Heavy Flavor Observables, SUSY, and the Higgs at 125 GeV

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based on arXiv:1211.1976 [hep-ph]

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Snapshot: the status of SUSY

- Theoretical impetus vs. a wealth of data
  - Null results in jets + MET for squarks, gluino below 1-1.5 TeV, multileptons for EW gauginos in 100-500 GeV range
  - Higgs discovery at 125 GeV
  - Null results for heavy MSSM Higgses
  - *B*- and *K*-physics observables
  - Dark matter direct detection

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Many complementary direct and indirect probes

Our focus on complementarity

- Quantitatively understand the impact of **direct** and **indirect** constraints on the MSSM parameter space
  - Assume **minimal flavor violation** and ***CP* conservation**
    - At tree level, have type II 2HDM and no FCNCs
    - At loop level, induce non-holomorphic Higgs couplings, parameterized by ε
  - ζ is alignment parameter for LH squark splitting effect on the down sector

$$\zeta = \frac{b_1 y_t^2 + b_3 y_b^2 y_t^2}{b_1 y_t^2 + b_2 y_b^2 + 2 b_3 y_b^2 y_t^2}$$

$$\begin{aligned}\hat{m}_Q^2 &= \tilde{m}_Q^2 \left(1 + b_1 V^\dagger y_u^2 V + b_2 y_d^2 \right.\\ &\qquad \left. + b_3 (y_d^2 V^\dagger y_u^2 V + V^\dagger y_u^2 V y_d^2)\right) \;, \\ \hat{m}_U^2 &= \tilde{m}_U^2 \left(1 + b_4 y_u^2\right) \;, \\ \hat{m}_D^2 &= \tilde{m}_D^2 \left(1 + b_5 y_d^2\right) \;,\end{aligned}$$

Example: $\xi_{sb}^{H/A}$ coupling

- Flavor changing coupling between bottom and strange induced by Higgsino-stop, gluino-squark, and wino-squarkloops
  - ζ is necessary for gluino and wino loops
  - If ζ=0, still have Higgsino loops
- These ε_{FC} parameters are non-decoupling!

$$\xi_{sb}^{H} \simeq \xi_{sb}^{A} \simeq \frac{\epsilon_{\rm FC}\ t_\beta^2}{(1+\epsilon_b t_\beta)(1+\epsilon_0 t_\beta)}\ V_{tb}V_{ts}^*$$

$$\epsilon_{\rm FC} = \epsilon_b^{\tilde{H}} + \zeta\epsilon_{\rm FC}^{\tilde{g}} + \zeta\epsilon_{\rm FC}^{\tilde{W}}$$

$$\begin{aligned}\epsilon_{\rm FC}^{\tilde{g}} &= \frac{\alpha_s}{4\pi}\frac{8}{3}\ \mu M_{\tilde{g}} \\ &\quad\times\left(g(M_3^2, m_{Q_3}^2, m_{D_3}^2) - g(M_3^2, m_Q^2, m_{D_3}^2)\right) \\ \epsilon_{\rm FC}^{\tilde{W}} &= -\frac{\alpha_2}{4\pi}\frac{3}{2}\ \mu M_2 \\ &\quad\times\left(g(\mu^2, M_2^2, m_{Q_3}^2) - g(\mu^2, M_2^2, m_Q^2)\right)\ ,\end{aligned}$$

$$\epsilon_b^{\tilde{H}} = \frac{\alpha_2}{4\pi}\frac{m_t^2}{2M_W^2}\ \mu A_t\ g(\mu^2, m_{Q_3}^2, m_{U_3}^2)$$

Direct and indirect observables

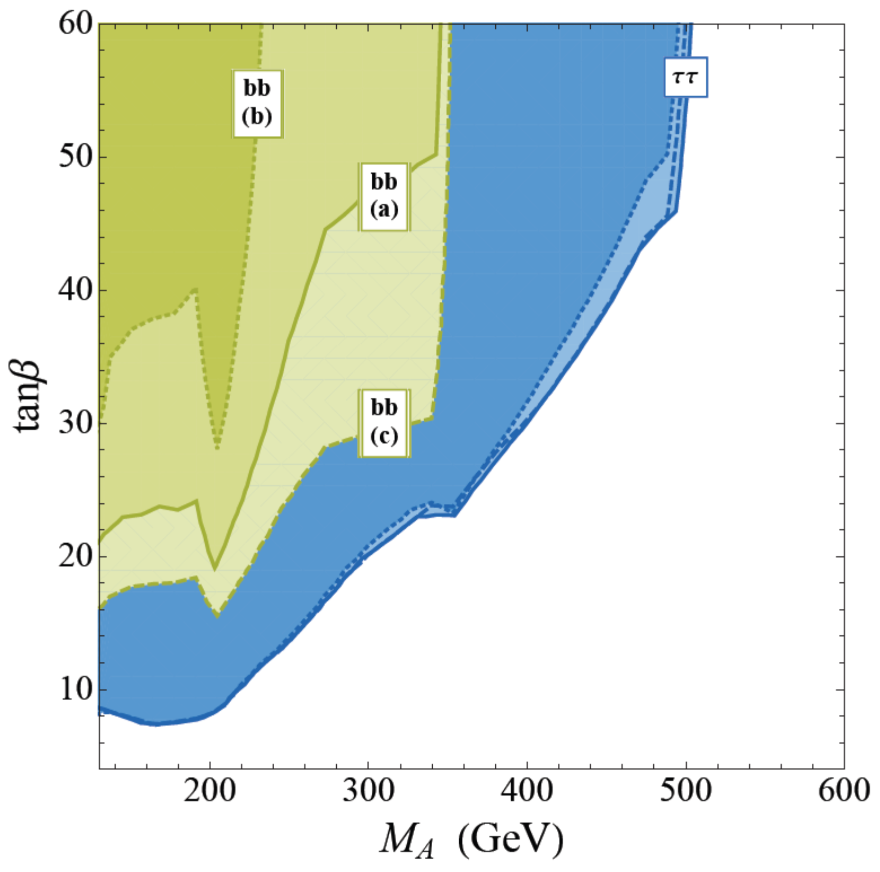
- $H/A \rightarrow bb$, $\tau\tau$
  - robust against changes in MSSM parameters
- $B \rightarrow \tau\nu$ and $K \rightarrow \mu\nu$
  - probe charged Higgs at tree level
  - cannot address $B \rightarrow D\tau\nu$ or $B \rightarrow D^* \tau\nu$ in MSSM+MFV
- $B_s \rightarrow \mu^+\mu^-$ (*new LHCb result claiming evidence in* ***1211.2674***)
  - probe neutral Higgs exchange
- $B \rightarrow X_s\gamma$
  - probe loops of stop-chargino, squark
- Also study vacuum stability, DM (see paper, 1211.1976)

H/A→bb, ττ constraints

- Consider four scenarios for understanding typical M_A vs. tan β constraints

Scenario	(a)	(b)	(c)	(d)
μ	1 TeV	4 TeV	-1.5 TeV	1 TeV
sign(A_t)	+	+	+	-

TABLE I. Illustrative MSSM scenarios discussed in the text. All sfermion masses are set to a common value 2 TeV, the gaugino masses to $6M_1 = 3M_2 = M_3 = 1.5$ TeV. The trilinear couplings $A_t = A_b = A_\tau$ are set such that the lightest Higgs mass is $M_h = 125$ GeV.



$$\Gamma_{Hbb} \simeq \Gamma_{Abb} \simeq \Gamma^{SM}_{hbb} \times \frac{t_\beta^2}{(1+\epsilon_b t_\beta)^2}$$

$$\Gamma_{H\tau\tau} \simeq \Gamma_{A\tau\tau} \simeq \Gamma^{SM}_{h\tau\tau} \times \frac{t_\beta^2}{(1+\epsilon_\tau t_\beta)^2}$$

B→τν, B→Dτν, B→D*τν, K→μν

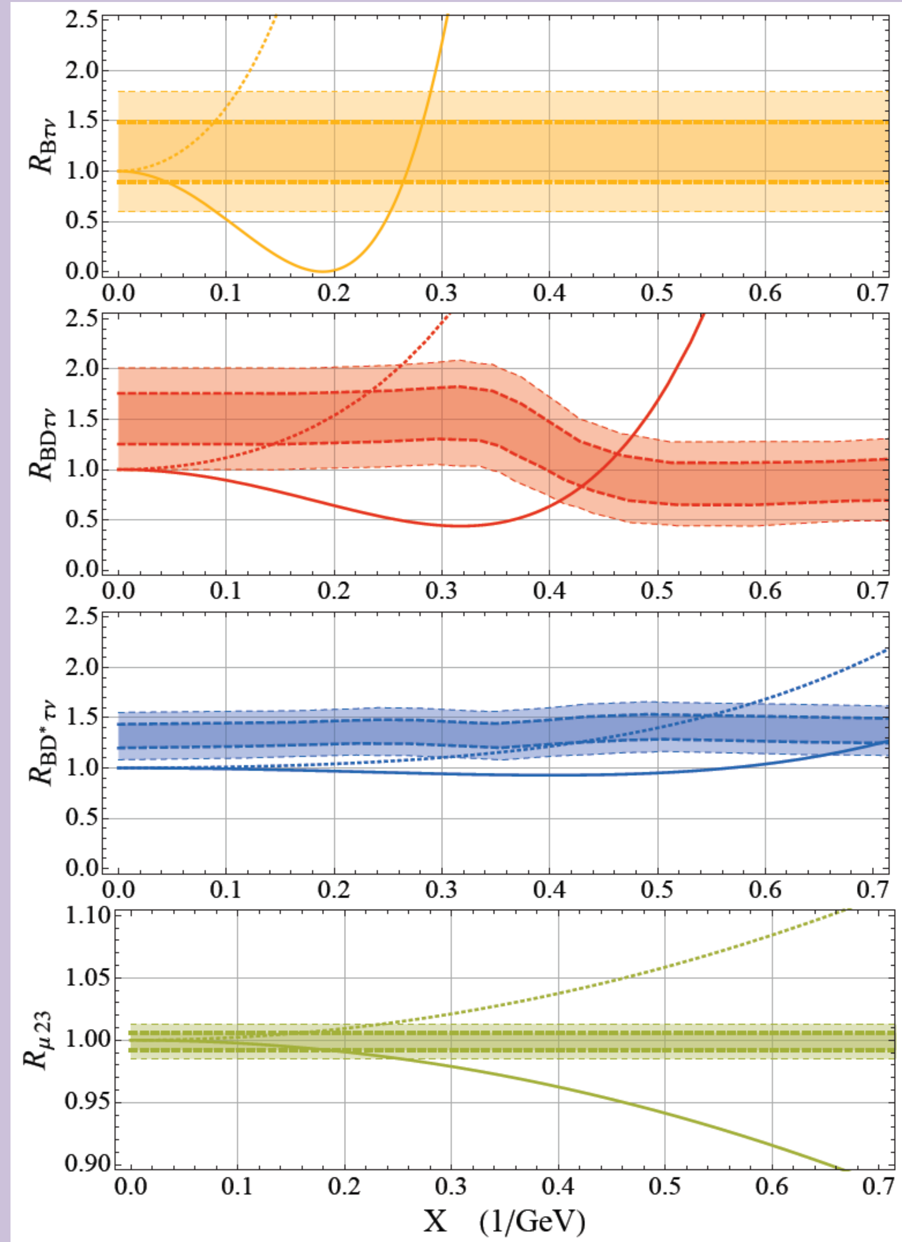
$$X^2_{B(K)} = \frac{1}{M^2_{H^\pm}} \frac{t^2_\beta}{(1+\epsilon_{0(s)}t_\beta)(1+\epsilon_\ell t_\beta)}$$

$$R_{B\tau\nu} = \frac{\mathrm{BR}(B\to\tau\nu)}{\mathrm{BR}(B\to\tau\nu)_{\mathrm{SM}}} = \left(1 - m^2_{B^+}X^2_B\right)^2 ,$$

$$R_{D\tau\nu} = \frac{\mathrm{BR}(B\to D\tau\nu)}{\mathrm{BR}(B\to D\tau\nu)_{\mathrm{SM}}} = \left(1 - 1.5\, m_\tau m_b X^2_B + 1.0\, m^2_\tau m^2_b X^4_B\right) ,$$

