B-decays at Large $\tan\beta$ as a Probe of SUSY Breaking

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  - $B \to X_s l^+ l^-$
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Introduction

- MSSM with R-parity
  - too many free parameters (124): mostly come from the flavor sector in the soft SUSY breaking Lagrangian
  - generic FCNC and CP problems

$\rightarrow$ soft terms are thought to be originated from more microscopic theory.

- mSUGRA model is a benchmark scenario:
  - with the radiative electroweak symmetry breaking condition it is described by 5 parameters

$$m_0, \quad m_{1/2}, \quad A_0, \quad \tan\beta, \quad \mathrm{sign}(\mu).$$

    $\rightarrow$ if we assume all the parameters are real, SUSY FCNC and SUSY CP problems can be evaded.

  - $M_1 : M_2 : M_3 \approx 1 : 2 : 6$. LSP is $\widetilde{B}-$like neutralino.
  - FCNC is uncontrollable beyond minimal Kähler potential:

$$\int d^4\theta c_{ij} \frac{Z^\dagger Z}{M_{pl}^2} \phi_i^\dagger \phi_j.$$

- Mediation models of SUSY breaking which predict flavor conserving soft terms
  - Gauge mediation (GMSB)
  - Anomaly mediation (AMSB)
  - Gaugino mediation ($\widetilde{g}$MSB)/ no-scale supergravity
  - Dilaton-domination in string theory
  - Dilaton/modulus mediation in heterotic M theory

- Generic soft SUSY-breaking Lagrangian

$$\mathcal{L}_{\rm SSB} = \frac{1}{2}M_\lambda\lambda\lambda - (m^2)^j_i z^i z^*_j - \frac{1}{6}A_{ijk}z^i z^j z^k.$$

- GMSB

M. Dine, A. E. Nelson (1993)
M. Dine, A. E. Nelson, Y. Shirman (1995)
M. Dine, A. E. Nelson, Y. Nir, Y. Shirman (1996)
G.F.Giudice, R. Rattazzi (1999)

  – N flavors of messenger superfields Ψ_i, Ψ^c_i *eg.* $\sim (\mathbf{5}+\bar{\mathbf{5}})$ of SU(5) couple to gauge singlet superfield X which aquire VEV in the scalar and F-component: $\langle X\rangle = M + \theta^2 F$

$$W = \lambda_i X \Psi_i \Psi^c_i.$$

  – Parameters (w/ rewsb)

$$N, \quad M, \quad \Lambda \equiv F/M, \quad \tan\beta, \quad {\rm sign}(\mu).$$

  – Soft terms are generated through usual gauge interactions

$$M_a = N\frac{\alpha_a(M)}{4\pi}\frac{F}{M},$$
$$(m^2)^j_i = 2N\delta^j_i \sum_a C^i_a \left(\frac{\alpha_a(M)}{4\pi}\right)^2\left(\frac{F}{M}\right)^2,$$
$$A_{ijk} = 0.$$

  $\rightarrow$ flavor universal because gauge interaction is flavor-blind

  – gravitino is LSP ($m_{3/2} = \frac{F}{\sqrt{3}M_{\rm pl}}$)
  – NLSP can be neutralino, stau or sneutrino.
  – perturbativity of gauge interactions up to $M_{\rm GUT}$ requires

$$\frac{1}{\alpha_{\rm GUT}} \approx 24. - \frac{N}{2\pi}\log\frac{M_{\rm GUT}}{M} \gtrsim 1$$

$\to N \lesssim 5$ for $M = 100$ TeV.

– Requiring the gravity contribution is suppressed at per mille level,

$$M \lesssim \frac{1}{10^{3/2}} \frac{\alpha}{4\pi} M_{\rm pl} \sim 10^{15}\ {\rm GeV}.$$

- AMSB

L. Randall, R. Sundrum (1999)
G. Giudice, M. Luty, H. Murayama, R. Rattazzi (1998)
J. L. Feng, T. Moroi (2000)

– SUSY breaking is mediated by superconformal anomaly

– Soft terms are proportional to the corresponding beta functions

$$\begin{aligned} M_\lambda &= \frac{1}{16\pi^2} b g^2 M_{\rm aux} \\ (m^2)_i^j &= \frac{1}{2} (\dot\gamma)_i^j M_{\rm aux}^2 \\ A_{ijk} &= -(\gamma_i^m Y_{mjk} + \gamma_j^m Y_{imk} + \gamma_k^m Y_{ijm}) M_{\rm aux} \\ 16\pi^2 \gamma_i^j &= \frac{1}{2} Y_{imn} Y^{jmn} - 2\delta_i^j g^2 C(i). \end{aligned}$$

$\to$ RG invariant (pure AMSB)

$\to$ Sleptons are tachyons.

