_0 is exchanged by $\tan\beta$. $\Rightarrow$**Free parameters:** $\boxed{\tan\beta, m_{1/2}, m_0, A_0 \text{ and } \mathrm{sign}(\mu)}$.

Nonholomorphic soft SUSY breaking terms

- MSSM: Trilinear soft breaking terms:

$$-\mathcal{L}_{soft} \supset \tilde{q}_{iL}.hu(A_u)_{ij}\tilde{u}^*_{jR} + h_d.\tilde{q}_{iL}(A_d)_{ij}\tilde{d}^*_{jR} + h_d.\tilde{l}_{iL}(A_e)_{ij}\tilde{e}^*_{jR} + h.c.$$

- In absence of any SM gauge singlet the above may be extended to include some trilinear non-holomorphic (NH) soft SUSY breaking terms along with a coupling term involving higgsinos without inviting any possibility of a quadratic divergence.
- NHSSM:

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

- General terms of nonholomorphic nature from S. Martin PRD 2000
- Thus we choose only scenarios whether there is no gauge singlet. Otherwise we would encounter tadpoles which would invite quadratic divergence. We consider terms like $\phi^2\phi^*$ and $\psi\psi$ as shown above.

Nonholomorphic terms: Past phenomenological analyses and present work

- 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 in R-parity conserved and violated scenarios.

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- Works performed under Constrained MSSM (CMSSM)/minimal supergravity(mSUGRA) setup that studied the Higgs sector while also studying the effects on B-physics related observables like $\mathrm{Br}(B \to X_s + \gamma)$: Hetherington JHEP 2001, Solmaz *et. al.* PRD 2005, PLB 2008, PRD 2015 [perfomed in a mixed type of inputs involving unification and electrweak scale]. Many of the above analyses commented on Fine-tuning. But an mSUGRA type of setup is essentially unrealistic since NH terms are highly Planck Mass suppressed in a supergravity setup.

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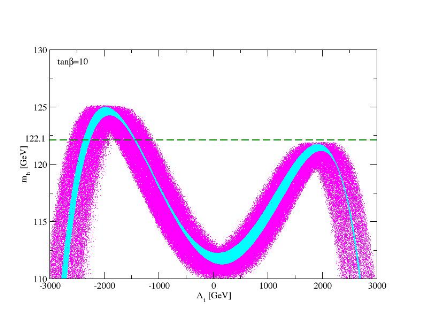
- Our work: Entirely MSSM type i.e. all the parameters are at the electroweak scale (using SARAH-SPHENO) and we additionally study the strong influence of NH terms on muon g-2. This is apart from exploring electroweak fine-tuning and analysing the scenario for a higgsino DM, Higgs mass, B-physics constraints etc. We additionally show how large tan β cases can be suitably accommodated while using constraints from $\mathrm{Br}(B \to X_s + \gamma)$ and muon $g - 2$.