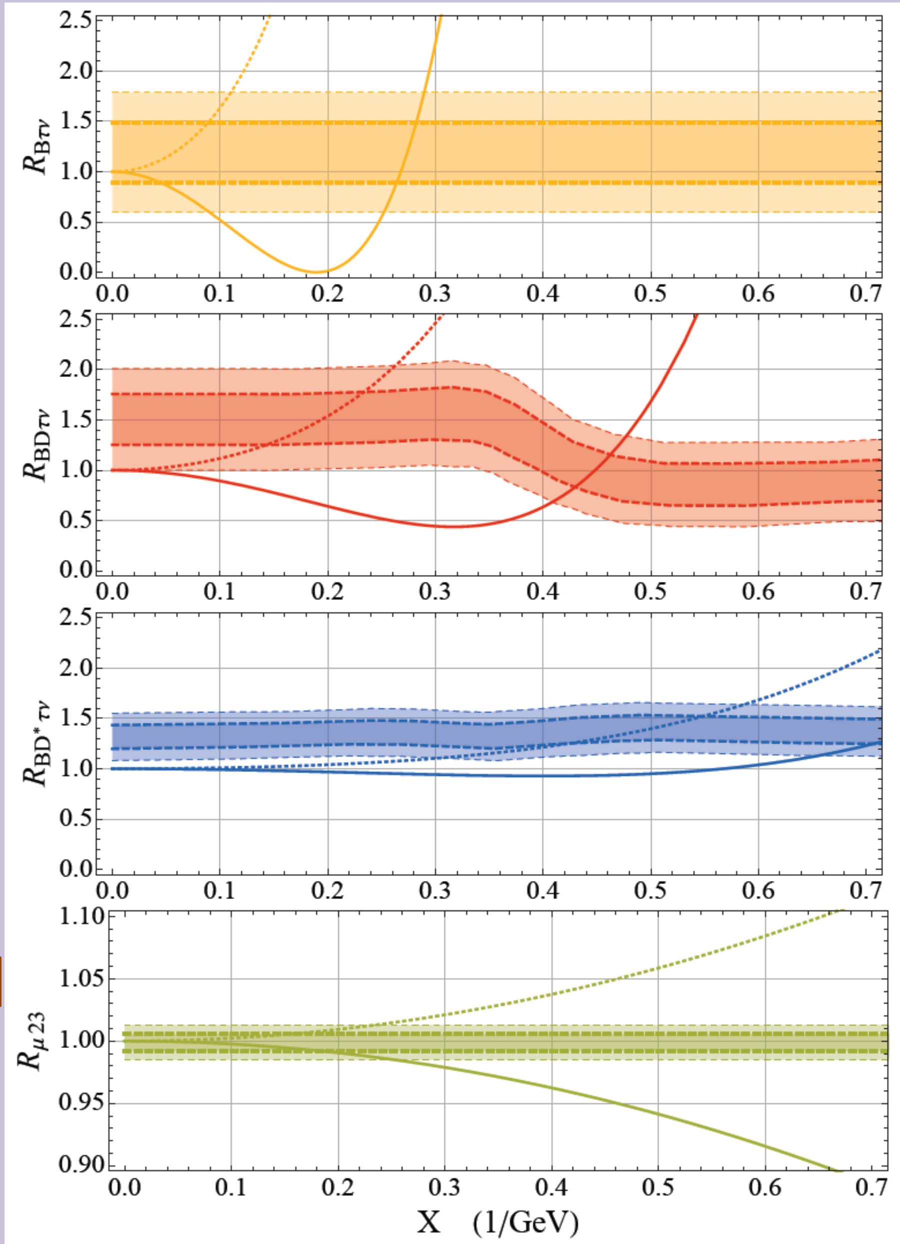
$$R_{D^*\tau\nu} = \frac{\mathrm{BR}(B\to D^*\tau\nu)}{\mathrm{BR}(B\to D^*\tau\nu)_{\mathrm{SM}}} = \left(1 - 0.12\, m_\tau m_b X^2_B + 0.05\, m^2_\tau m^2_b X^4_B\right)$$

$$R_{\mu 23} = \frac{\mathrm{BR}(K\to\mu\nu)}{\mathrm{BR}(K\to\mu\nu)_{\mathrm{SM}}} = \left(1 - m^2_{K^+}X^2_K\right) .$$



B→τν, B→Dτν, B→D*τν, K→μν

- Cannot address B→τν, B→Dτν, B→D*τν simultaneously
- MSSM charged Higgs is typically destructive with SM
  - From vacuum stability requirements, cannot find regions in parameter space where the sign of ε flips and changes the interference to be constructive

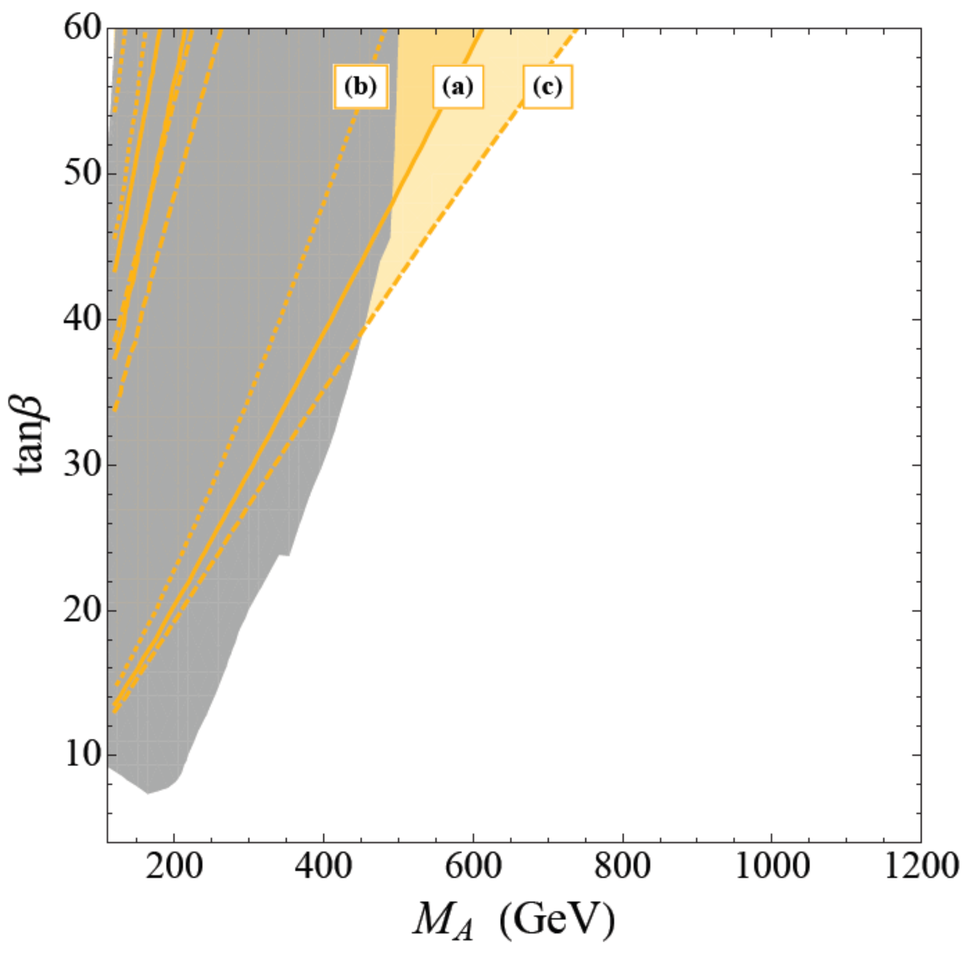


B→τν

$$\text{BR}(B \to \tau\nu)_{\text{SM}} = (0.97 \pm 0.22) \times 10^{-4}$$

$$\text{BR}(B \to \tau\nu)_{\text{exp}} = (1.16 \pm 0.22) \times 10^{-4}$$

- Again, charged Higgs is destructive with SM
- B→τν can be stronger than direct searches



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

- As we have seen, LHCb has an impressive, **new** measurement for $B_s \to \mu^+\mu^-$

1211.2674

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.32 \pm 0.17) \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = (3.2\ ^{+1.4}_{-1.2}\ ^{+0.5}_{-0.3}) \times 10^{-9}$$

$$1.1 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} < 6.4 \times 10^{-9}$$

@ 95% C.L.