– minimal AMSB

$$(m^2)_i^j \to (m^2)_i^j + m_0^2 \delta_i^j$$

– Parameters

$$M_{\rm aux}, \quad m_0, \quad \tan\beta, \quad {\rm sign}(\mu).$$

– $M_1 : M_2 : M_3 = 2.8 : 1 : -8.3$, *i.e.* $M_{1,2} M_3 < 0$

– $|M_2| < |M_1| < |\mu| \to W$-inos are LSPs, $\widetilde{\chi}_1^0 \approx \widetilde{W}^0$, $\widetilde{\chi}_1^\pm \approx \widetilde{W}^\pm$

- $\widetilde{g}$MSB

D. E. Kaplan, G. D. Kribs, M. Schmaltz (2000)
Z. Chacko, M .A. Luty, A. E. Nelson, E. Pontón (2000)

  – Supersymmetry breaking on 'source' brane is mediated to 'matter' brane through an extra dimension by bulk gauge/gaugino fields.
  – Parameters

$$L^{-1}, \quad M_{1/2}, \quad \tan\beta, \quad \text{sign}(\mu)$$

  – Soft terms at compactification scale L^{-1}:

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2} \; (M_{1/2} = \frac{1}{ML}\frac{F}{M}), \quad m^{2\,j}_{\;i} = 0, \quad A_{ijk} = 0.$$

  – gravitino LSP in most of parameter space $(m_{3/2} = \frac{F}{\sqrt{3}M_{\rm pl}})$, stau NLSP
  – If $L^{-1} \sim M_{\rm pl}$, $\widetilde{g}$MSB is similar to no-scale supergravity.

- Dilaton domination in string theory
  – Parameters

$$M_{\rm aux}, \quad \tan\beta, \quad \text{sign}(\mu).$$

  – Soft terms at $M_{\rm GUT} \approx 2 \times 10^{16}$

$$M_\lambda = \sqrt{3}M_{\rm aux}, \quad m^{2\,j}_{\;i} = |M_{\rm aux}|^2\,\delta_i^j, \quad A_{ijk} = \sqrt{3}M_{\rm aux}.$$

  – CCB minimum $\to$ entire parameter space is excluded

- Heterotic M theory with dilaton/moduli mediations

– Parameters

$$m_{3/2}, \quad \sin\theta, \quad \epsilon, \quad \tan\beta, \quad \mathrm{sign}(\mu).$$

– soft terms at string scale

$$\begin{aligned}
M_a &= \frac{\sqrt{3}m_{3/2}}{1+\epsilon}\left[\sin\theta + \frac{\epsilon}{\sqrt{3}}\cos\theta\right], \\
A_{ijk} &= -\frac{\sqrt{3}m_{3/2}}{3+\epsilon}\left[(3-2\epsilon)\sin\theta + \sqrt{3}\cos\theta\right], \\
\left(m^2\right)^i_j &= \delta^i_j m^2_{3/2}\left[1 - \frac{3}{(3+\epsilon)^2}\Big(\epsilon(6+\epsilon)\sin^2\theta + (3+2\epsilon)\cos^2\theta\right. \\
&\quad \left. -2\sqrt{3}\sin\theta\cos\theta\Big)\right].
\end{aligned}$$

Indirect Searches of the MSSM

- Indirect searches:
  - can probe particles running in the loops, even ones too heavy to be produced at colliders.
  - sensitive to flavor structure.
  - complementary to the direct search for SUSY particles.
  - We study

    $$(g-2)_\mu, \quad B \to X_s + \gamma, \quad B_s \to \mu^+\mu^-, \quad B \to X_s l^+ l^-$$

    at large $\tan\beta$.
- Large $\tan\beta$:
  - Yukawa coupling unification
  - Large y_b correction (HRS effect)

    $$y_b = \frac{g m_b}{\sqrt{2} m_W \cos\beta} \frac{1}{1 + \Delta_b \tan\beta},$$

    with

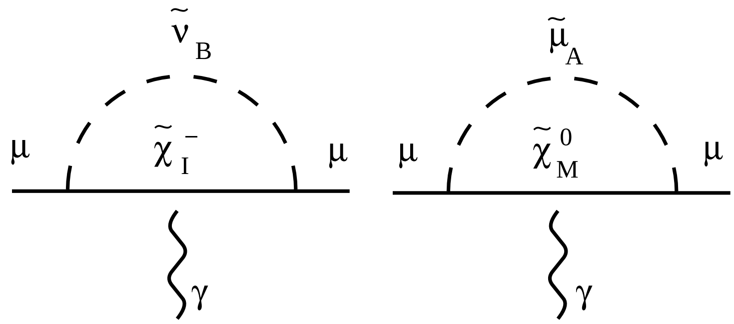
    $$\Delta_b \approx \frac{2\alpha_s}{3\pi} \mu M_3 \, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}).$$

