@日大理工 13. Jun. 2001.

超対称大統一理論における右巻きニュートリノとFCNC過程、レプトンフレーバーの破れおよびミュー粒子の異常磁気能率

奥村健一(ICRR)

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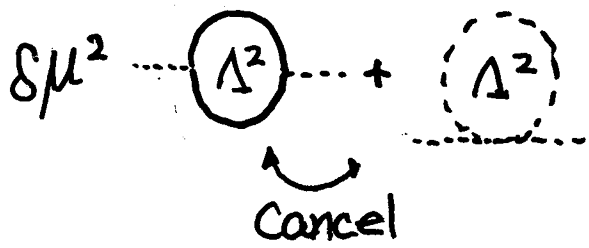
hep-ph/0009196

hep-ph/0104146

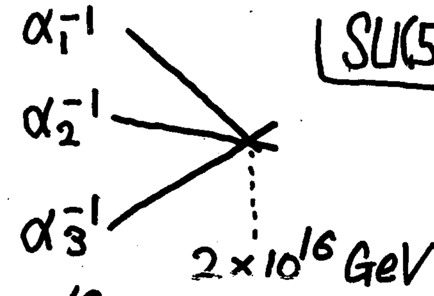
I. INTRODUCTION

- **SUSY SM is well motivated!**

Hierarchy problem



Gauge coupling unification



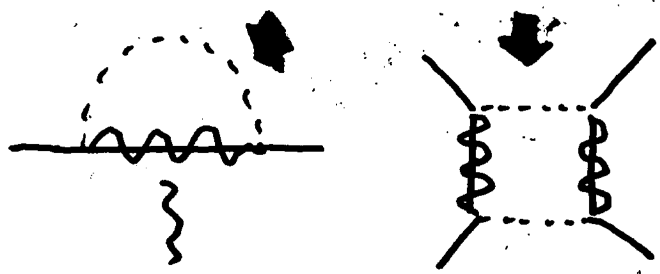
$SU(5) \subset G$

- SUSY introduces scalar/fermionic partners of the SM fields.

$$q \leftrightarrow \tilde{q} \qquad G^{\mu} \leftrightarrow \tilde{G}$$

- Indirect search ⇔ Direct search

(Loop effects) LEP, Tevatron, LHC.



muon $g-2$ BNL E821 2.6σ deviation?

⇔ forbidden/suppressed processes in the SM.

(near) Symmetry of the SM

- CP EDM, ...
- lepton # m_ν $0\nu\beta\beta$
- baryon # nucleon decay Super Kamiokande
- flavor
  - lepton flavor violation (LFV)
    - $\mu \to e\gamma$, $\mu N \to e N$ PSI, BNL
    - $\tau \to \mu\gamma$, ...
  - flavor changing neutral current (FCNC)
    - $B \to X_s\gamma$, K^0-$\bar{K}^0$ / B^0-$\bar{B}^0$ mixing
    - .... Belle, Babar, BTeV ...

◎ Not only SUSY ⇒ physics @ GUT scale.

↳ radiative corrections to SUSY particles.

$\underline{SU(5)\ \text{SUSY GUT} \oplus \nu_R}$ ↜ ν-oscillation Seesaw mechanism

realistic mass relations for quarks and leptons

↳ Higher dimensional operators.

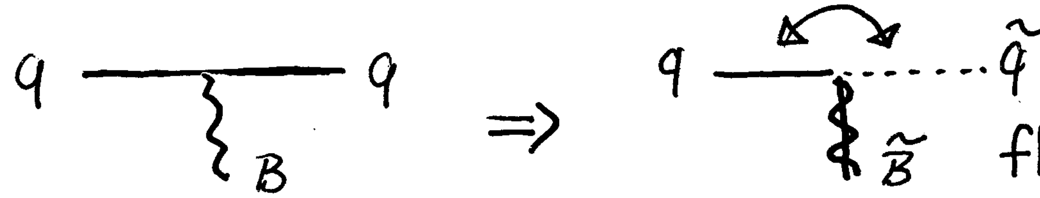
- SUSY flavor problem

$$\left\{\begin{array}{ll} \text{quark} & q\,;\,u\,;\,d \\ \text{lepton} & \ell\,,\,e \\ \text{gauge} & B\,,\,W\,,\,G \end{array}\right. \Leftrightarrow \left\{\begin{array}{ll} \text{squark} & \tilde{q}\,,\tilde{u}\,,\tilde{d} \\ \text{slepton} & \tilde{\ell}\,,\tilde{e} \\ \text{gaugino} & \tilde{B}\,,\tilde{W}\,,\tilde{G} \end{array}\right.$$

$$-\mathcal{L}_{\cancel{SUSY}} = \text{①}\left\{\begin{array}{l} m^2_{Q_{ij}}\tilde{q}^*_i\tilde{q}_j + m^2_{U_{ij}}\tilde{u}^*_i\tilde{u}_j + m^2_{D_{ij}}\tilde{d}^*_i\tilde{d}_j \\ + m^2_{L_{ij}}\tilde{\ell}^*_i\tilde{\ell}_j + m^2_{E_{ij}}\tilde{e}^*_i\tilde{e}_j + m^2_{H_d}h^*_d h_d + m^2_{H_u}h^*_u h_u \end{array}\right.$$

$$\text{②}\left\{\begin{array}{l} + \left[A_{u_{ij}} h_u \tilde{u}^*_i\tilde{q}_j + A_{d_{ij}} h_d \tilde{d}^*_i\tilde{q}_j + A_{e_{ij}} h_d \tilde{e}^*_i\tilde{\ell}_j \right. \\ \left. \quad + B\mu h_u h_d + \text{H.c.} \right] \end{array}\right.$$