- We have several SUSY contributions that come with separate signs and can cancel
  - Higgsino vs. gluino loop, and SM vs. SUSY, total SUSY amplitude

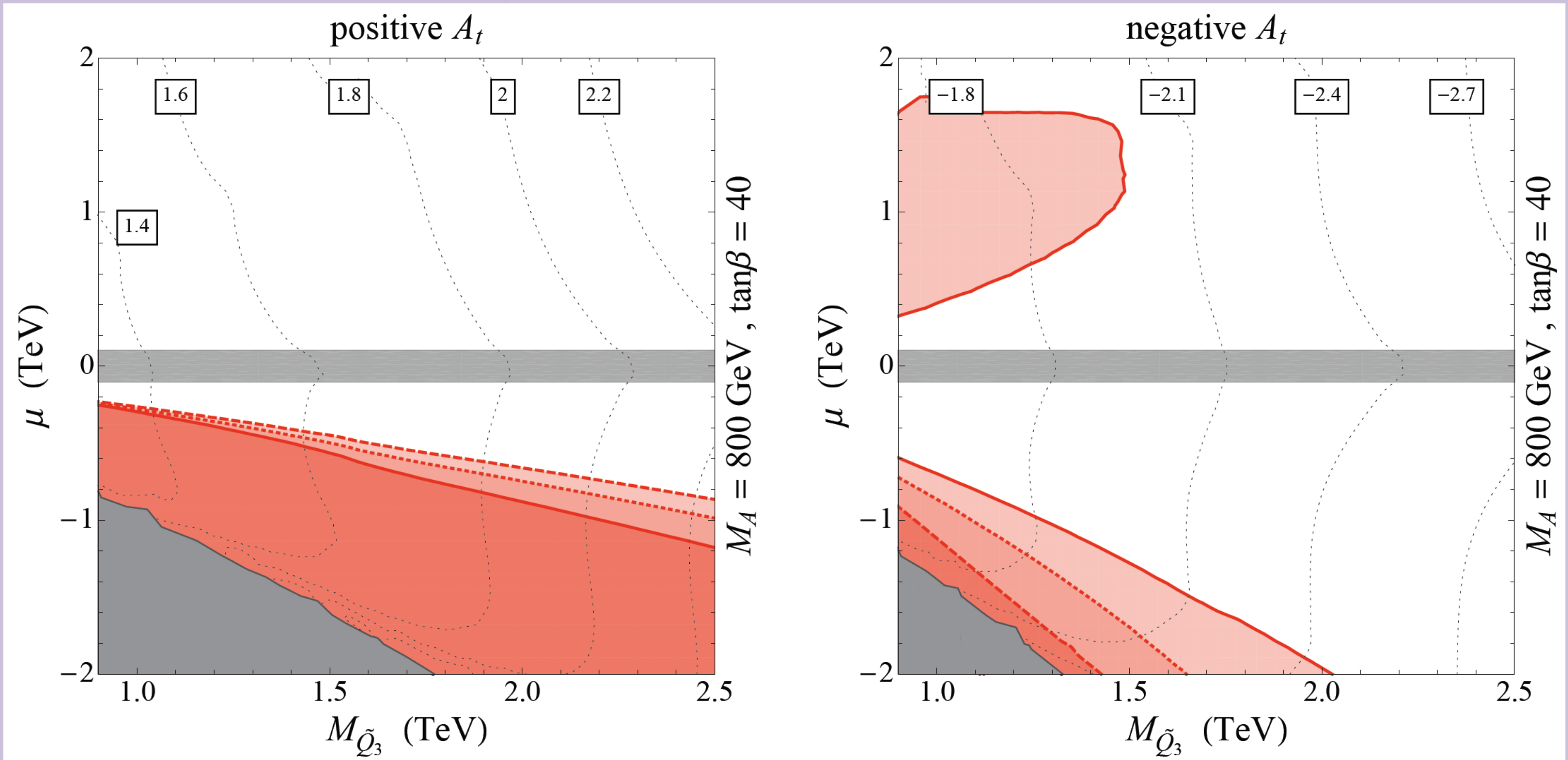
$$R_{B_s\mu\mu} = \frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \simeq |\mathcal{A}|^2 + |1 - \mathcal{A}|^2$$

$$\epsilon_{\mathrm{FC}} = \epsilon_b^{\tilde{H}} + \zeta \epsilon_{\mathrm{FC}}^{\tilde{g}} + \zeta \epsilon_{\mathrm{FC}}^{\tilde{W}}$$

$$\mathcal{A} = \frac{4\pi}{\alpha_2} \frac{m_{B_s}^2}{4M_A^2} \frac{\epsilon_{\mathrm{FC}}\ t_\beta^3}{(1+\epsilon_b t_\beta)(1+\epsilon_0 t_\beta)(1+\epsilon_\ell t_\beta)} \frac{1}{Y_0}$$

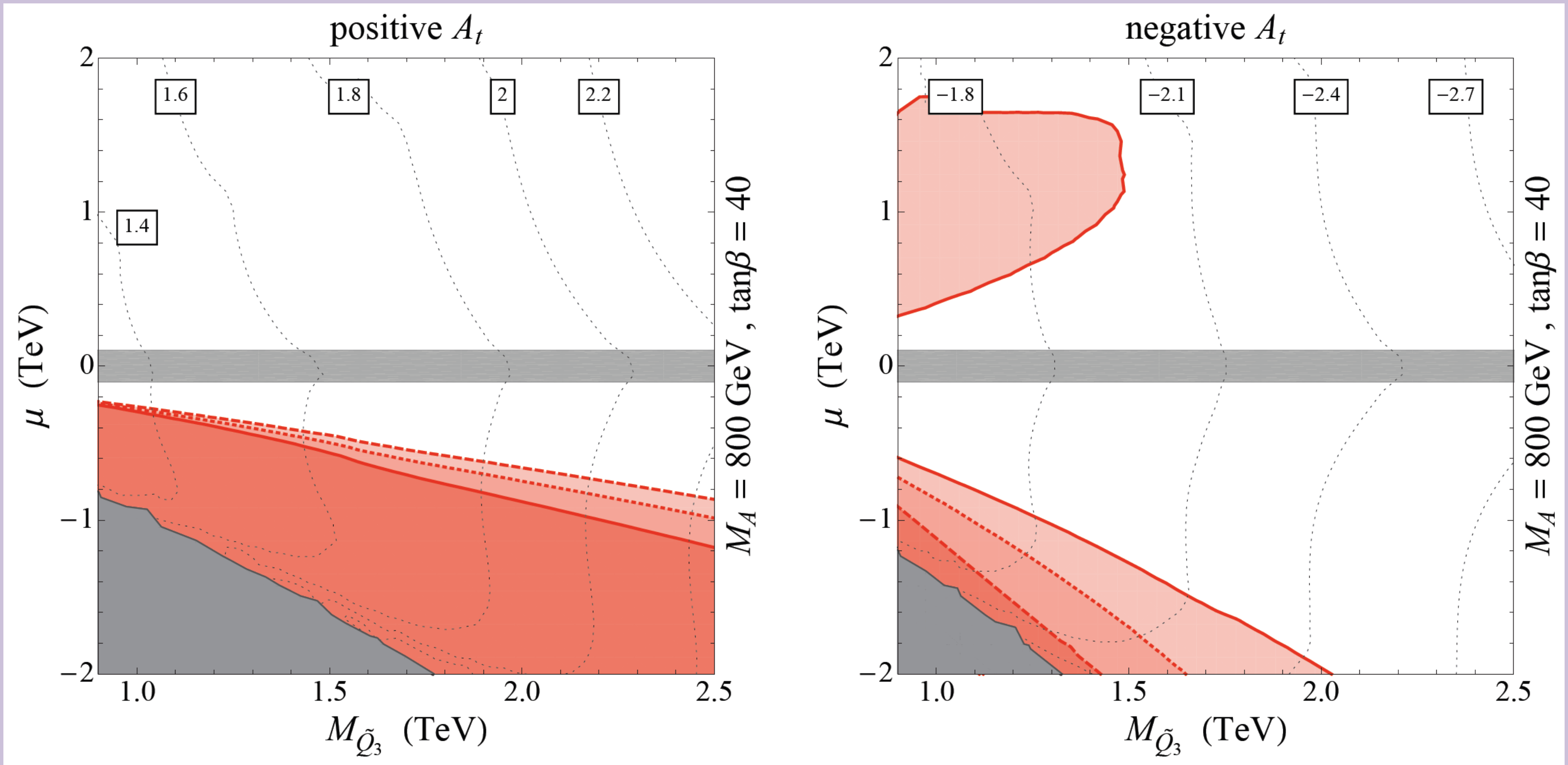
$B_s \to \mu^+\mu^-$

- Adjust A_t to get Higgs mass of 125 GeV (not satisfied in lower left corner)
- Solid lines = degenerate squarks = no gluino contribution
- Dashed (ζ=1), dotted (ζ=0.5), with first two squark gens heavier by 50%
- Gray band = chargino search at LEP



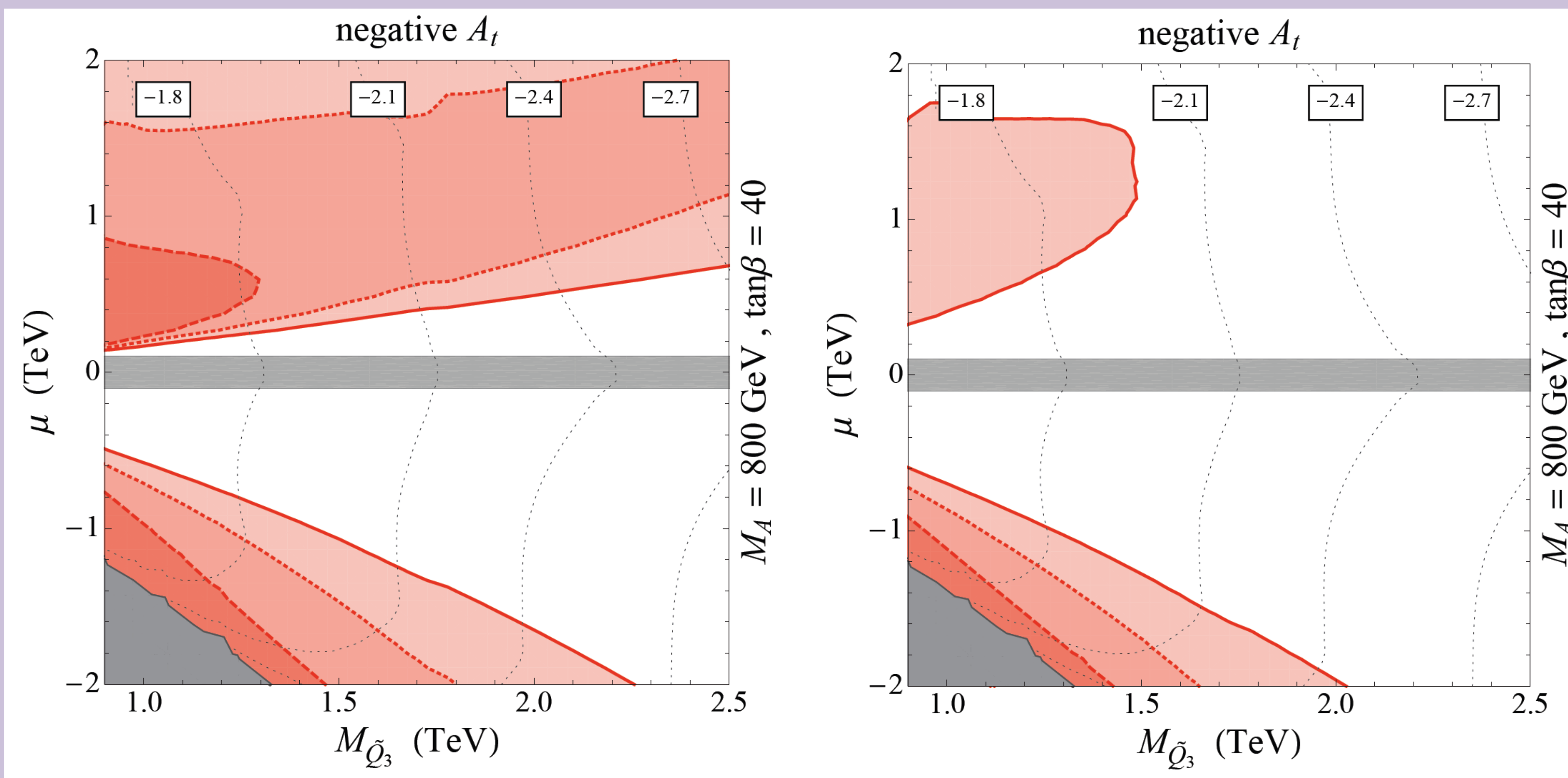
$B_s \rightarrow \mu^+\mu^-$

- Switching sign of μ switches relative sign between SM and SUSY
- Switching sign of A_t switches relative sign between Higgsino and gluino
- For positive (negative) μA_t, SUSY is destructive (constructive) with SM