- $(g-2)_\mu$
  - New Physics contribution to $a_\mu = (g_\mu - 2)/2$

    $$\mathcal{L}_{eff} = \frac{e}{2} \frac{m_\mu}{\Lambda^2} \, \overline{\mu} \sigma^{\mu\nu} \left(C_R P_R + C_L P_L \right) \mu F_{\mu\nu},$$

    $$\delta a_\mu = \frac{m_\mu^2}{\Lambda^2} \left(C_R + C_L \right).$$

  - MSSM contribution



$\delta a_\mu > 0$ if $M_2 \mu > 0$.

– BNL E821

$$
\begin{aligned}
a_\mu^{\rm exp} &= 11\,659\,203(15) \times 10^{-10} \\
\rightarrow a_\mu^{\rm exp} - a_\mu^{\rm SM} &= (26 \pm 16) \times 10^{-10}
\end{aligned}
$$

1.6σ deviation from the SM calculation.

- Effective Hamiltonian for $B \rightarrow X_s \gamma, B_s \rightarrow \ell^+\ell^-, B \rightarrow X_s \ell^+ \ell^-$:

$$
\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1,\cdots,10,S,P} C_i(\mu) Q_i(\mu),
$$

where

$$
\begin{aligned}
Q_1 &= (\bar{s}_\alpha \gamma_\mu P_L c_\beta)(\bar{c}_\beta \gamma^\mu P_L s_\alpha) \\
Q_2 &= (\bar{s}_\alpha \gamma_\mu P_L c_\alpha)(\bar{c}_\beta \gamma^\mu P_L s_\beta) \\
Q_3 &= (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu P_L q_\beta) \\
Q_4 &= (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu P_L q_\alpha) \\
Q_5 &= (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu P_R q_\beta) \\
Q_6 &= (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_{q=u,d,s,c,b} (\bar{q}_\beta \gamma^\mu P_R q_\alpha) \\
Q_7 &= \frac{e}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R b_\alpha F_{\mu\nu}
\end{aligned}
$$

$$
\begin{aligned}
Q_8 &= \frac{g_s}{16\pi^2} m_b \bar{d}_\alpha \sigma^{\mu\nu} P_R T^a_{\alpha\beta} s_\beta G^a_{\mu\nu} \\
C_{9V} &= \frac{e^2}{16\pi^2} (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \left(\bar{l}\gamma^\mu l\right) \\
Q_{10A} &= \frac{e^2}{16\pi^2} (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \left(\bar{l}\gamma^\mu \gamma_5 l\right) \\
Q_S &= \frac{e^2}{16\pi^2} m_b (\bar{s}_\alpha P_R b_\alpha) \left(\bar{l} l\right) \\
Q_P &= \frac{e^2}{16\pi^2} m_b (\bar{s}_\alpha P_R b_\alpha) \left(\bar{l} \gamma_5 l\right) \\
Q_T &= \frac{e^2}{16\pi^2} (\bar{s} \sigma_{\mu\nu} P_R b) \left(\bar{l} \sigma^{\mu\nu} P_R l\right)
\end{aligned}
$$

- $B \to X_s \gamma$
  - SM prediction:

$$\mathcal{B}(B \to X_s \gamma)_{\rm SM} = (3.29 \pm 0.33) \times 10^{-4}$$

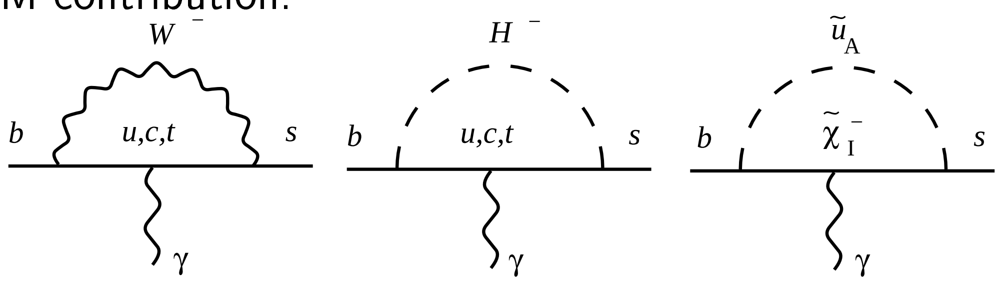
  - Current experimental bound:

$$B(B \to X_s \gamma)_{\rm exp} = (3.21 \pm 0.43_{(stat)} \pm 0.27_{(sys)}{}^{+0.18}_{-0.10(th)}) \times 10^{-4},$$