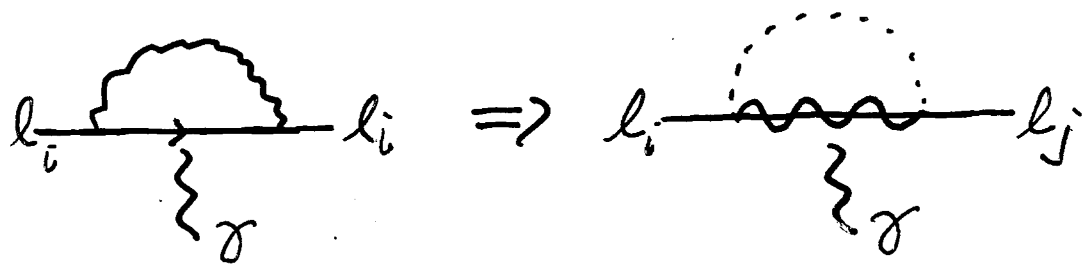
$$\text{③}\left\{ + \frac{1}{2}M_1 \overline{\tilde{B}^c}\tilde{B} + \frac{1}{2}M_2\overline{\tilde{W}^c}\tilde{W} + \frac{1}{2}M_3\overline{\tilde{G}^c}\tilde{G}\right.$$



flavor mixing

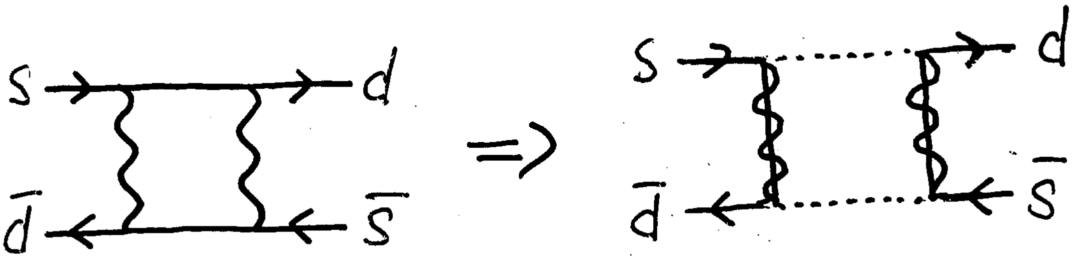
(g-2)

$\mu \to e\gamma$



K^0-$\bar{K}^0$

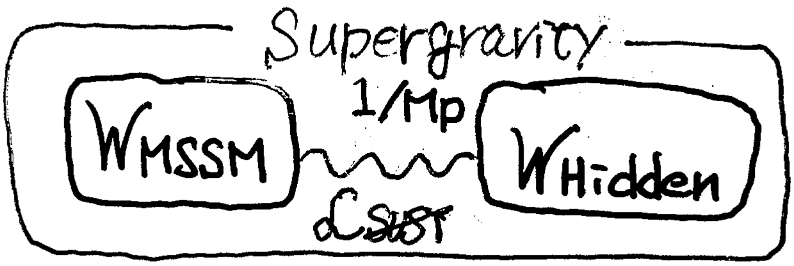
B^0-$\bar{B}^0$



too large contributions!

- Minimal supergravity

SUSY breaking effects are mediated from the hidden sector by supergravity interactions at the Planck scale.



"Minimal" form

① $$\begin{cases} m^2_{Q\,ij} = m^2_{U\,ij} = m^2_{D\,ij} = m^2_{L\,ij} = m^2_{E\,ij} = m_0^2\,\delta_{ij} \\ m^2_{H_u} = m^2_{H_d} = m_0^2 \end{cases}$$

② $$\left[\; A_{u\,ij} = m_0 A_0\, y_{u\,ij},\quad A_{d\,ij} = m_0 A_0\, y_{d\,ij},\quad A_{e\,ij} = m_0 A_0\, y_{e\,ij} \right.$$