What a difference a day makes! (Rather, new data)

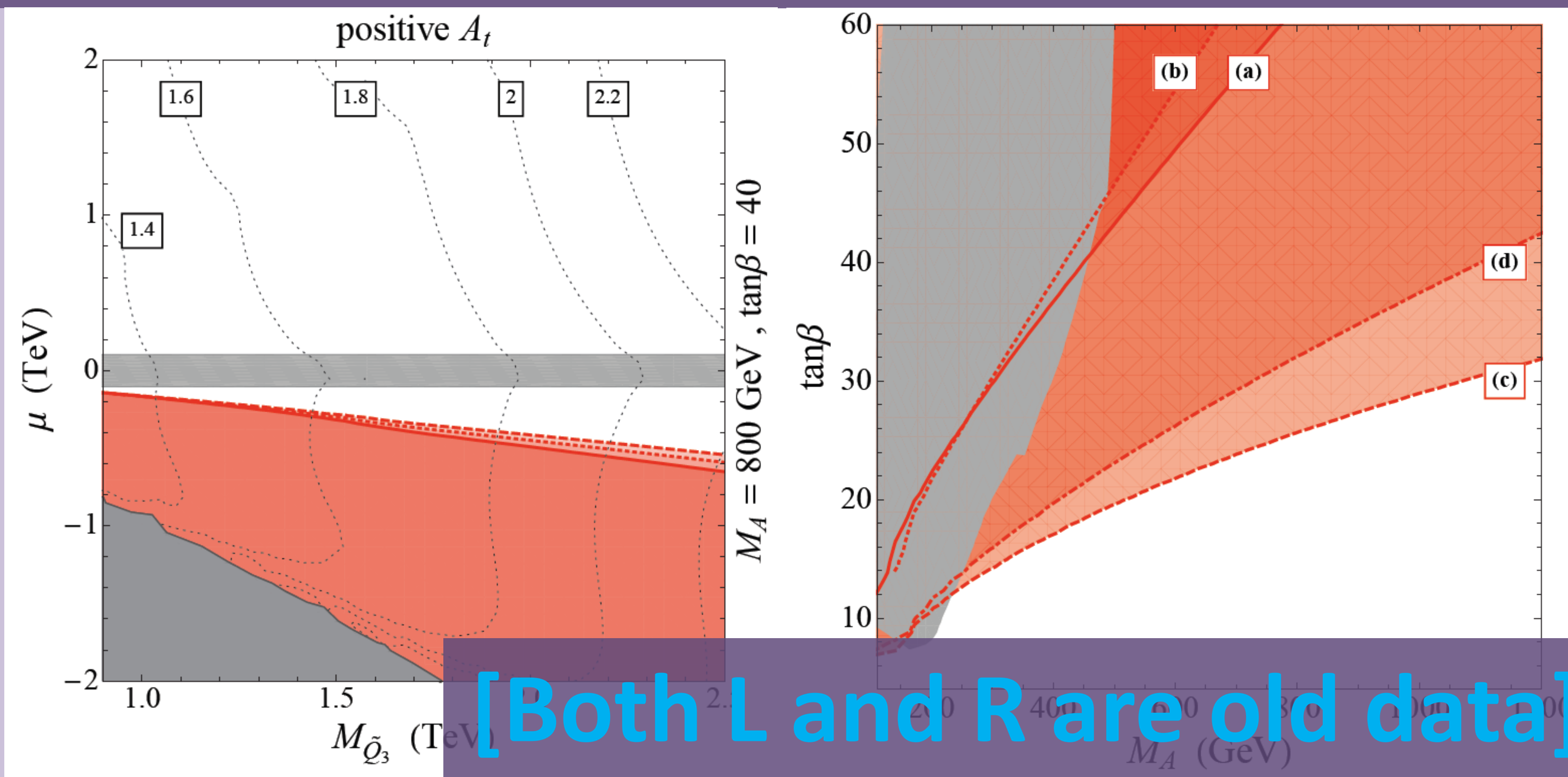
[L: *old* 4.2 × 10^{-9}; R: *new* (1.1-6.4) × 10^{-9}]



Blanket statements about the MSSM at large tan β are easy to make but too naïve

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

- Switching sign of A_t switches relative sign between Higgsino and gluino



[Both L and R are old data]

$B \to X_s\gamma$

$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{SM}} = (3.15 \pm 0.23) \times 10^{-4}$$

$$\mathrm{BR}(B \to X_s\gamma)_{\mathrm{exp}} = (3.43 \pm 0.22) \times 10^{-4}$$

$$R_{bs\gamma} = \frac{\mathrm{BR}(B \to X_s\gamma)}{\mathrm{BR}(B \to X_s\gamma)_{\mathrm{SM}}} ,$$

$$\simeq 1 - 2.55\, C_7^{\mathrm{NP}} - 0.61\, C_8^{\mathrm{NP}} + 0.74 C_7^{\mathrm{NP}} C_8^{\mathrm{NP}} + 1.57\, (C_7^{\mathrm{NP}})^2 + 0.11\, (C_8^{\mathrm{NP}})^2 ,$$

- Here, SUSY contributions come from loops of charged Higgs–top, neutral Higgs–bottom, Higgsino–stop, gaugino–squark
  - These do decouple with the SUSY scale
  - $C_{7,8}^{\mathrm{gaugino}}$ has a ζ piece and 2-loop piece (important for large tan β)

$B \to X_s \gamma$

- Probes light charged Higgs masses even for low tan β
  - [Stop-chargino loop negligible here]