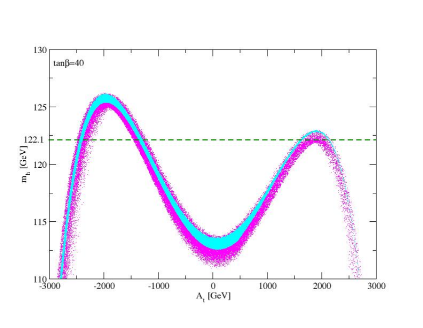
NHSSM: scalars and electroweakinos

- $$\textit{Squarks}: \quad M_{\tilde{u}}^2 = \begin{bmatrix} m_{\tilde{Q}}^2 + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W) M_Z^2 \cos 2\beta + m_u^2 & -m_u(A_u - (\mu + A_u')\cot\beta) \\ -m_u(A_u - (\mu + A_u')\cot\beta) & m_{\tilde{u}}^2 + \frac{2}{3}\sin^2\theta_W M_Z^2 \cos 2\beta + m_u^2 \end{bmatrix},$$
  $$\textit{Sleptons}: \quad M_{\tilde{e}}^2 = \begin{bmatrix} M_{\tilde{l}_L}{}^2 + M_z^2 (T_{3L}^{\tilde{e}} - Q_e \sin^2\theta_W)\cos 2\beta + m_e^2 & -m_e(A_e - (\mu + A_e')\tan\beta) \\ -m_e(A_e - (\mu + A_e')\tan\beta) & M_{\tilde{l}_R}{}^2 + M_Z^2 Q_e \sin^2\theta_W \cos 2\beta + m_e^2 \end{bmatrix}.$$
- $$\text{Higgs mass corrections}: \Delta m_{h,top}^2 = \frac{3 g_2^2 \bar{m}_t^4}{8\pi^2 M_W^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{\bar{m}_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right],$$
  Here, $X_t = A_t - (\mu + A_t')\cot\beta$.
- $$\textit{Charginos}: M_{\widetilde{\chi}^{\pm}} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & -(\mu - \mu') \end{pmatrix},$$
  $m_{\widetilde{\chi}_1^{\pm}} \gtrsim 100$ GeV $\Rightarrow |\mu - \mu'| \gtrsim 100$ GeV. However $|\mu|$ can be small.
- $$\textit{Neutralinos}: M_{\widetilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z \cos\beta \sin\theta_W & M_Z \sin\beta \sin\theta_W \\ 0 & M_2 & M_Z \cos\beta \cos\theta_W & -M_Z \sin\beta \cos\theta_W \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & -(\mu - \mu') \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & -(\mu - \mu') & 0 \end{pmatrix}$$
- If $M_1 << M_2 < |(\mu - \mu')| \Rightarrow \widetilde{\chi}_1^0$ is bino-like. Similarly, if M_2 is the smallest $\Rightarrow \widetilde{\chi}_1^0$ is Wino-like or if $|(\mu - \mu')|$ is the smallest $\Rightarrow \widetilde{\chi}_1^0$ is Higgsino-like.

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 $|A_t|$.

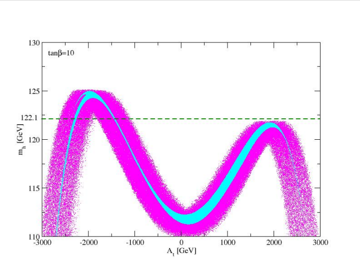


m_h against A_t for $\tan\beta = 40$.
- Since A_t' is associated with a suppression by $\tan\beta$ [off-diag term in stop sector: $X_t = A_t - (\mu + A_t')\cot\beta$], m_h is affected only marginally.

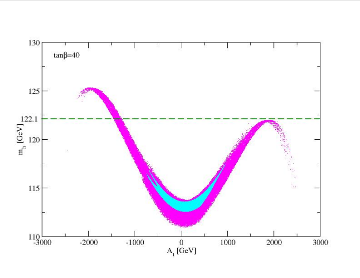
- $0 \leqslant \mu \leqslant 1\ \mathrm{TeV}$, $-2 \leqslant \mu' \leqslant 2\ \mathrm{TeV}$, $-3 \leqslant A_t' \leqslant 3\ \mathrm{TeV}$. *Further details:*
- Code:SARAH-SPHENO, A 3 GeV uncertainty in computation of m_h in SUSY is assumed.

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' via the stop mixing effect $(A_t \to A_t - (\mu + A_t')\cot\beta)$ is small. μ' may affect the chargino loop contributions. 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

At the tree level, the Higgs potential remains unaltered in NHSSM (wrt MSSM).

$$V = (m_{H_u}^2 + \mu^2)|H_u^0|^2 + (m_{H_d}^2 + \mu^2)|H_d^0|^2 - b(H_u^0 H_d^0 + h.c.) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2$$

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

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

- 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 $\Delta(b) \simeq \frac{4M_A^2}{m_Z^2 \tan\beta}$.