③ $$\left[\; M_1 = M_2 = M_3 = M_0 \right.$$

parameterized by 3 parameters m_0, M_0, A_0

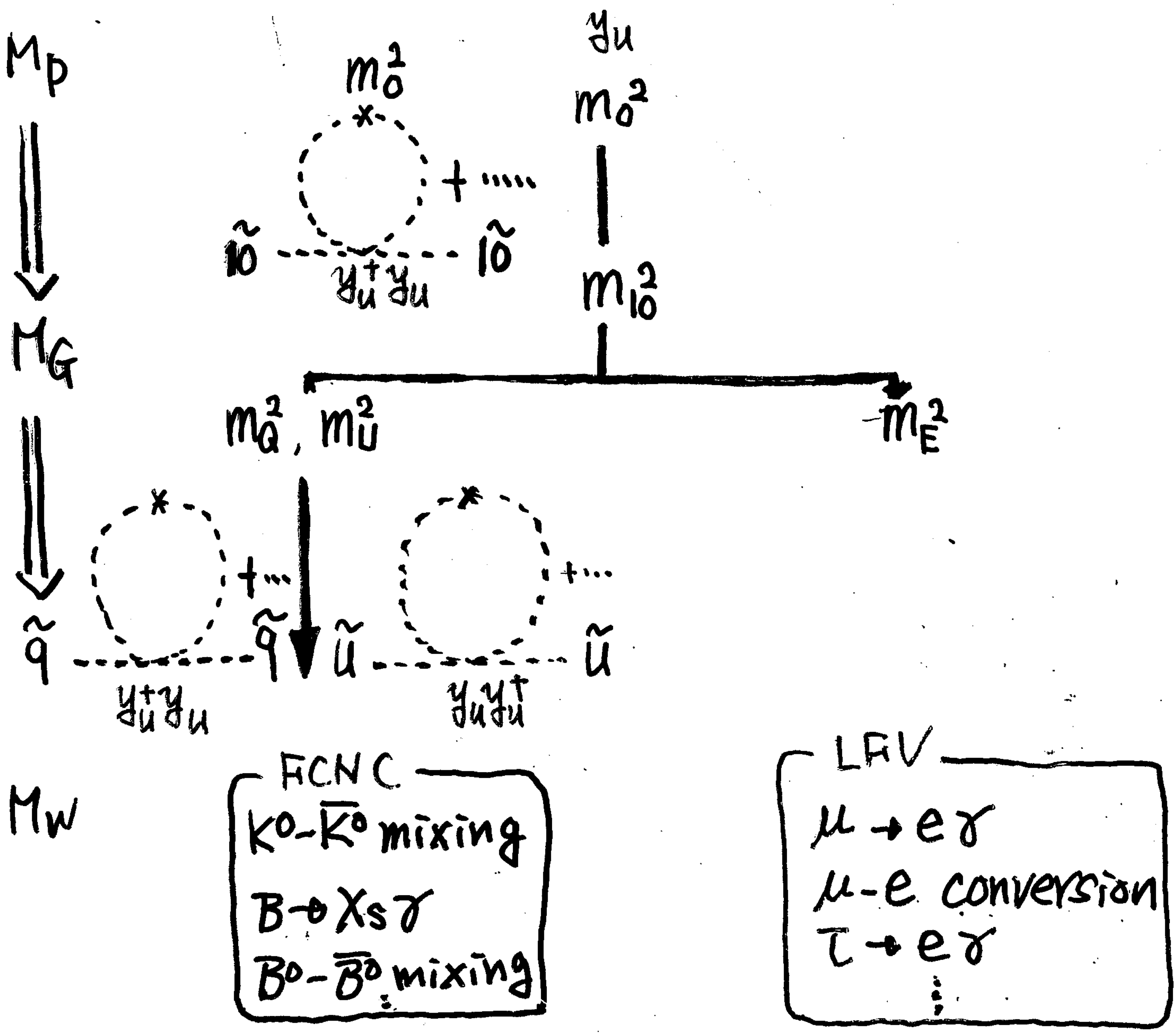
No new source of flavor mixing

Radiative corrections from the interactions below the Planck scale modify the above structure.

● SUSY GUT and LFV/FCNC

In the SUSY GUT, interactions through large top Yukawa coupling constant induce $\left\{ \begin{array}{l} \text{LFV} \\ \text{FCNC} \end{array} \right.$ processes.

ex) SU(5) $\mathbf{10}\{Q, \bar{U}, E\}$ $\bar{\mathbf{5}}\{\bar{D}, L\}$



Barbieri - Hall

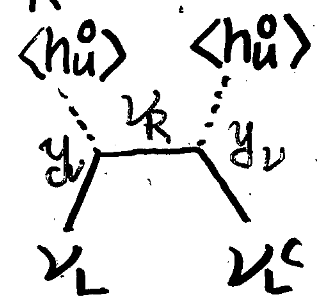
- Neutrino Yukawa coupling
- The experimental evidences of ν-oscillati

$\left\{ \begin{array}{l} \text{atmospheric} \\ \text{solar} \left\{ \begin{array}{l} \text{LMA. SMA} \\ \text{vacuum} \end{array} \right. \end{array} \right. \Rightarrow$ small ν-masses

- Seesaw Mechanism

$$\mathcal{L} = y_\nu \bar{\nu}_R \ell h_u + \frac{1}{2} M_R \bar{\nu}_R^c \nu_R$$

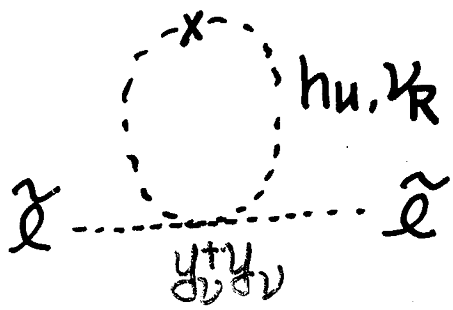
$$m_\nu = y_\nu^T \frac{1}{M_R} y_\nu \langle h_u \rangle^2$$



$$y_\nu \sim 1 \rightarrow M_R \simeq 10^{14-15}\ \text{GeV}$$

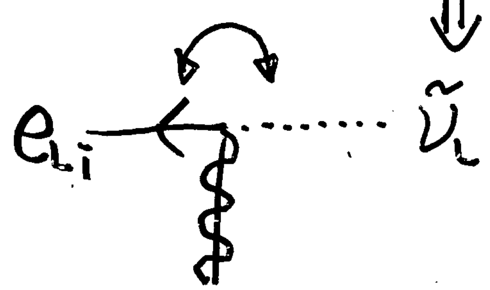
New sources of flavor mixing y_ν appears above M_R