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μ	1 TeV	4 TeV	-1.5 TeV	1 TeV
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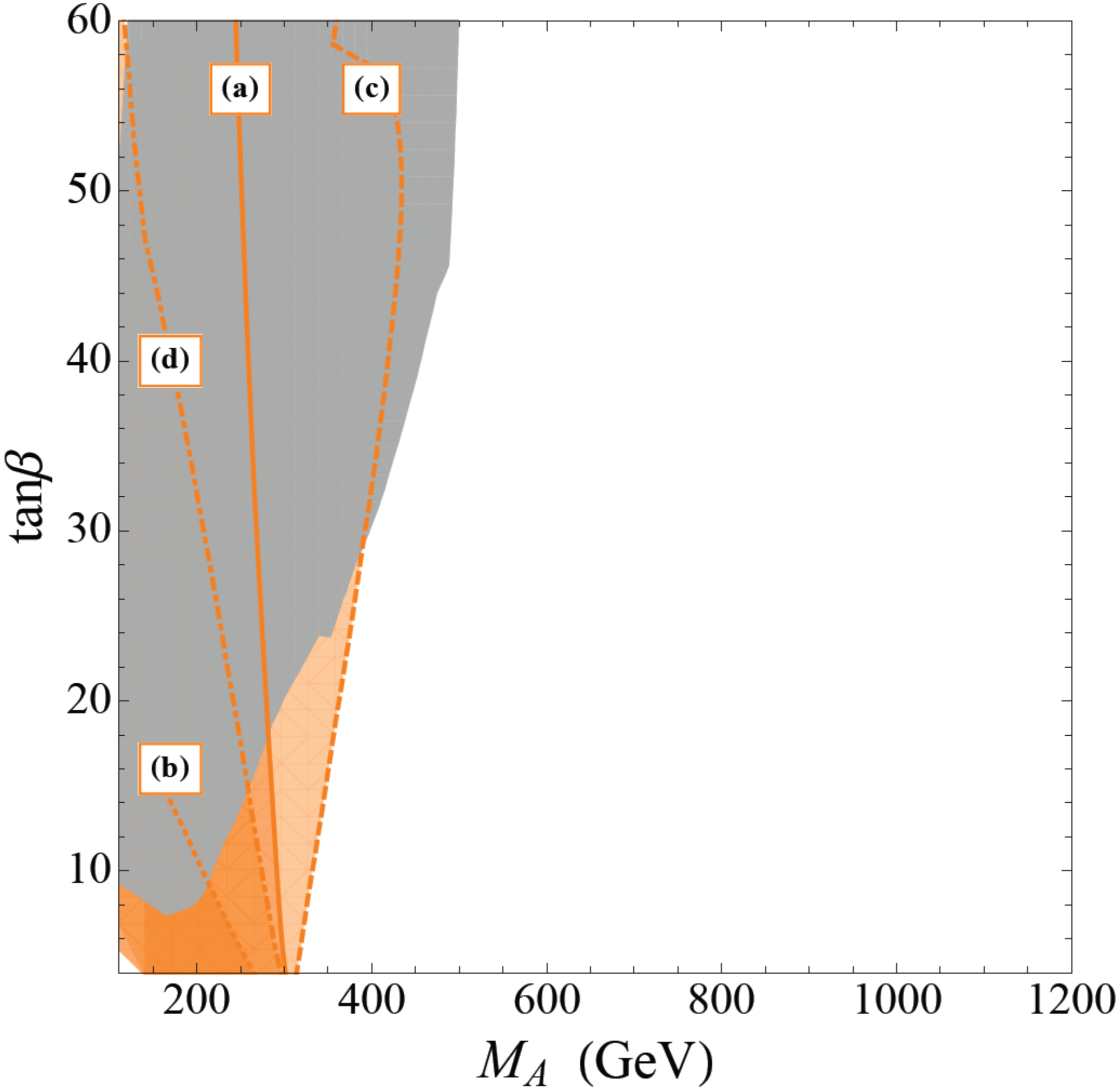
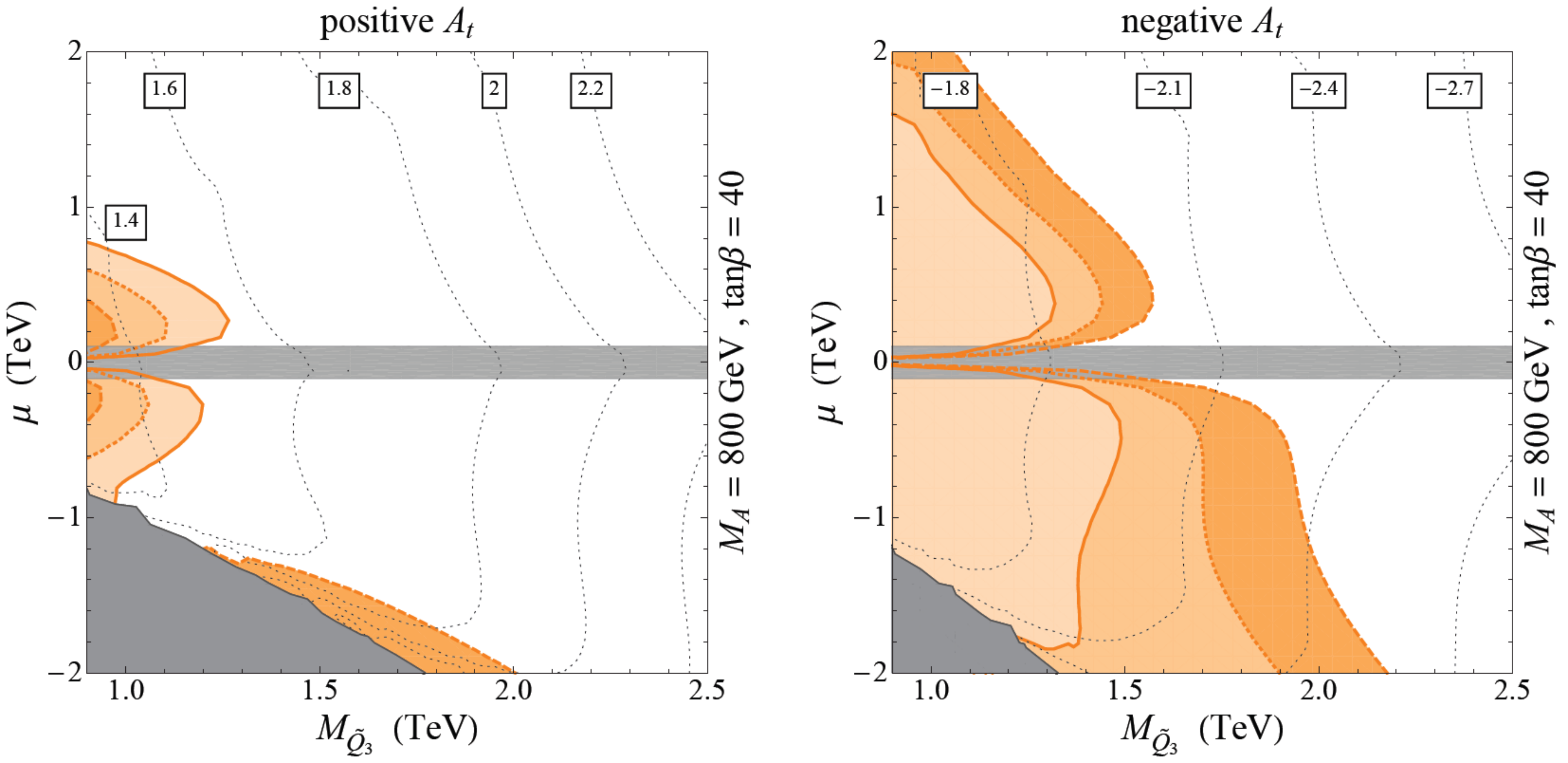
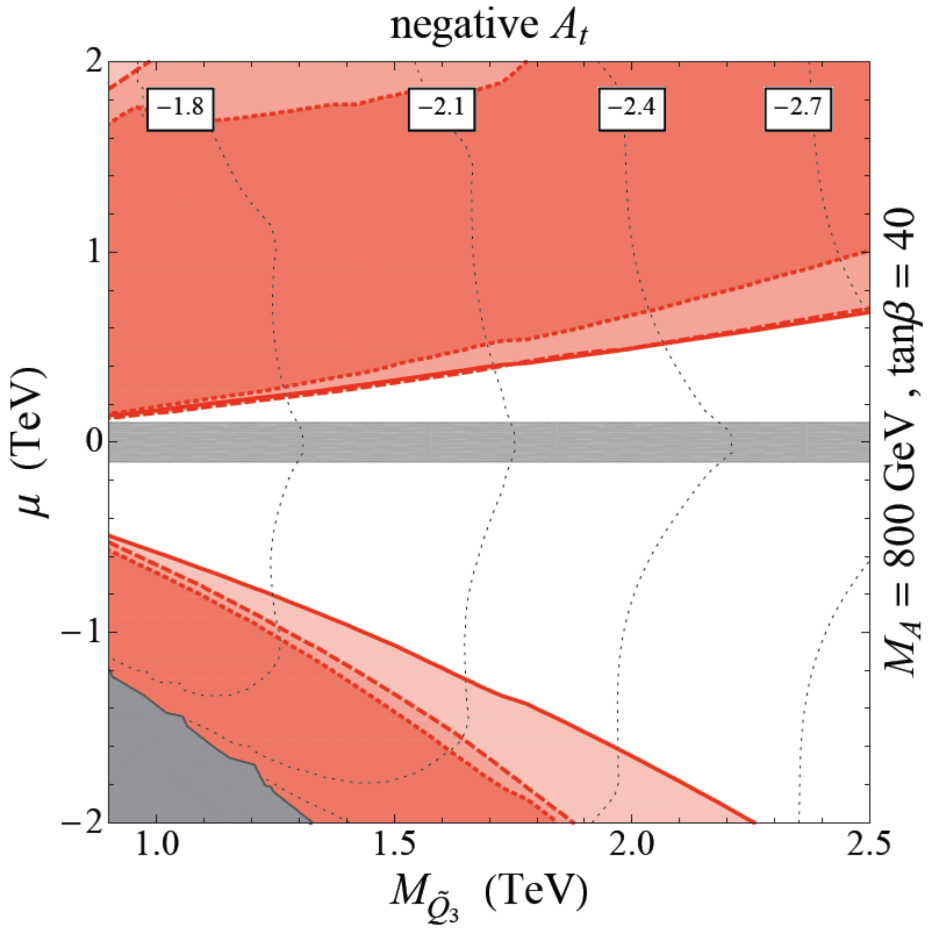


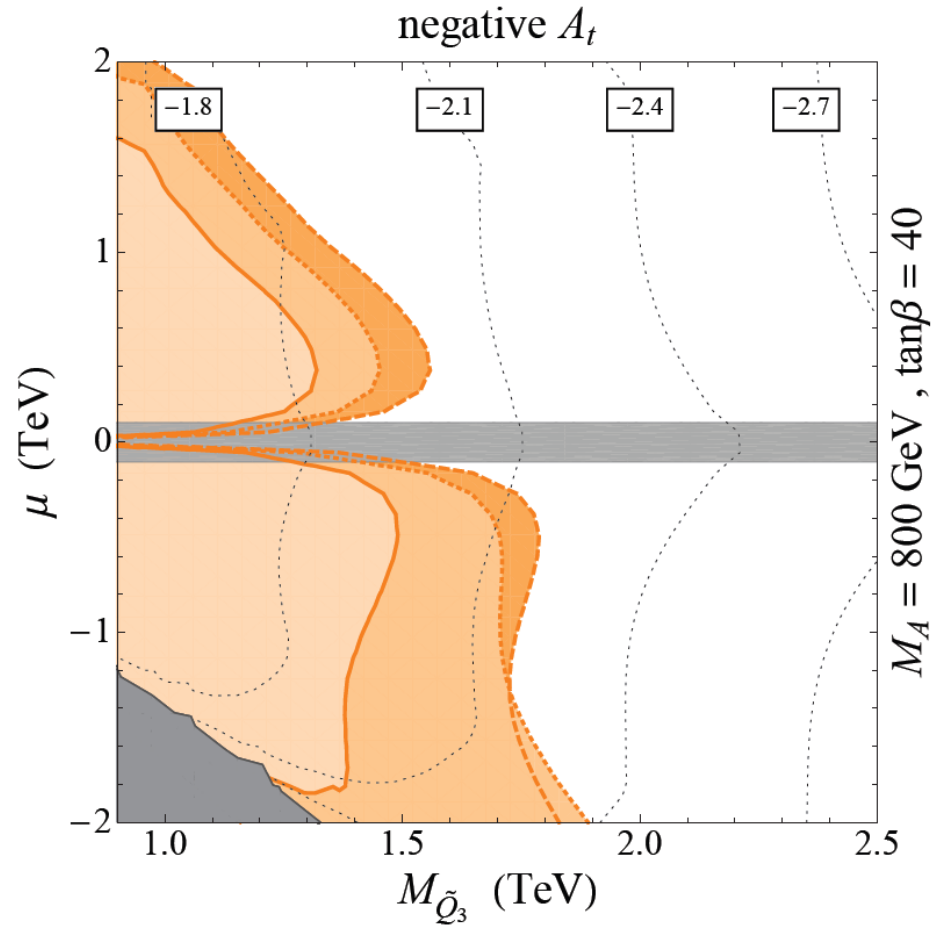
$B \to X_s\gamma$

- [Charged Higgs interferes constructively with SM (but small, M_A = 800 GeV)]
- For positive (negative) μ, gluino interferes destructively (constructively)
- For positive (negative) μA_t, constructive (destructive) with SM



Constraints with RGEs for mass splittings





(old $B_s \rightarrow \mu^+\mu^-$ for 4.2×10^{-9})

Conclusions

- MSSM with MFV is well constrained by complementary probes
  - As is well-known in interpreting loop processes, possible cancellations are important
- FCNC constraints depend crucially on μ, A_t, first-third generation mass squared splitting ΔQ_{13}, and alignment in flavor space ζ
  - Generally, positive μ and A_t are favored
  - We can accommodate a SM-Higgs at 125 GeV
    - SUSY amplitudes cancel against SM in this region and SUSY amplitudes are suppressed compared to negative μ

m_h corrections from third gen sfermions

$$\Delta M_h^2 \simeq \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)+\frac{X_t^2}{m_{\tilde{t}}^2}-\frac{X_t^4}{12m_{\tilde{t}}^4}\right]$$
$$-\frac{3}{48\pi^2}\frac{m_b^4}{v^2}\frac{t_\beta^4}{(1+\epsilon_b t_\beta)^4}\frac{\mu^4}{m_{\tilde{b}}^4}$$
$$-\frac{1}{48\pi^2}\frac{m_\tau^4}{v^2}\frac{t_\beta^4}{(1+\epsilon_\ell t_\beta)^4}\frac{\mu^4}{m_{\tilde{\tau}}^4},$$

$$X_t = A_t - \mu/\tan\beta$$

Explaining $R_{\mu 23}$

A highly sensitive probe of $U(3)^5$ violating structures is therefore provided by comparing the value of $|V_{us}|$ determined using $K_{\mu 2}$ decays, which are helicity suppressed, and $K_{\ell 3}$ decays, which are helicity allowed.[6] In practice, to minimize the impact of the uncertainties from f_K and the electromagnetic corrections for $K_{\mu 2}$, it is more convenient to consider the ratio

$$R_{\mu 23} = \left(\frac{f_K/f_\pi}{f_+(0)}\right)^{-1} \left(\left|\frac{V_{us}}{V_{ud}}\right| \frac{f_K}{f_\pi}\right)_{\mu 2} \frac{|V_{ud}|_{0^+\to 0^+}}{[|V_{us}|f_+(0)]_{\ell 3}},$$