CLEO(2001)

:strong constraint to New Physics.

  - MSSM contribution:



$\widetilde{g}, \widetilde{\chi}^0$ contributions are negligible.
$H^\pm$-contribution constructive with the SM.
$\widetilde{\chi}^\pm$-contribution destructive with the SM if $M_3 \mu > 0$.

- $B_s \to l^+ l^-$
  - C_S and C_P dominate:

$$\mathcal{B}(B_s \to \mu^+\mu^-) = 8.75 \times 10^{-8} \left(\frac{|V_{ts}|}{0.040}\right)^2 \left(\frac{f_{B_s}}{210\text{MeV}}\right)^2 \times \left\{|M_{B_s} C_S|^2 + |M_{B_s} C_P + \frac{2m_\mu}{M_{B_s}} C_{10A}|^2\right\}]$$

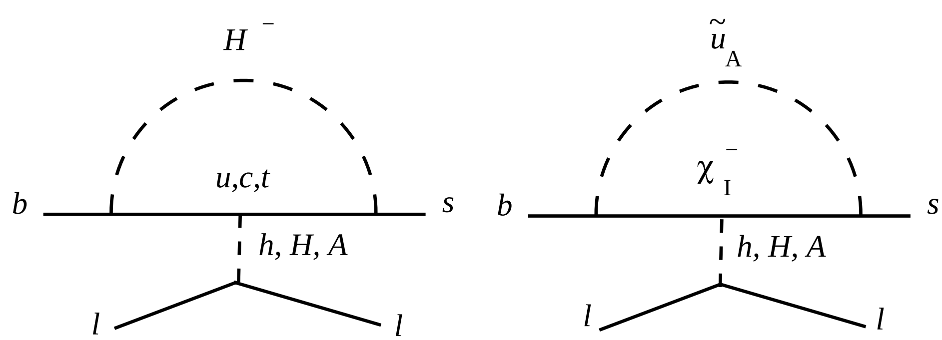
  - SM predictions

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.7 \pm 1.2) \times 10^{-9}$$

  - Experiments (CDF at Tevatron Run-I)

$$\mathcal{B}(B_s \to \mu^+\mu^-) < 2.6 \times 10^{-6} \quad (\text{@}90\%\text{CL})$$

  - Tevatron Run-II
    For $\mathcal{B}(B_s \to l^+ l^-) \approx 5 \times 10^{-8}$,
    ~ 5 events 2 fb^{-1} (Run-IIa)
    $\sim 25 - 50$ events 10-20 fb^{-1}. (Run-IIb)
  - Enhancement of 'Higgs penguins' at large $\tan\beta$:



$C_{S,P}$'s are no longer negligible.

$$\mathcal{B}(B_s \to \mu^+\mu^-) \propto \tan^6\beta$$

  - sensitive to $\tan\beta, m_A, \tilde{t}_1, A_t$.

- Numerical Analysis:
  - Direct search limits:

$$m_h^{\rm SM} > 113.5 \text{ GeV}, \quad m_{\tilde{\tau}_1} > 72 \text{ GeV}, \quad \cdots$$

  - $2.0 < \mathcal{B}(B \to X_s\gamma) < 4.5$
  - We did not impose neutralino LSP, nor no-CCB minima.
- mSUGRA:
  - Large $\mathcal{B}(B \to \mu^+\mu^-)$ ($\gtrsim 5 \times 10^{-8}$) possible for large δa_μ