$\Delta m_L^2 =$



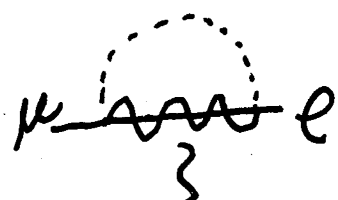
F. Borzumati . A. Masiero

$\Downarrow$



$\mu \to e\gamma$

$\tau \to e\gamma$



J.Hisano, T.Moroi

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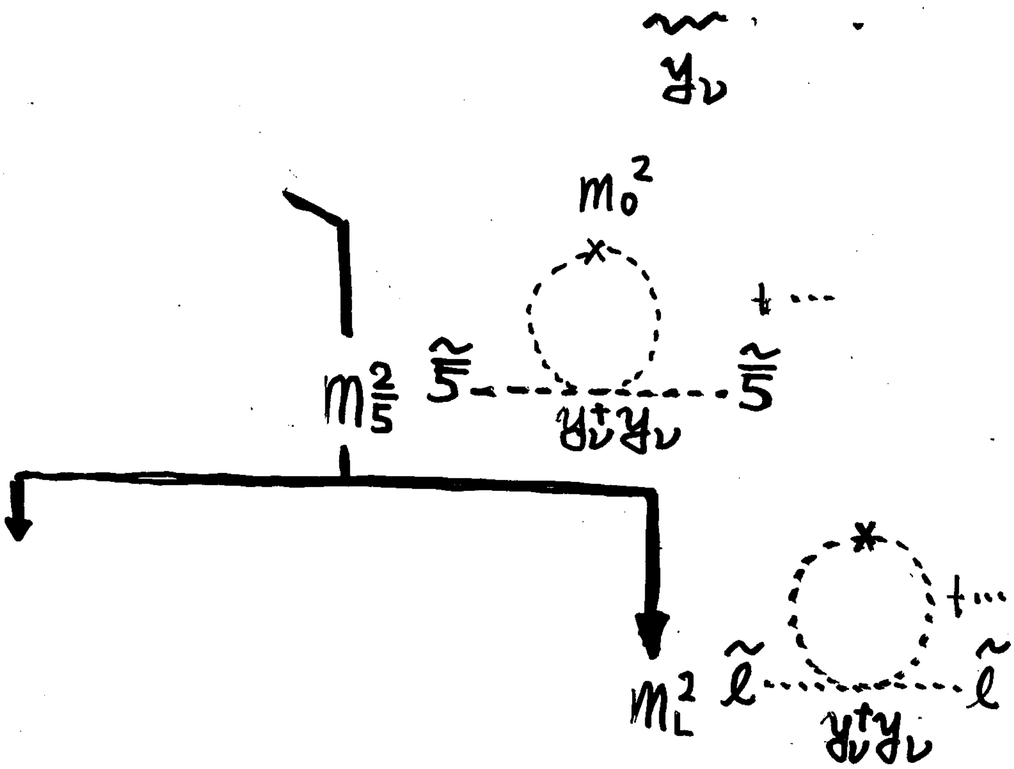


We consider FCNC and LFV processes in the model which incoporates the seesaw mechanism as neutrino mass generation

II. Model

We consider SU(5) SUSY GUT with right-handed neutrino $N\ (\nu_R, \tilde{\nu}_R)$

$\mathbf{10}_i \{Q_i, \bar{U}_i, \bar{E}_i\}$ $\quad \bar{\mathbf{5}}_i \{\bar{D}_i, L_i\}$ $\quad \mathbf{1}_i \{N_i\}$ $\quad i = 1-3$

$\mathbf{5} : H \{H_c, H_u\}$ $\quad \bar{\mathbf{5}} : \bar{H} \{\bar{H}_c, H_d\}$

M_P

$$\boxed{W_{SUSYRN} = \frac{1}{8}\, 10_i \hat{\lambda}_{u_i} 10_i H + \bar{5}_i \lambda_{d_{ij}} 10_j \bar{H} + 1_i \hat{\lambda}_{\nu_i} \bar{5}_i H + \frac{1}{2} 1_i M_{\nu_{ij}} 1_j + \cdots}$$

Large Yukawa (diagonal) $\begin{cases} \hat{y}_{u_i} = \hat{\lambda}_{u_i} \\ \hat{y}_{\nu_i} = \hat{\lambda}_{\nu_i} \end{cases}$ $\quad$ Small Yukawa $\begin{cases} y_{d_{ij}} = \lambda_{d_{ij}} \\ y_{e_{ij}} = \lambda^T_{d_{ij}} \end{cases}$

M_{GUT}

$$\boxed{W_{MSSMRN} = \bar{U}_i \hat{y}_{u_i} Q_i H_u + \bar{D}_i y_{d_{ij}} Q_j H_d + \bar{E}_i y_{e_{ij}} L_j H_d + \underbrace{N_i \hat{y}_{\nu_i} L_i H_u + \frac{1}{2} N_i M_{\nu_{ij}} N_j}_{\Downarrow} + \mu_H H_d H_u}$$

M_R

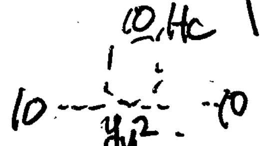
$$\frac{1}{2} (H_u N)^T \hat{y}_\nu \frac{1}{M_\nu} \hat{y}_\nu (H_u N) \Rightarrow m_\nu = \hat{y}_\nu \frac{1}{M_\nu} \hat{y}_\nu \langle h_u^0 \rangle$$

$$\boxed{y_e = y_d^T} \Rightarrow \quad \frac{m_b}{m_\tau} \quad \underbrace{\frac{m_s}{m_\mu} \quad \frac{m_d}{m_e}}_{\text{fail.}}$$

" GUT relation "

● Radiative corrections ($M_P \to M_G$)

$$\mathbf{10}: \ \Delta m^2_{10}\,(m_Q^2, m_U^{2T}, m_E^{2T}) \simeq -\frac{6}{(4\pi)^2}\begin{bmatrix} y_u^2 & & \\ & y_c^2 & \\ & & y_t^2 \end{bmatrix}(3+A_0^2)\,m_0^2 \ln\left(\frac{M_G}{M_P}\right)$$