1005.2323

Vacuum stability

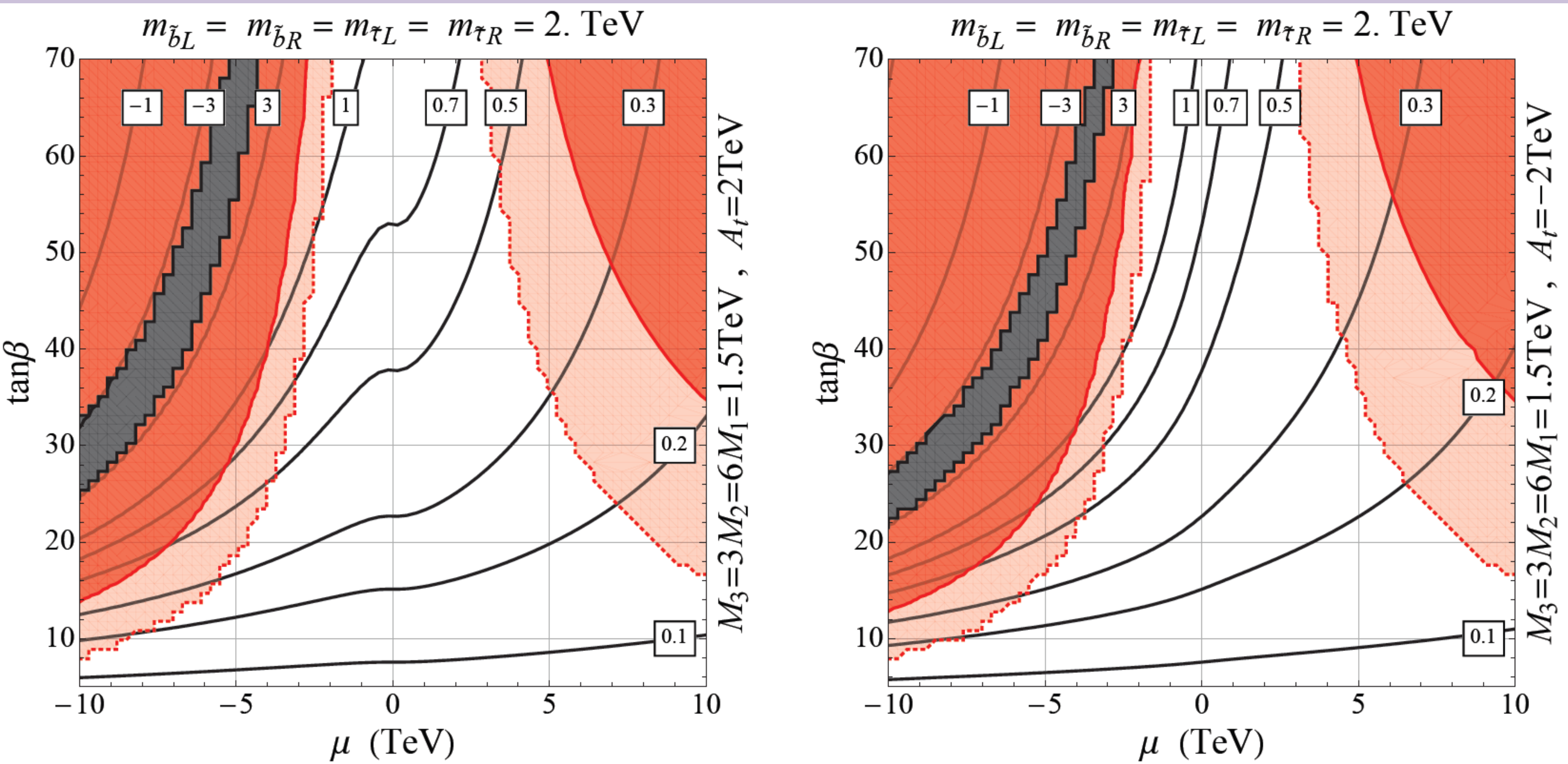


FIG. 2. Constraints from vacuum stability in the μ–$\tan\beta$ plane. We set the sbottom and stau soft masses to 2 TeV and the gaugino masses to $6M_1 = 3M_2 = M_3 = 1.5$ TeV. In the left (right) plot, the trilinear coupling of the stops is $A_t = 2$ TeV ($A_t = -2$ TeV). The labeled contours show the values of the bottom Yukawa coupling. In the light red (light gray) regions, a charge and color breaking vacuum exists that is deeper than the electroweak breaking vacuum, but the electroweak vacuum has a lifetime that is longer than the age of the universe. In the dark red (gray) regions, the electroweak vacuum is not stable on cosmological time scales. Finally, in the black regions, one of the sbottoms becomes tachyonic.

$B_s \to \mu^+\mu^-$ (old version)

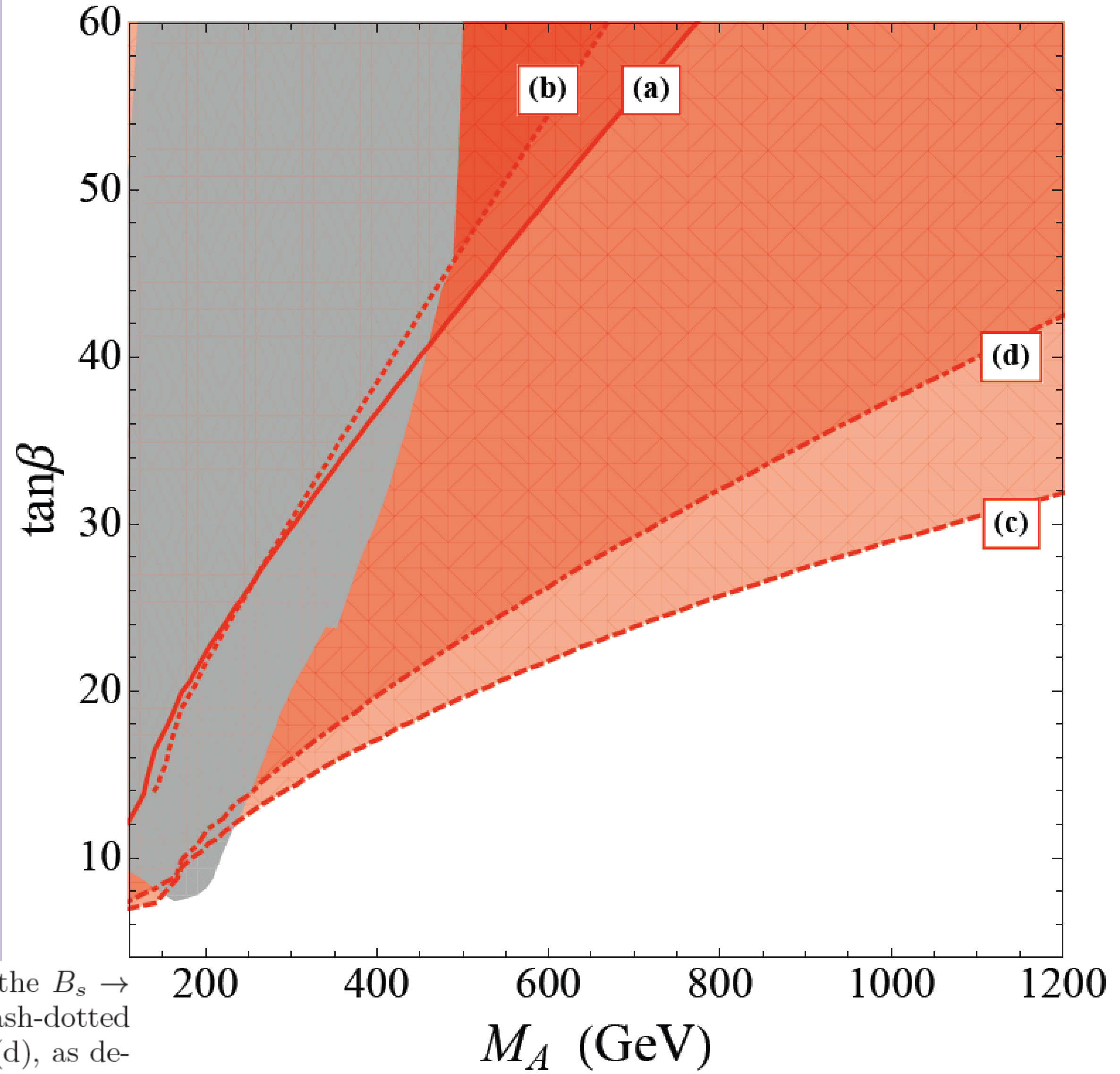


FIG. 5. Constraints in the M_A–$\tan\beta$ plane from the $B_s \to \mu^+\mu^-$ decay. The red solid, dotted, dashed and dash-dotted contours correspond to scenarios (a), (b), (c) and (d), as described in the text. The gray region is excluded by direct searches of MSSM Higgs bosons in the $H/A \to \tau^+\tau^-$ channel.