  $\Rightarrow$ for a moderately large $\tan\beta$, a small value of Δ_{Total} means a small value of μ. Δ_{p_i} details.

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- The fact that V is independent of μ', Δ_{Total} depends on μ and higgsino DM mass satisfies $m_{\tilde{\chi}_1^0} \sim |\mu - \mu'|$ indicates isolation of higgsino mass from electroweak fine-tuning. Thus Δ_{Total} can be very small while the DM is a higgsino, a feature unavailable in MSSM.

Electroweak fine-tuning and higgsino dark matter

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- LEP Chargino limit: $|\mu - \mu'| \gtrsim 104\ \mathrm{GeV}$. μ itself can be very small causing Δ_{Total} to be small. Δ_{Total} may also become very large for large μ for the same higgsino mass $\mu - \mu'$.

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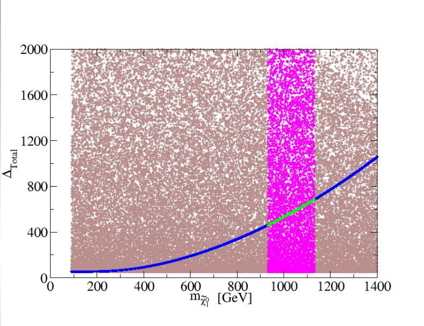
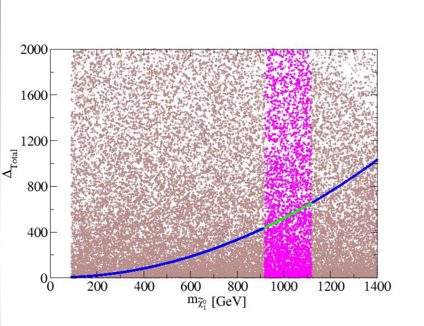


Δ_{Total} vs $m_{\tilde{\chi}_1^0}$ for $\tan\beta = 10$

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 can be too high or too low (~ 50).

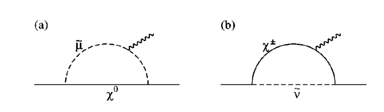


Δ_{Total} vs $m_{\tilde{\chi}_1^0}$ for $\tan\beta = 40$

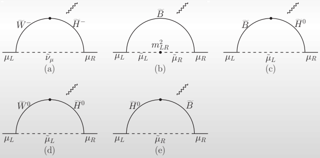
EWFT in NHSSM can be vanishingly small.

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:



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

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

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

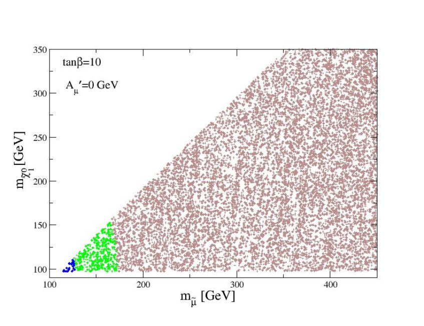
$$\Delta a_\mu(\tilde{B}, \tilde{H}, \tilde{\mu}_R) \simeq -1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\ \mathrm{GeV})^2}{M_1\mu}\right)\left(\frac{f_N}{1/6}\right),$$

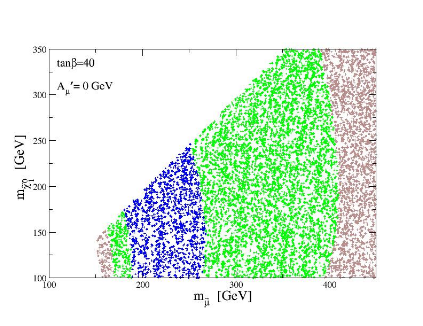
$$\Delta a_\mu(\tilde{\mu}_L, \tilde{\mu}_R, \tilde{B}) \simeq 1.5 \times 10^{-9} \left(\frac{\tan\beta}{10}\right)\left(\frac{(100\ \mathrm{GeV})^2}{m^2_{\tilde{\mu}_L} m^2_{\tilde{\mu}_R}/M_1\mu}\right)\left(\frac{f_N}{1/6}\right).$$

- 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 is thus enhanced by $\tan\beta$ causing a significant change in Δa_μ.