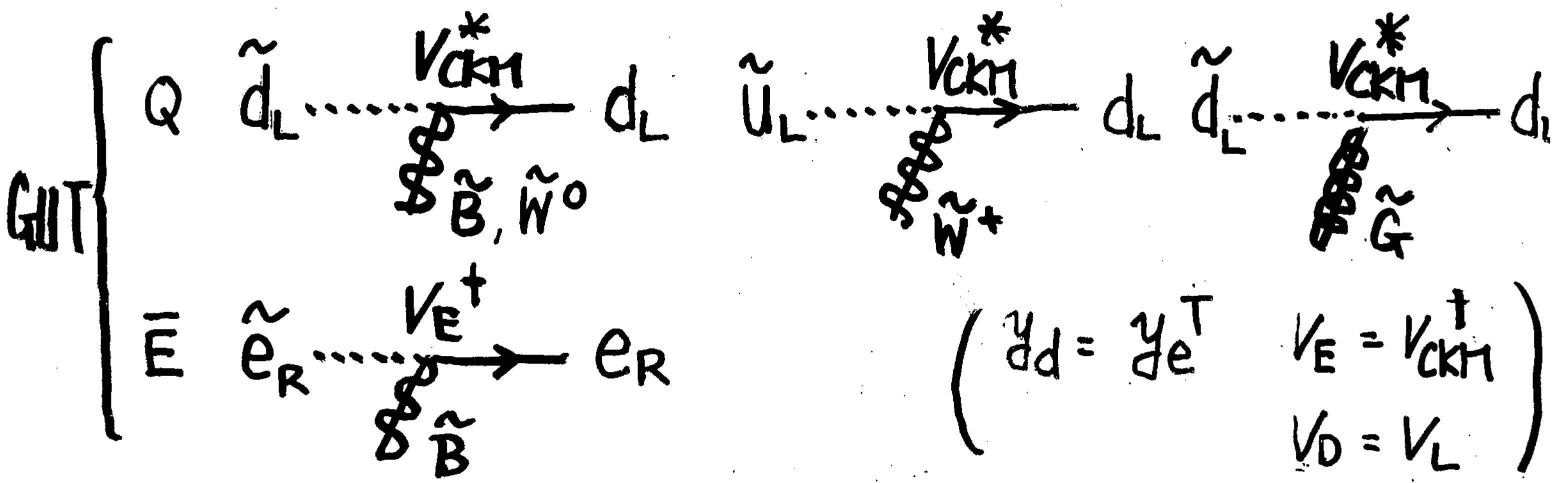
$$\bar{\mathbf{5}}: \ \Delta m^2_{\bar 5}\,(m_D^{2T}, m_L^2) \simeq -\frac{2}{(4\pi)^2}\begin{bmatrix} y_{\nu_1}^2 & & \\ & y_{\nu_2}^2 & \\ & & y_{\nu_3}^2 \end{bmatrix}(3+A_0^2)\,m_0^2 \ln\left(\frac{M_G}{M_P}\right)$$

$$\simeq \frac{1}{3}\left(\frac{\hat{y}_{\nu i}}{y_t}\right)^2 (\Delta m^2_{10})_3$$

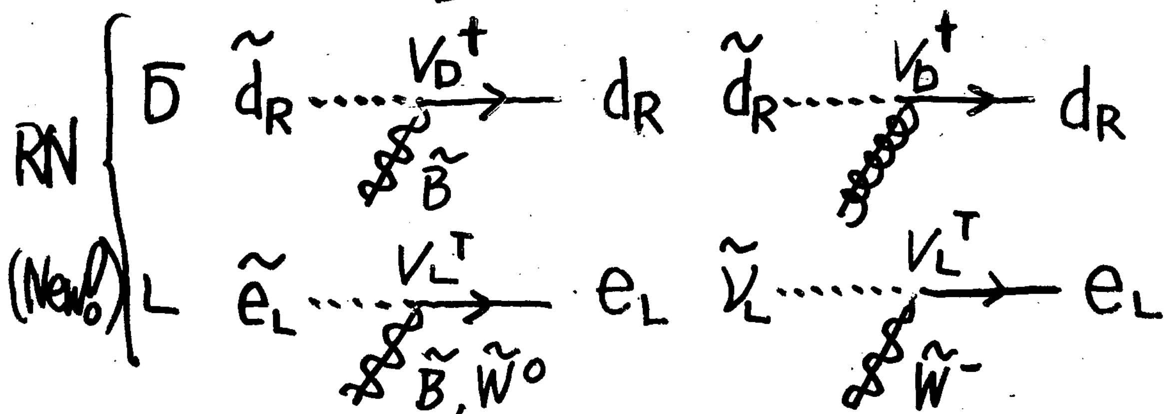
diagonal

degeneracy is resolved!

$$\boxed{W = \bar{D}\, V_D^T\, \hat{y}_d\, V_{CKM}^\dagger\, Q H_d + \bar{E}\, V_E^T\, \hat{y}_e\, V_L\, L H_d + \cdots}$$



$$\left(\begin{array}{ll} y_d = y_e^T & V_E = V_{CKM}^\dagger \\ & V_D = V_L \end{array}\right)$$



New flavor mixing

① opposite chirality $\quad \begin{matrix} \tilde{d}_L \\ \tilde{e}_R \end{matrix} \Leftrightarrow \begin{matrix} \tilde{d}_R \\ \tilde{e}_L \end{matrix}$

② large mixing ($V_L \Leftrightarrow V_{MNS}$)