    A. Dedes, H.K. Dreiner, U. Nierste (2001)
- $\mathcal{B}(B_s \to \mu^+\mu^-)$ is sensitive to SUSY breaking mediation models.
  - AMSB ($\mu > 0$) $\to$ $\mu M_3 < 0$
    * $\mathcal{B}(B \to X_s\gamma)$ too strong because chargino contribution is constructive to the SM.
    * HRS effect constrains $\tan\beta \lesssim 35$.
    * $\mathcal{B}(B_s \to \mu^+\mu^-)$ is small.
  - m_A is sensitive to $\tan\beta$
    * $\frac{dm^2_{H_d}}{dt} = 2\sum_i C_i^H \alpha_i |M_i|^2 - 3\lambda_b(|A_b|^2 + m^2_{H_d} + m^2_{\tilde{Q}_3} + m^2_{\tilde{b}})$ $\to m^2_{H_d}$ can be even negative for large $\tan\beta$.
    * $m_A^2 \approx 2|\mu|^2 + m^2_{H_d} + m^2_{H_u}$ is lowered at large $\tan\beta$.
    * Due to its small gauge interaction, $\tilde{\tau}_R$ can be easily driven to negative !!

$$\frac{dm^2_{\tilde{\tau}}}{dt} = \frac{12}{5}\alpha_1|M_1|^2 - 2\lambda_\tau(|A_\tau|^2 + m^2_{H_d} + m^2_{\tilde{L}_3} + m^2_{\tilde{\tau}})$$

    * mSUGRA: can satisfy both small m_A and $m_{\tilde{\tau}_R} > 0$ simultaneously $(m_0, m_{1/2})$

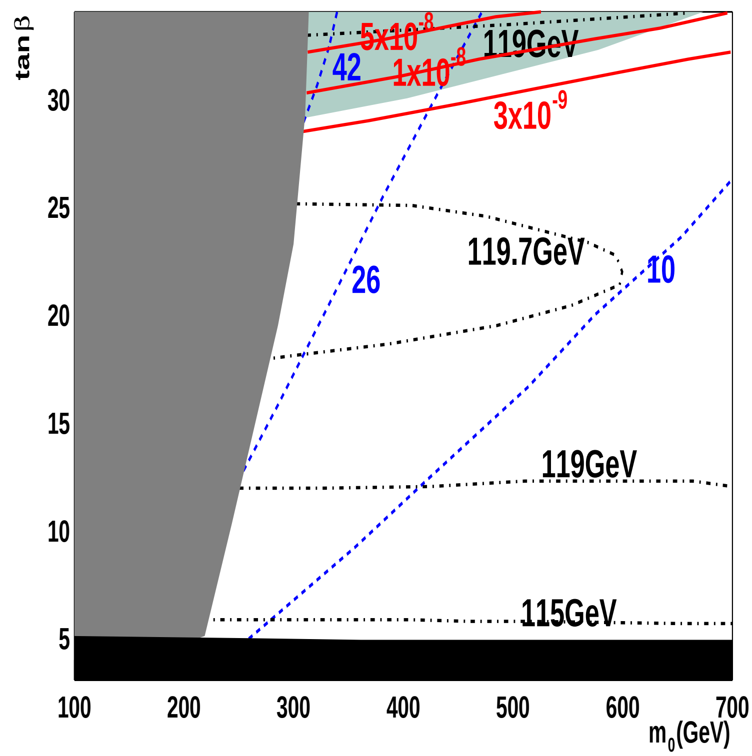
GMSB ($\widetilde{g}$MSB): both scalar and gaugino masses are controlled by a single mass parameter Λ ($M_{1/2}$)

* In GMSB, large M is favored $\leftarrow$ long running distance makes scalars lighter.
  For large N, scalar masses are suppressed relative to gaugino masses $\rightarrow \mathcal{B}(B_s \rightarrow \mu^+\mu^-)$ is enhanced.

AMSB

$m_{\rm aux} = 50$ (TeV)