$B_s \to \mu^+\mu^-$ (old version)

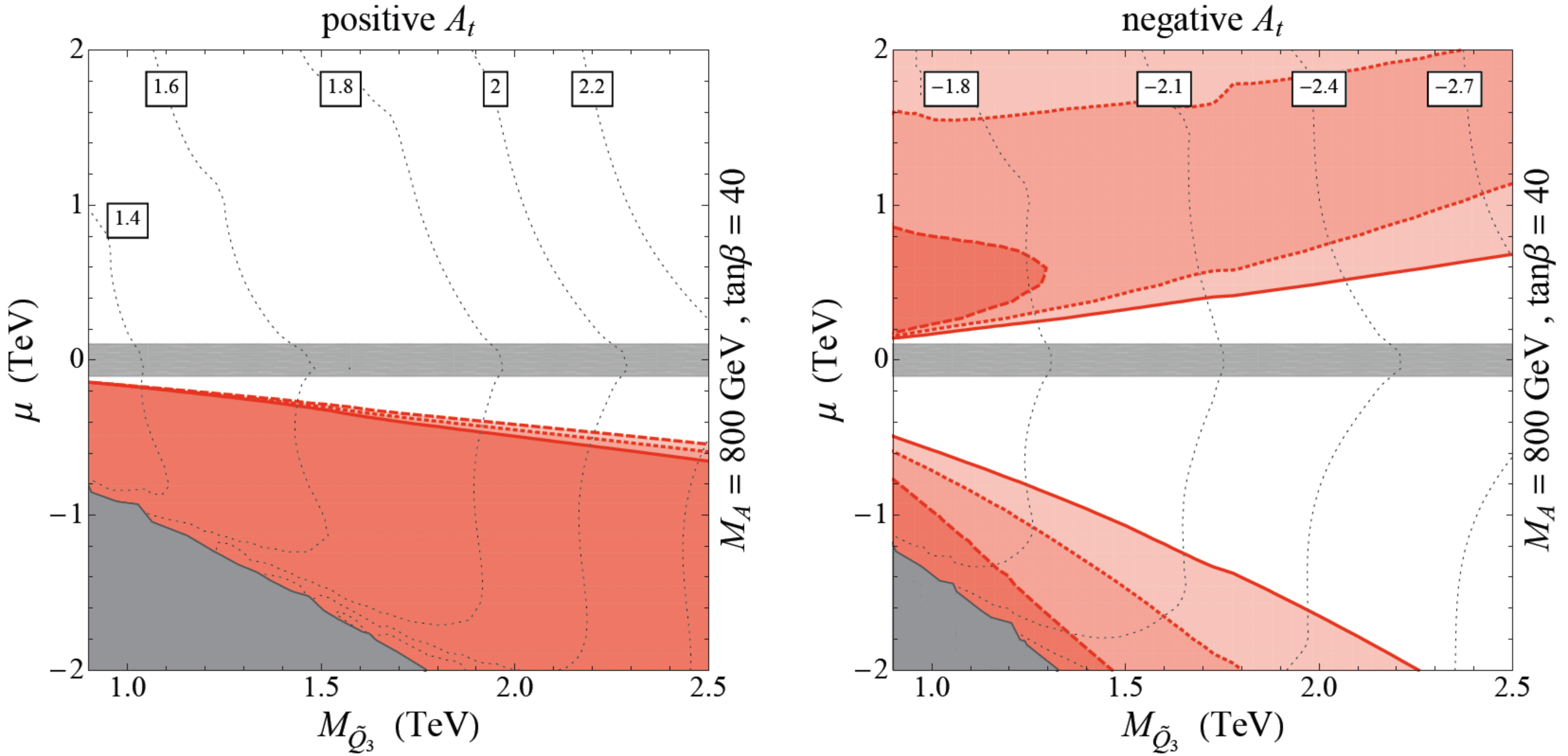


FIG. 6. Constraints in the m_{Q_3}–μ plane from the $B_s \to \mu^+\mu^-$ decay, with fixed $M_3 = 3M_2 = 6M_1 = 1.5$ TeV, $M_A = 800$ GeV and $\tan\beta = 40$. The solid bounded regions correspond to a degenerate squark spectrum. The dashed and dotted bounded regions correspond to choosing the first two squark generations 50% heavier than the third generation squark masses, with an alignment of $\zeta = 1$ and $\zeta = 0.5$, respectively. The gray horizontal band corresponds to the constraint from direct searches of charginos at LEP. The vertical dotted lines show contours of constant A_t such that $M_h = 125$ GeV. In the gray regions in the lower left corners, the lightest Higgs mass is always below $M_h < 125$ GeV, taking into account a 3 GeV theory uncertainty.

$B \to X_s\gamma$

$$C^{H}_{7,8} = \left(\frac{1-\epsilon'_0 t_\beta}{1+\epsilon_b t_\beta} + \frac{\epsilon'_{\rm FC}\epsilon_{\rm FC} t_\beta^2}{(1+\epsilon_b t_\beta)(1+\epsilon_0 t_\beta)}\right)\frac{m_t^2}{2M_{H^\pm}^2} h_{7,8}(r_t) + \frac{\epsilon_{\rm FC} t_\beta^3}{(1+\epsilon_b t_\beta)^2(1+\epsilon_0 t_\beta)}\frac{m_b^2}{2M_A^2} z_{7,8}\ ,$$

$$C^{\tilde H}_{7,8} = -\frac{t_\beta}{1+\epsilon_b t_\beta}\ \frac{m_t^2}{2} A_t\mu\ f^{\tilde H}_{7,8}(m^2_{Q_3}, m^2_{U_3}, \mu^2)\ ,$$

$$\frac{g_2^2}{g_3^2}\ C^{\tilde g}_{7,8} = \frac{t_\beta}{1+\epsilon_0 t_\beta}\ M_W^2 \mu M_3\ \zeta\ \left(f^{\tilde g}_{7,8}(m^2_Q, m^2_{D_3}, M_3^2) - f^{\tilde g}_{7,8}(m^2_{Q_3}, m^2_{D_3}, M_3^2)\right)$$

$$-\frac{\epsilon_{\rm FC} t_\beta^2}{(1+\epsilon_b t_\beta)(1+\epsilon_0 t_\beta)}\ M_W^2 \mu M_3\ f^{\tilde g}_{7,8}(m^2_{Q_3}, m^2_{D_3}, M_3^2)\ ,$$

$$C^{\tilde W}_{7,8} = \frac{t_\beta}{1+\epsilon_0 t_\beta}\ M_W^2 \mu M_2\ \zeta\ \left(f^{\tilde W}_{7,8}(M_2^2, \mu^2, m^2_Q) - f^{\tilde W}_{7,8}(M_2^2, \mu^2, m^2_{Q_3})\right)$$

$$-\frac{\epsilon_{\rm FC} t_\beta^2}{(1+\epsilon_b t_\beta)(1+\epsilon_0 t_\beta)}\ M_W^2 \mu M_2\ f^{\tilde W}_{7,8}(M_2^2, \mu^2, m^2_{Q_3})\ .$$

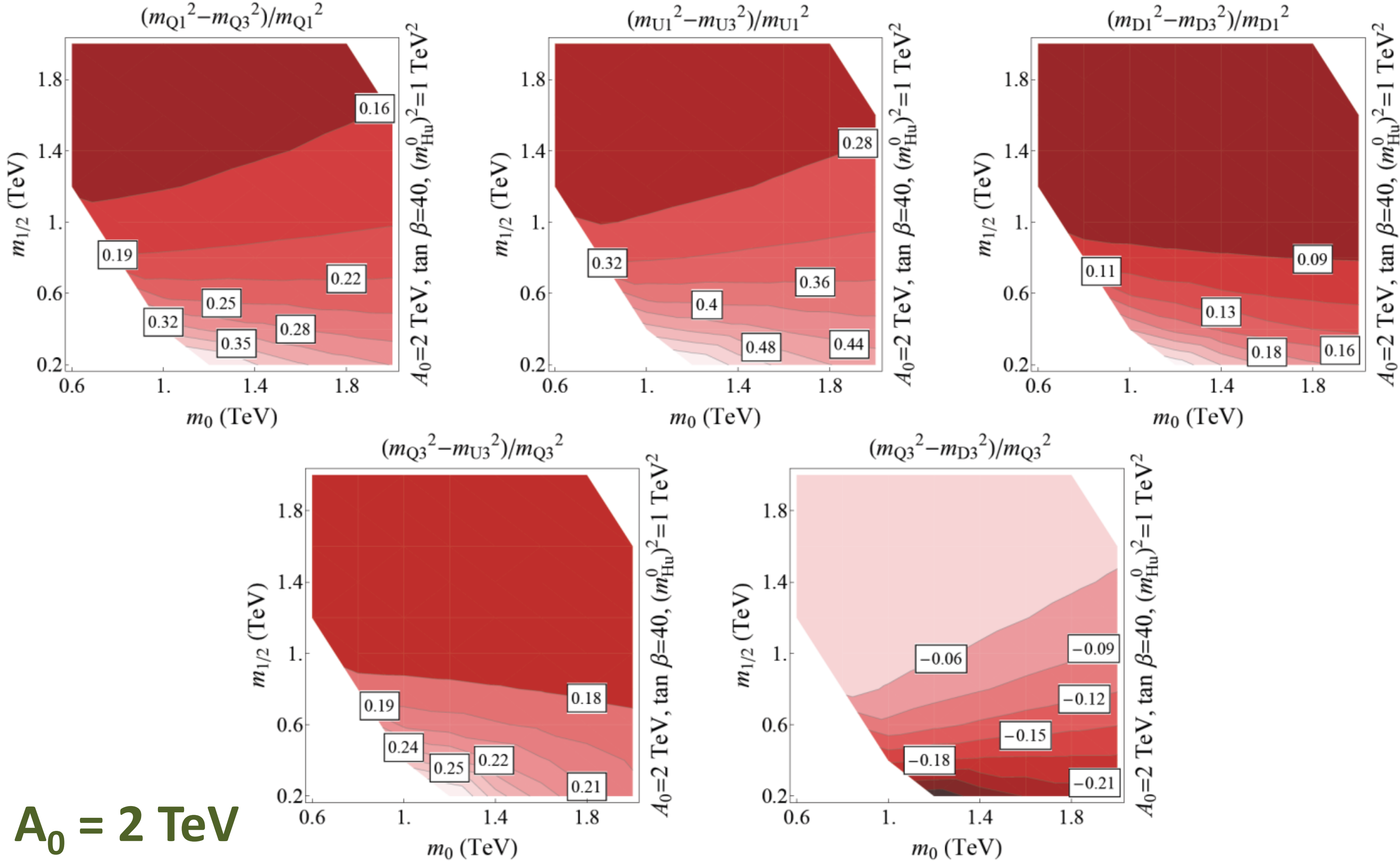
Auxilliary functions

$$g(x,y,z) = \frac{x\log x}{(x-y)(x-z)} + \frac{y\log y}{(y-x)(y-z)} + \frac{z\log z}{(z-x)(z-y)} \; .$$