- **Higher dimensional operator**

$$y_d = y_e^T \Rightarrow \frac{m_s}{m_\mu} \quad \frac{m_d}{m_e} \quad \times$$

$\frac{M_G}{M_P} \simeq \mathcal{O}(10^{-2}) \Rightarrow$ Higher dim. op. can not be neglected @ M_G

especially,

$$\delta W = \frac{1}{M_P}(24 \cdot \bar{5}_i) K_{d ij} \mathbf{10}_j \bar{H}$$

$$SU(5) \Rightarrow SU(3) \times SU(2) \times U(1)$$

$$\langle 24 \rangle = V_G \begin{array}{c} \left(\begin{array}{ccccc} \frac{1}{3} & & & & \\ & \frac{1}{3} & & & \\ & & \frac{1}{3} & & \\ & & & -\frac{1}{2} & \\ & & & & -\frac{1}{2} \end{array} \right) \end{array} \begin{array}{l} \left.\vphantom{\begin{array}{c}1\\1\\1\end{array}}\right\} \bar{D} \\ \left.\vphantom{\begin{array}{c}1\\1\end{array}}\right\} L \end{array}$$

$$y_d = \lambda_d + \frac{1}{3}\frac{V_G}{M_P} K_d$$

$$y_e = \lambda_d^T - \frac{1}{2}\frac{V_G}{M_P} K_d^T$$

$$\boxed{y_e = y_d^T - \frac{5}{6}\underbrace{\frac{V_G}{M_P}}_{\mathcal{O}(10^{-2})} K_d^T}$$

We can incoporate realistic mass relations $\frac{m_s}{m_\mu}$, $\frac{m_d}{m_e}$ with K_d

However $K_{d ij} \lesssim \mathcal{O}(1)$ is expected.

$$\boxed{V_D^T \hat{y}_d V_{CKM}^\dagger - V_L^T \hat{y}_e V_E = \frac{5}{6}\frac{V_G}{M_P} K_d}$$

$|K_{d\,ij}| < \mathcal{O}(1)$

$$\Rightarrow \hat{y}_d V_{CKM}^\dagger V_E^\dagger - V_D^* V_L^T \hat{y}_e = \frac{5}{6}\frac{V_G}{M_P} K_d'$$

$$\left| (\cdots y_b)\left(\ \square\ \right) - \left(\ \square\ \right)\begin{pmatrix}\vdots \\ y_\tau\end{pmatrix}\right| \lesssim \mathcal{O}(10^{-2})$$

$$\Rightarrow V_L^* V_D^T \hat{y}_d - \hat{y}_e V_E V_{CKM} = \frac{5}{6} K_d''$$

$$V_{CKM}^\dagger V_E^\dagger \hat{y}_e - \hat{y}_d V_D^* V_L^T = -\frac{5}{6} K_d''^\dagger$$

$$\left| \left(\ \square\ \right)\begin{pmatrix}\vdots \\ y_\tau\end{pmatrix} - (\cdots y_b)\left(\ \square\ \right)\right| \lesssim \mathcal{O}(10^{-2})$$

$$V_E = \begin{array}{c} \\ e_R \\ \mu_R \\ \tau_R \end{array}\!\!\begin{array}{c} \begin{array}{ccc} d_L & s_L & b_L \end{array} \\ \begin{pmatrix} \cos\theta_E & \sin\theta_E & \\ -\sin\theta_E & \cos\theta_E & \\ & & 1 \end{pmatrix} \end{array} V_{CKM}^\dagger$$

※ We neglect CP phases except for KM phase

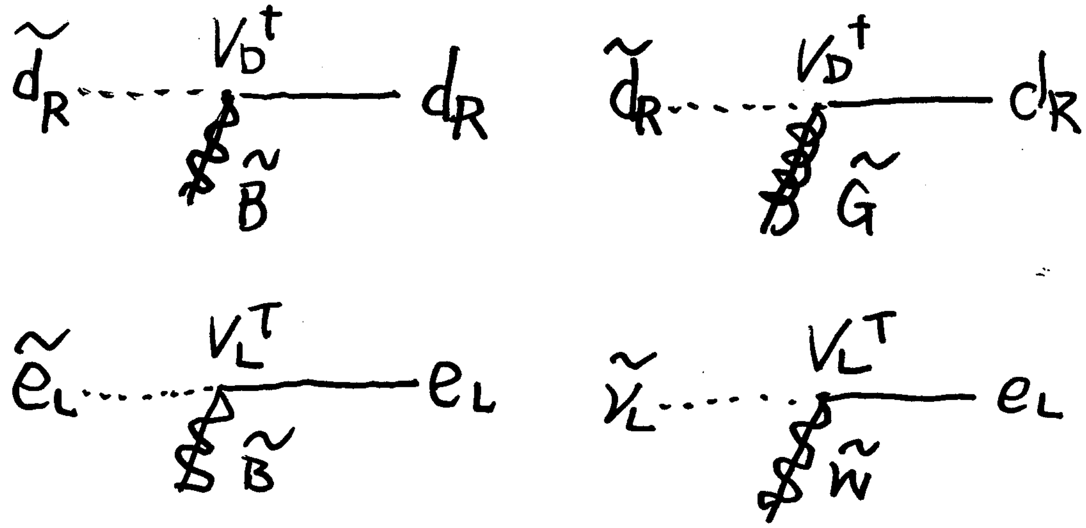
$$V_D = \begin{array}{c} \\ d_R \\ s_R \\ b_R \end{array}\!\!\begin{array}{c} \begin{array}{ccc} \nu_e & \nu_\mu & \nu_\tau \end{array} \\ \begin{pmatrix} \cos\theta_D & \sin\theta_D & \\ -\sin\theta_D & \cos\theta_D & \\ & & 1 \end{pmatrix} \end{array} \underset{\substack{\updownarrow \\ V_{MNS}}}{V_L}$$

The effect of the higher dimensional operator can be parameterized by θ_E, θ_D

III LFV FCNC processes

- $g-2$
- $\mu \to e\gamma$ $(\tau \to e\gamma)$
- $b \to s\gamma$
- ε_K
- Δm_{B_d} (Δm_{B_s})