$\mu > 0$

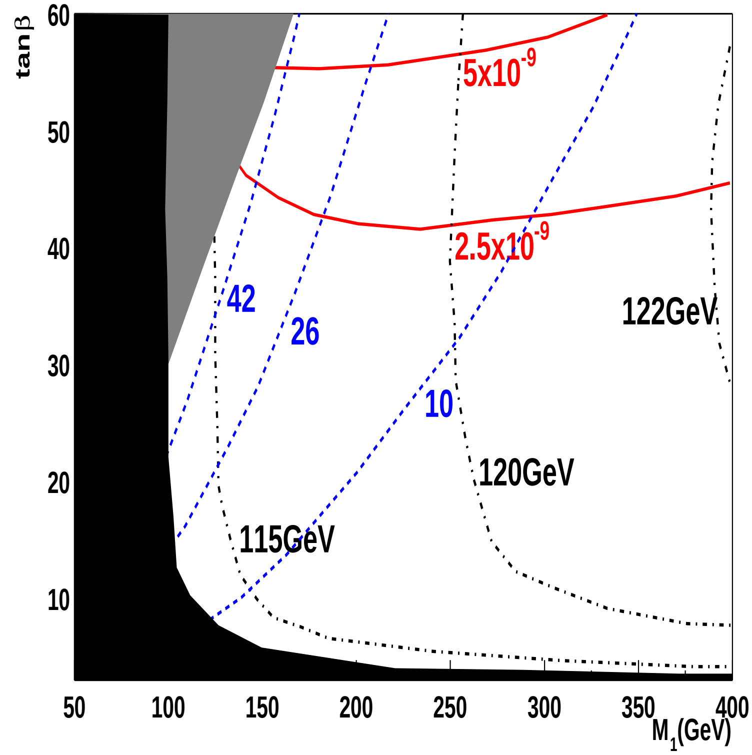


GMSB

$N = 1$

$M = 10^6$ (GeV)

$\mu > 0$

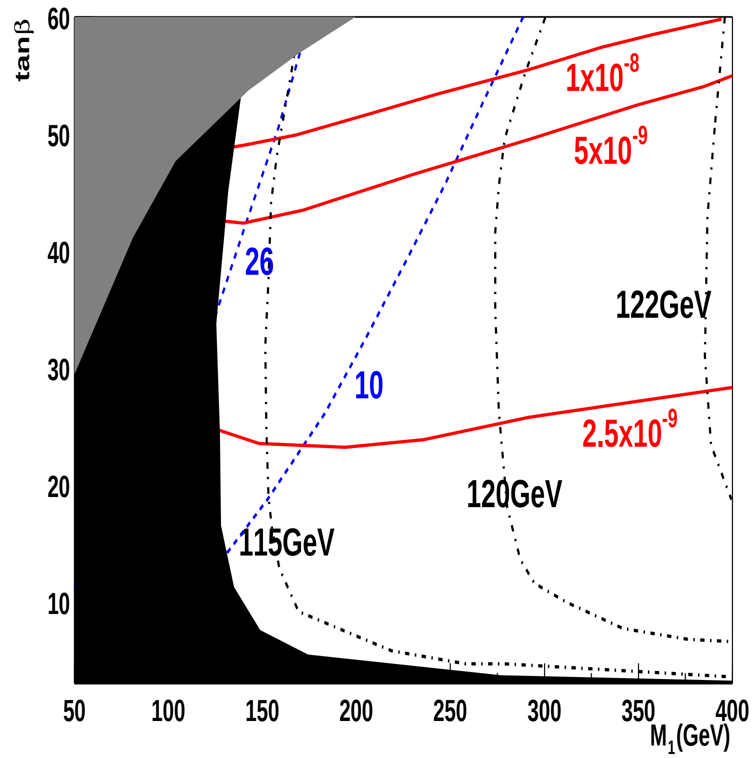


GMSB

$N = 1$

$M = 10^{15}$ (GeV)