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

Results of muon g-2 in MSSM



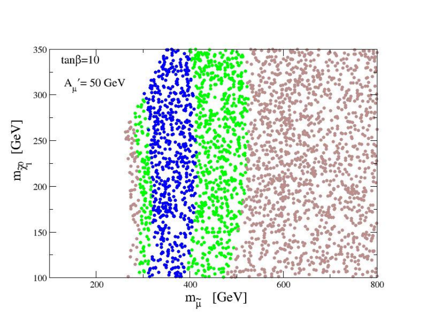


Plot in $m_{\widetilde{\chi}_1^0}$ vs $m_{\tilde{\mu}_1}$ plane for $\tan\beta = 10$ Same for $\tan\beta = 40$.

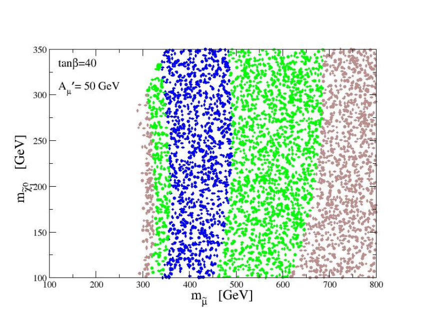
$\mu = 500$ GeV and $M_2 = 1500$ GeV. Blue, green and brown regions satisfy the muon g-2 constraint at 1σ, 2σ and 3σ levels respectively. All the squark and stau masses are set at 1 TeV. All trilinear parameters are zero except $A_t = -1.5$ TeV that is favourable to satisfy the Higgs mass data. Only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



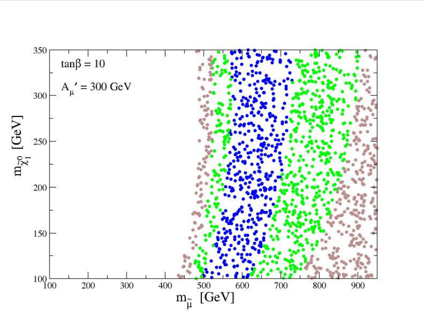
$m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{\mu}_1}$ plane for $\tan\beta = 10$.
Upper limit of $m_{\tilde{\mu}_1}$:400 GeV at 1σ.



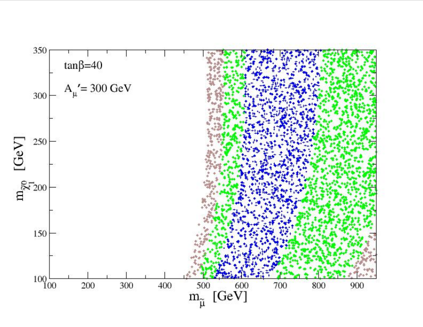
Same for $\tan\beta = 40$.
Upper limit of $m_{\tilde{\mu}_1}$:500 GeV at 1σ

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.