Effects of right-handed neutrino



● g − 2

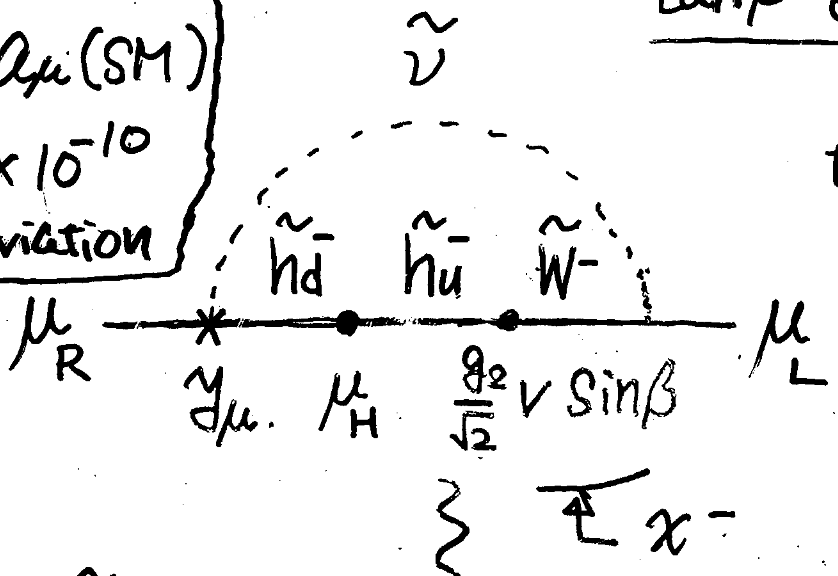
Insensitive to flavor mixing $\Rightarrow$ **mass spectrum**

$$\mathcal{L} = \frac{1}{2}\left(\frac{e}{2m_\mu}\right) a_\mu \bar{\mu}\, \sigma^{\alpha\beta} \mu\, F_{\alpha\beta}$$

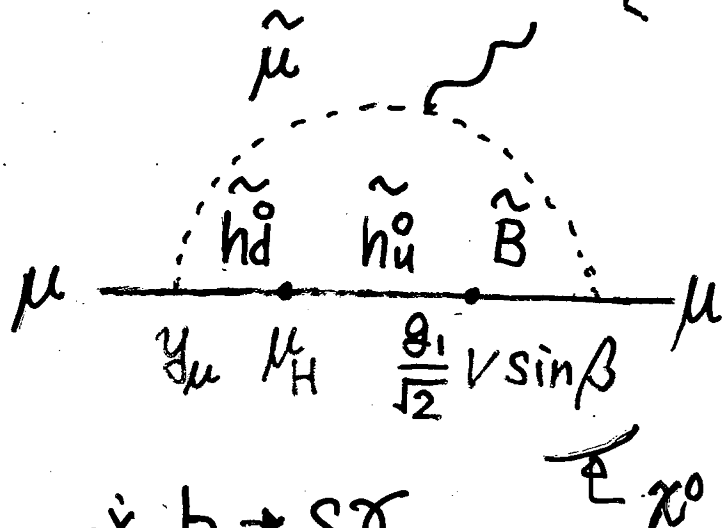
BNL E821
$a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM})$
$= 43(16) \times 10^{-10}$
2.6 σ deviation