$\mu > 0$

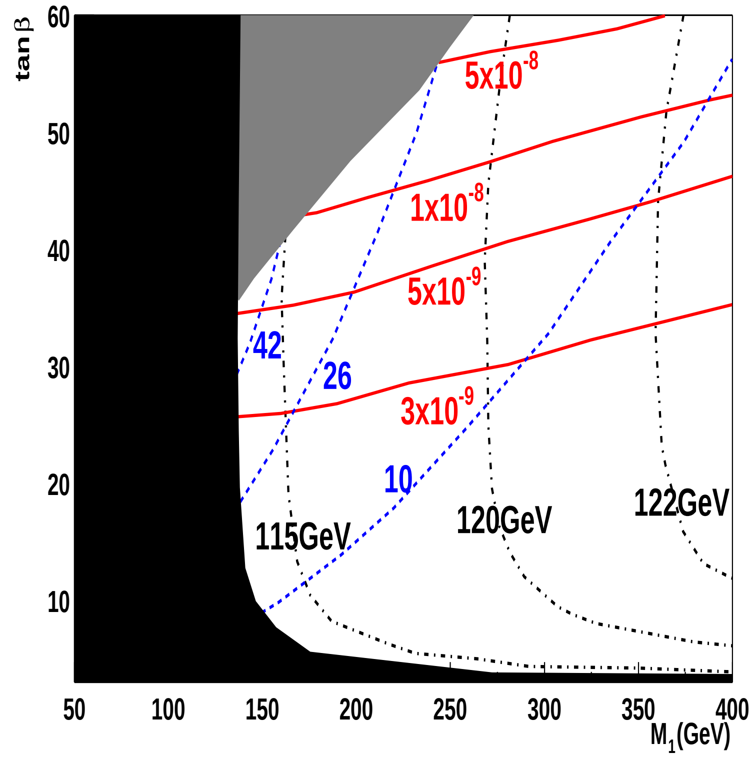


GMSB

$N = 5$

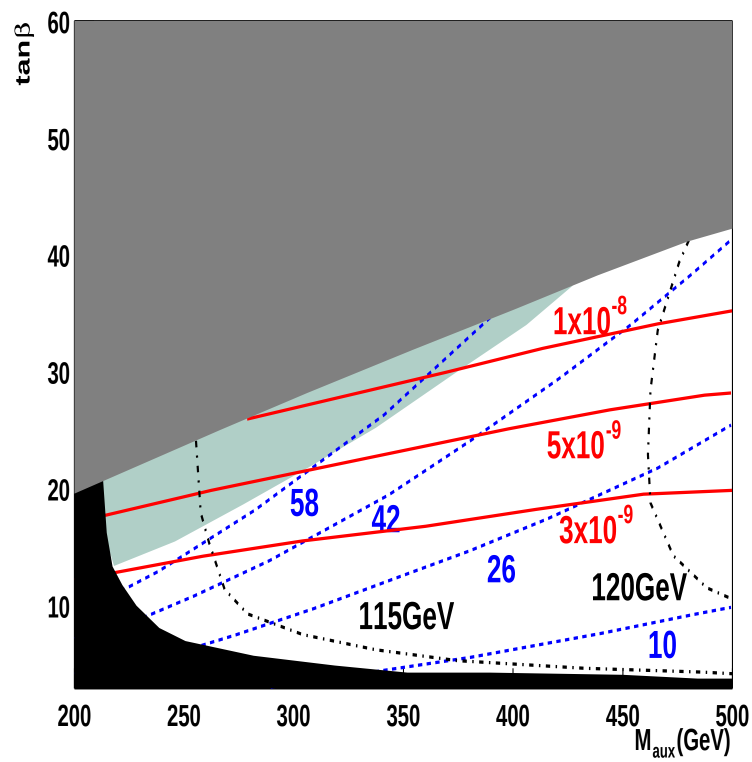
$M = 10^{15}$ (GeV)

$\mu > 0$



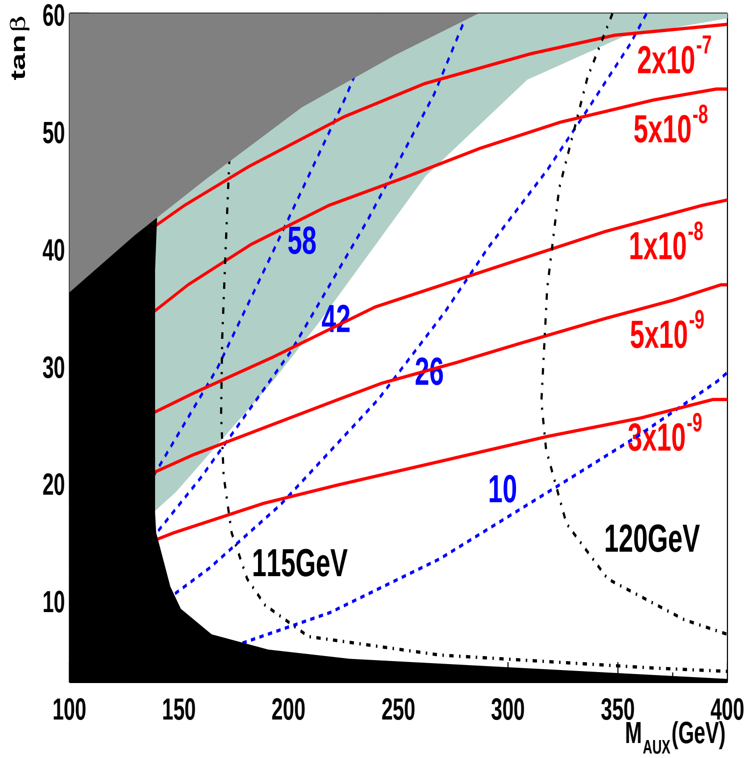
no-scale ($\widetilde{g}$MSB)