Benchmark Points

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.*

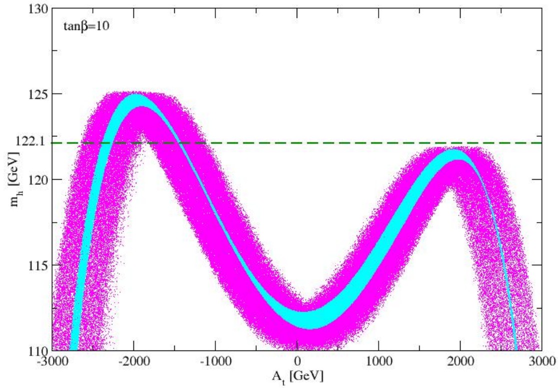
Parameters	MSSM	NHSSM	MSSM	NHSSM
$m_{1,2,3}$	472, 1500, 1450	472, 1500, 1450	243, 250, 1450	243, 250, 1450
$m_{\tilde{Q}_3}/m_{\tilde{U}_3}/m_{\tilde{D}_3}$	1000	1000	1000	1000
$m_{\tilde{Q}_2}/m_{\tilde{U}_2}/m_{\tilde{D}_2}$	1000	1000	1000	1000
$m_{\tilde{Q}_1}/m_{\tilde{U}_1}/m_{\tilde{D}_1}$	1000	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

It would be interesting to explore various beyond the MSSM scenarios with nonholomorphic susy breaking soft terms.

Thank you

Backup pages



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

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

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

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

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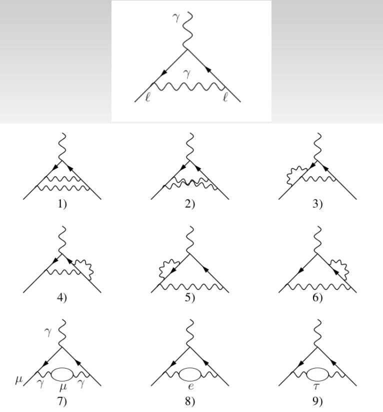
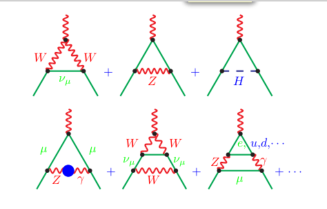
SM contributions: a_μ^{SM}

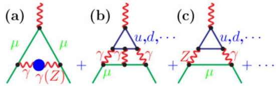
1 and 2-loop QED:



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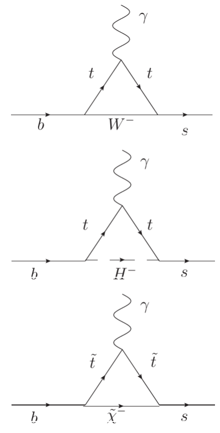
$\mathrm{Br}(B \to X_s + \gamma)$ in MSSM

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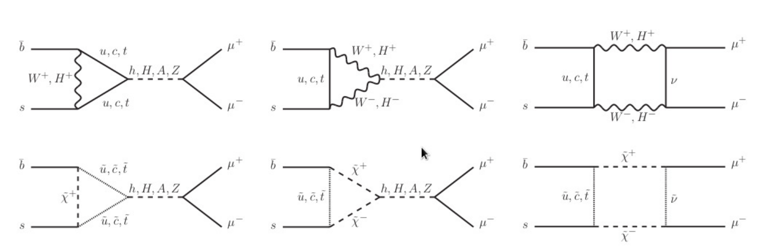
$B_s \to \mu^+\mu^-$ in MSSM



- Dominant SM contribution from : Z penguin top loop & W box diagram.
- SM value : $BR(B_s \to \mu^+\mu^-)$=$3.23 \pm 0.27 \times 10^{-9}$.
- 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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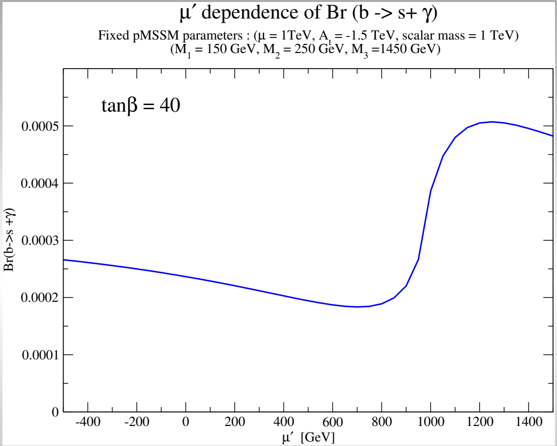