$$h_7(x) = \frac{3-5x}{12(1-x)^2} + \frac{2-3x}{6(1-x)^3}\log x \; ,$$

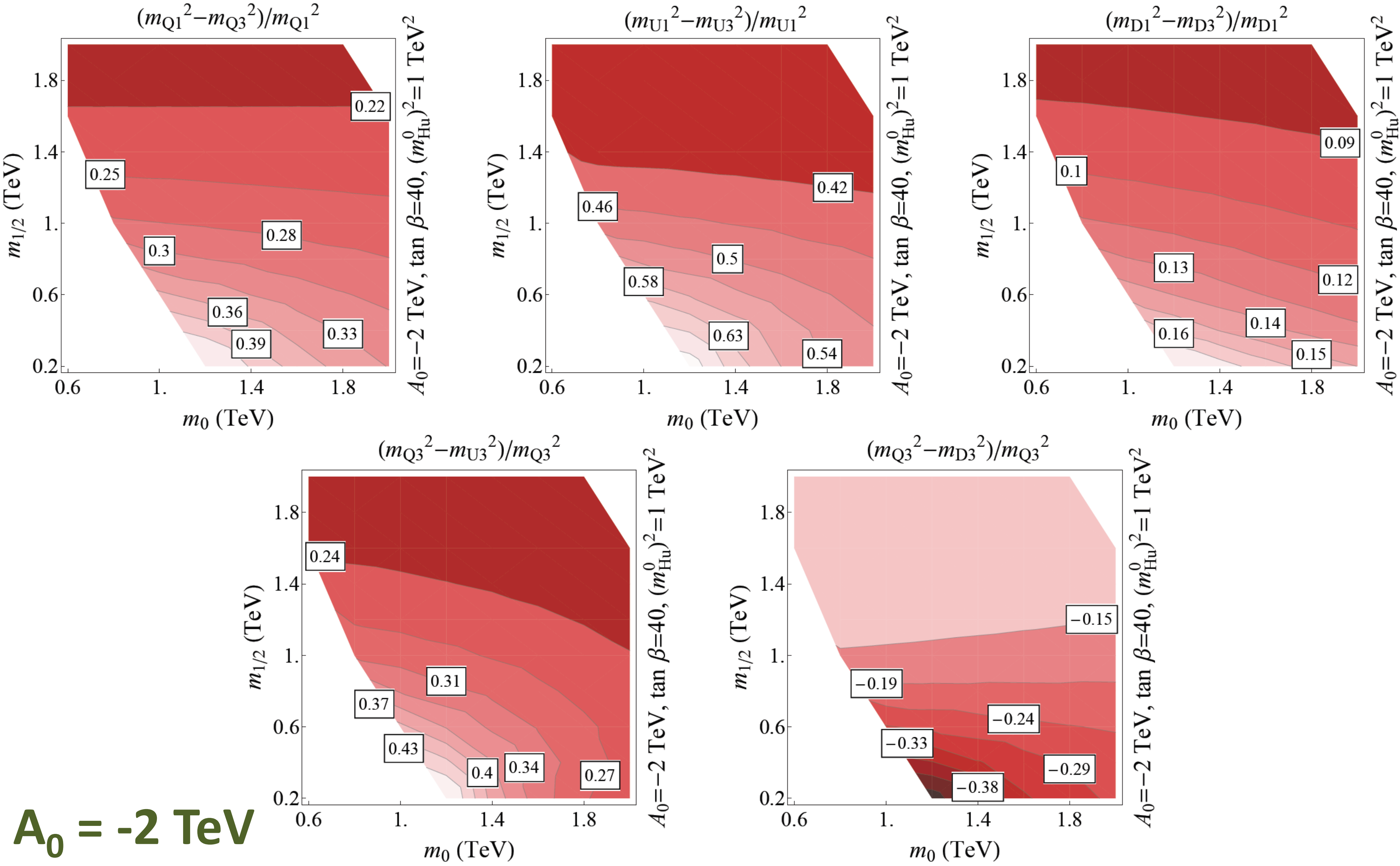
$$h_8(x) = \frac{3-x}{4(1-x)^2} + \frac{1}{2(1-x)^3}\log x \; .$$

Characteristic mass splittings from RGEs



A_0 = 2 TeV

Characteristic mass splittings from RGEs



A_0 = -2 TeV

Dark matter

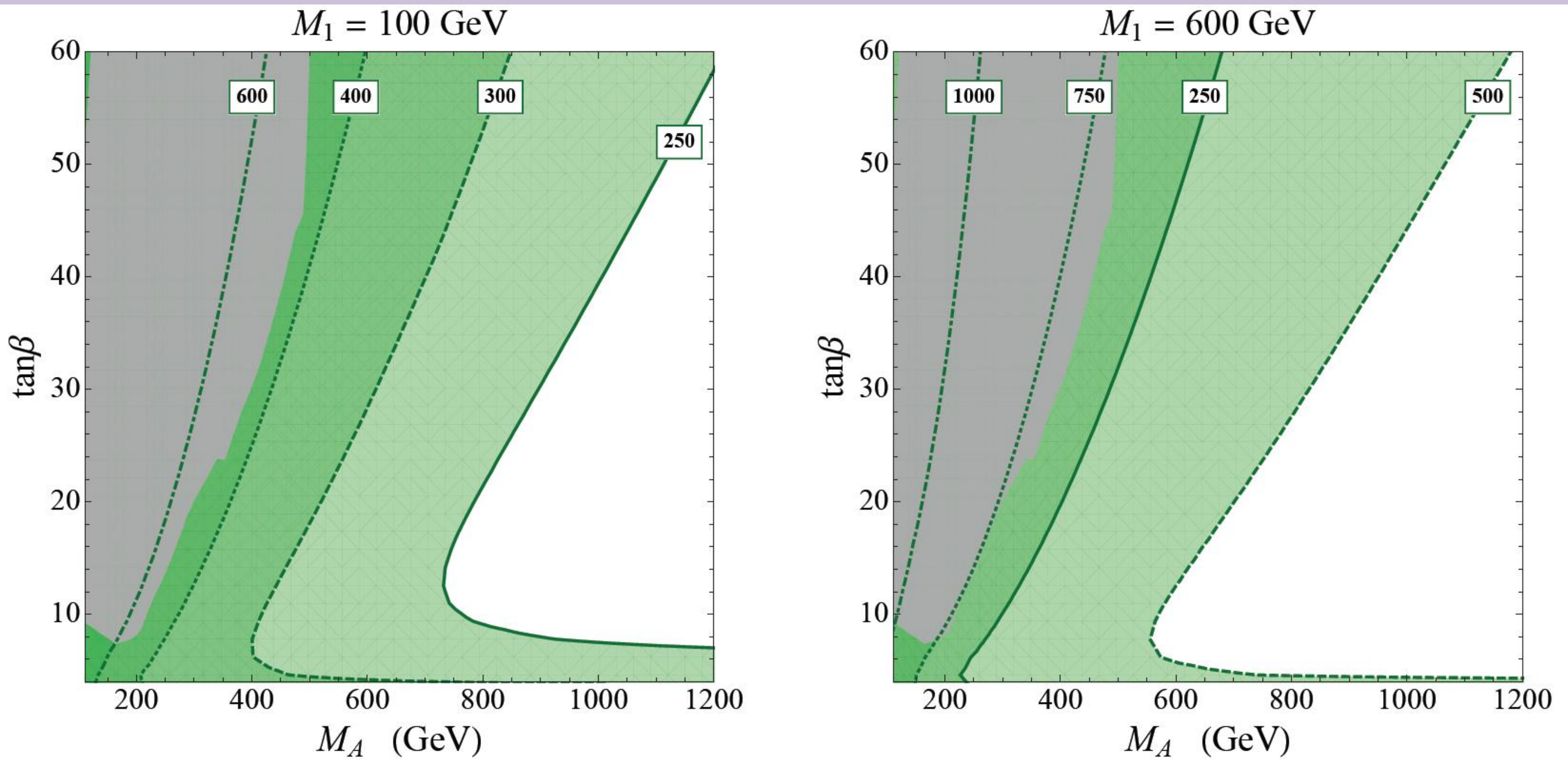


FIG. 12. Constraints in the M_A–$\tan\beta$ plane from Dark Matter direct detection. The green solid, dashed, dotted and dash-dotted contours correspond to different values of μ as indicated. The gray region is excluded by direct searches of MSSM Higgs bosons in the $H/A \to \tau^+\tau^-$ channel.

Dark matter

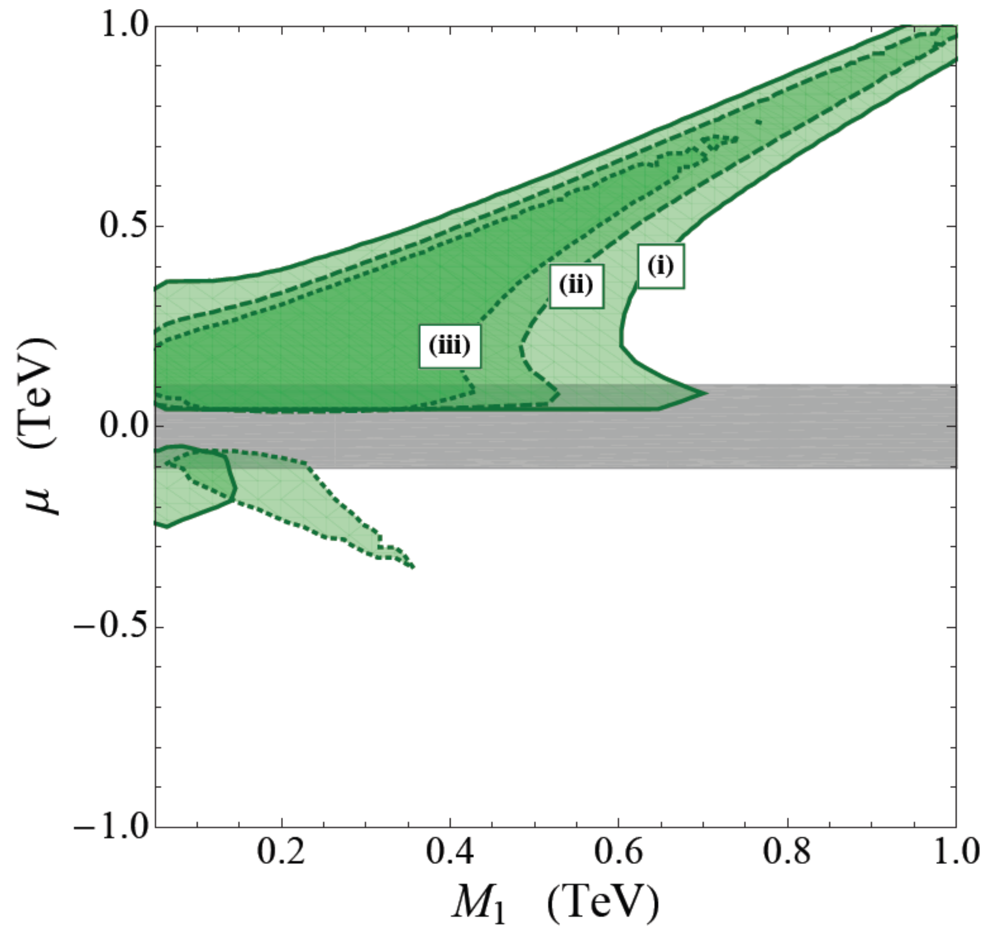


FIG. 13. Constraints in the M_1–μ plane from Dark Matter direct detection. The solid, dashed, and dotted contours correspond to different choices for M_A and $\tan\beta$ as defined in the text. The horizontal gray band is excluded by direct chargino searches.