$\mu > 0$



dilaton

$\mu > 0$

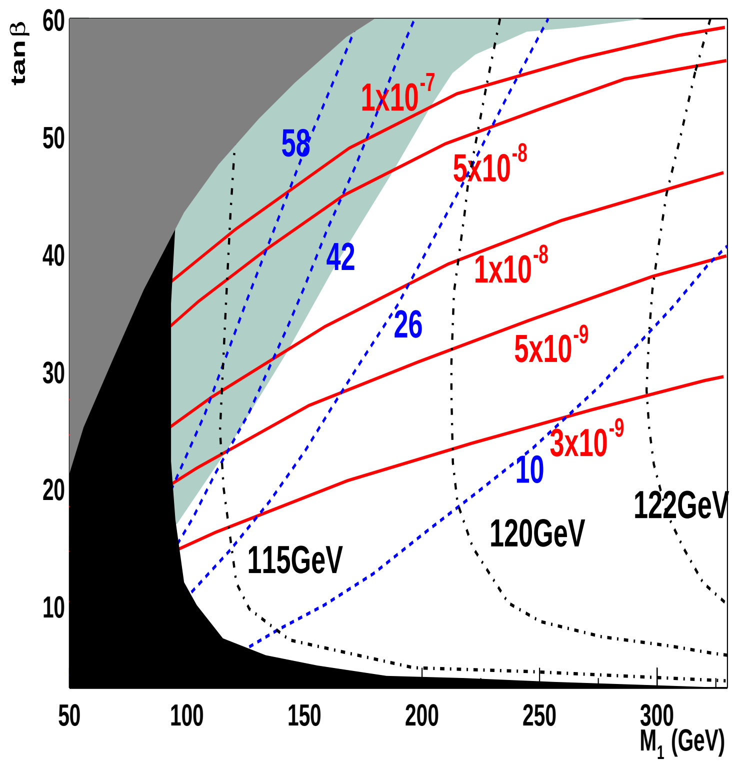


heterotic M

$\epsilon = 0.5$

$\theta = 0.15\pi$

$\mu > 0$

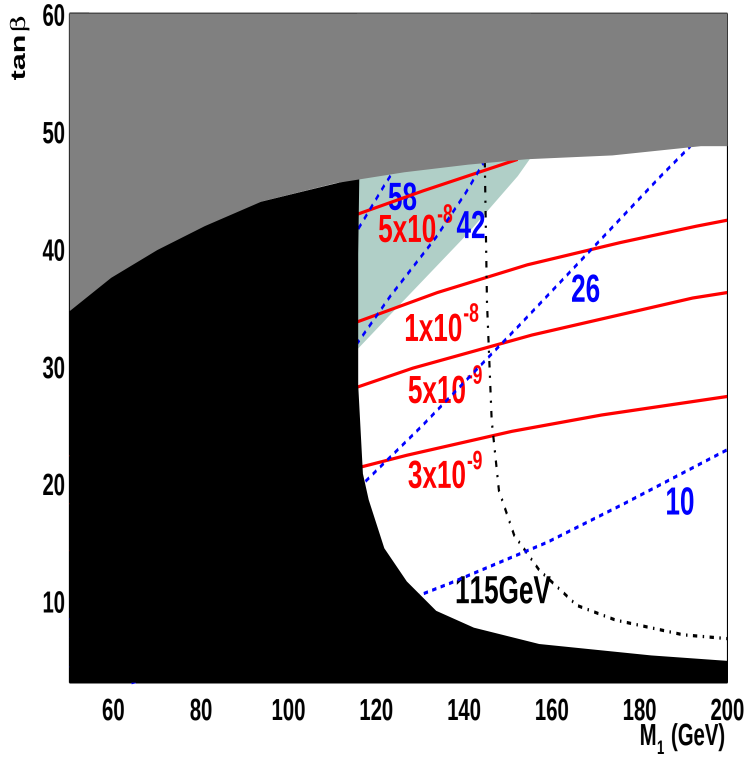


heterotic M

$\epsilon = -0.8$

$\theta = 0.15\pi$

$\mu > 0$



Conclusions

- $(g-2)_\mu$,$\mathcal{B}(B \to X_s\gamma)$, $\mathcal{B}(B_s \to \mu^+\mu^-)$, in several mediation models of SUSY breaking
- Large enhancement of $\mathcal{B}(B_s \to \mu^+\mu^-)$ is possible in some scenarios at large $\tan\beta$
- If $B_s \to \mu^+\mu^-$ is discovered at Tevatron Run-II, with BR$\approx 5 \times 10^{-8}$, mAMSB, GMSB with low N, $\widetilde{g}$MSB will be excluded.