Dependence of $\mathrm{Br}(B \to X_s + \gamma)$ on μ'

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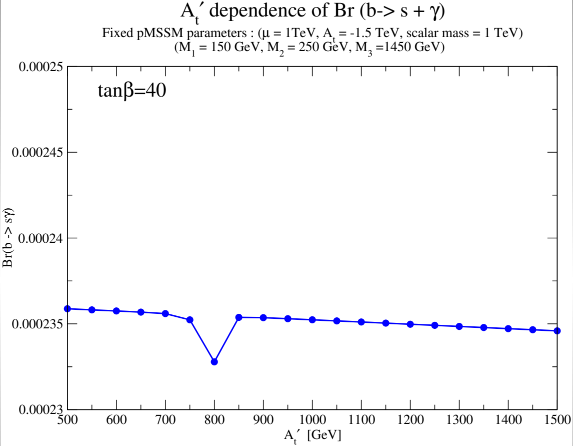

Dependence of $\mathrm{Br}(B \to X_s + \gamma)$ on A_t'

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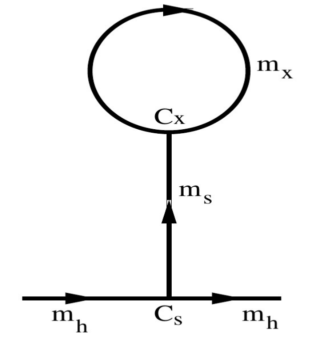
General terms of nonholomorphic nature

Terms of nonholomorphic nature: Back

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

Ref: S. Martin PRD 2000

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

Bino,Wino and Higgsino LSP: features

- **Bulk annihilation:** Annihilation via t-channel right handed component of sfermion exchange. Unless sfermions are light, a Bino dominated LSP typically gives a larger amount of DM relic density (over-abundance). Tight situation after Higgs@125.
- **Stau coannihilation region:** Coannihilation with sfermions, particularly staus.
- **Funnel region:** (mSUGRA, large $\tan\beta$ via RGE effect) Some small Higgsino content allows a Bino-dominated LSP to have the right degree of pair-annihilation via *s*-channel Higgs (A,H).
- **Focus Point/Hyperbolic Branch (FP/HB) region:** $m_0 >> m_{1/2}$ where μ becomes small so that the mass of lighter chargino is close to that of LSP. LSP has a considerable mixing of Higgsino (apart from the principal part Bino). $\Rightarrow$LSP-chargino coannihilation that satisfies the WMAP data.
- Wino-LSP: The dominant final state is the pair of W-bosons (W^+W^-) while the mediating particles are $\chi_1^\pm$.
- Higgsino LSP: May pair-annihilate to produce W-bosons in the final state. Additionally, there may be Z-boson final states via $\chi_1^0\chi_1^0 \to ZZ$ bosons via t-channel $\tilde{\chi}_i^0$ exchange.

Diags

Neutralino Relic Density Annihilation And Coannihilation Processes

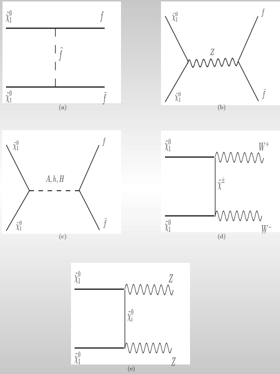

Figure 3.1: A few of the dominant neutralino annihilation diagrams.

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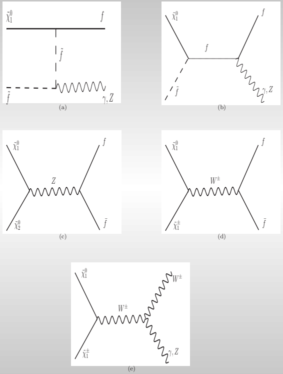

Figure 3.2: A few of the dominant neutralino coannihilation diagrams.

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