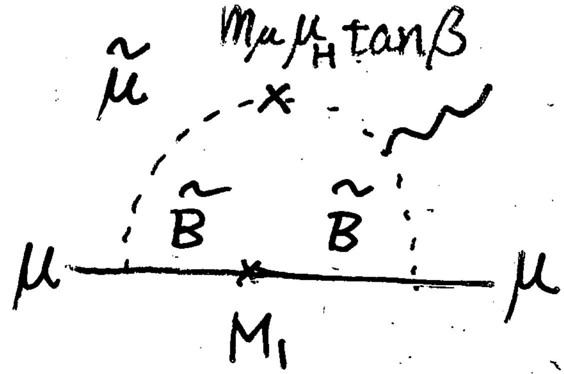
<ins>tanβ enhancement</ins>

$\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$



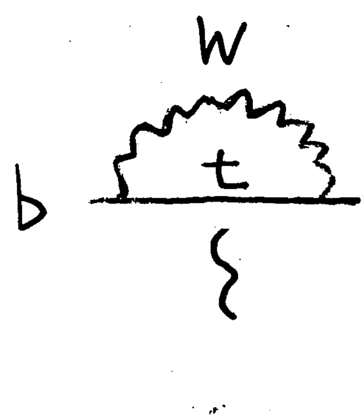
$\propto m_\mu \mu_H \tan\beta$

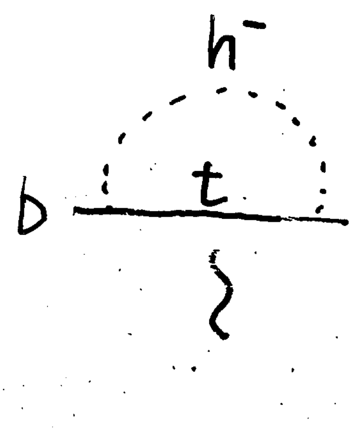


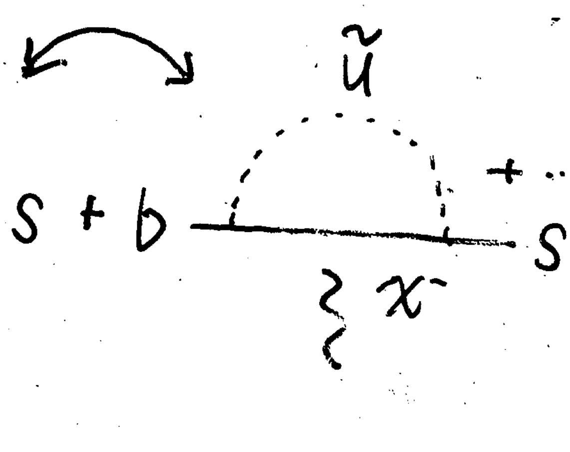


⁘ <ins>b → sγ</ins>

enhance or cancel $\mu_H \tan\beta$





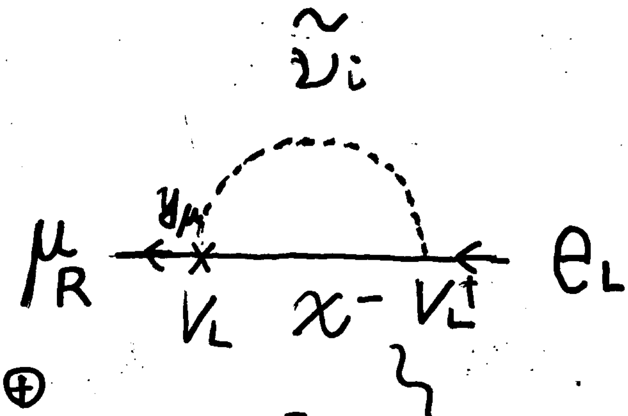


• $\mu \to e\gamma$

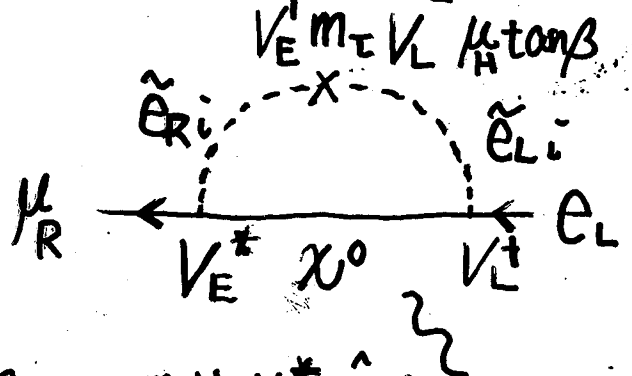
$$\mathcal{L} = -\frac{4G_F}{\sqrt{2}} m_{e_i} \left\{ A_R^{ij} (\underbrace{\overline{\ell_{Ri}}\, \sigma^{\mu\nu} \ell_{Lj}}_{\text{Chirality flip.}}) + A_L^{ij} (\overline{\ell_{Li}}\, \sigma^{\mu\nu} \ell_{Rj}) \right\} F^{\mu\nu}$$

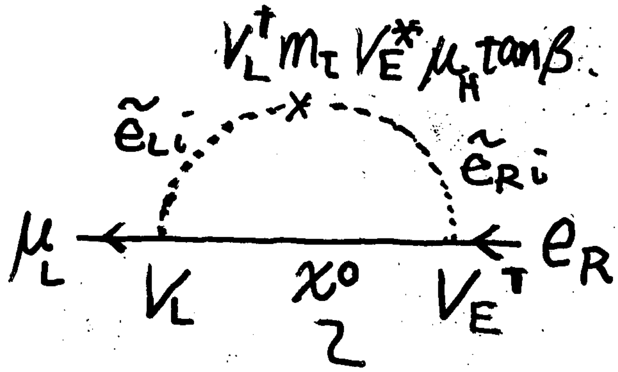
$+ \mathrm{H.c.}$

ν_R

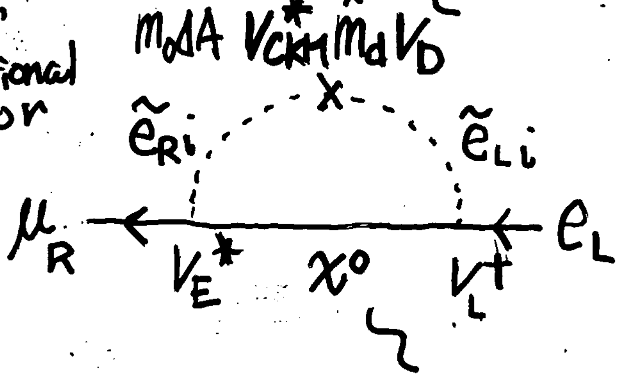


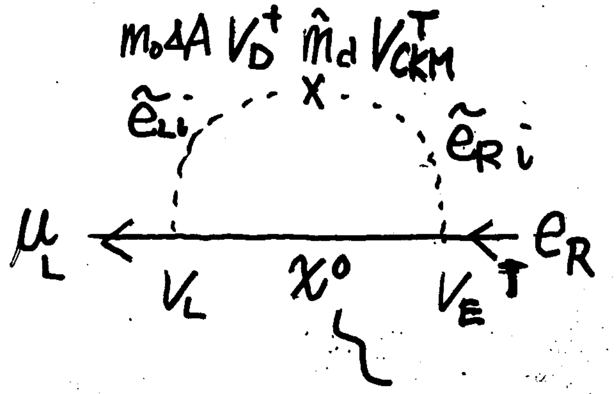
SU(5)⊕ ν_R

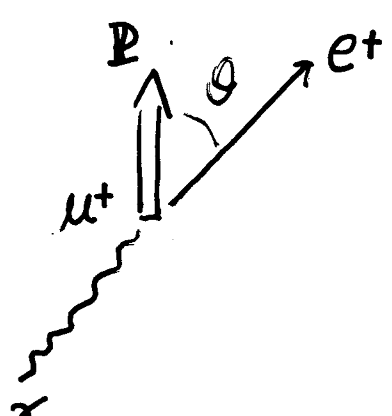




Higher dimensional operator







$$\frac{dB(\mu^+ \to e^+\gamma)}{d\cos\theta} = \frac{1}{2} B(\mu^+ \to e^+\gamma) \{ 1 + A\, P \cos\theta \}$$

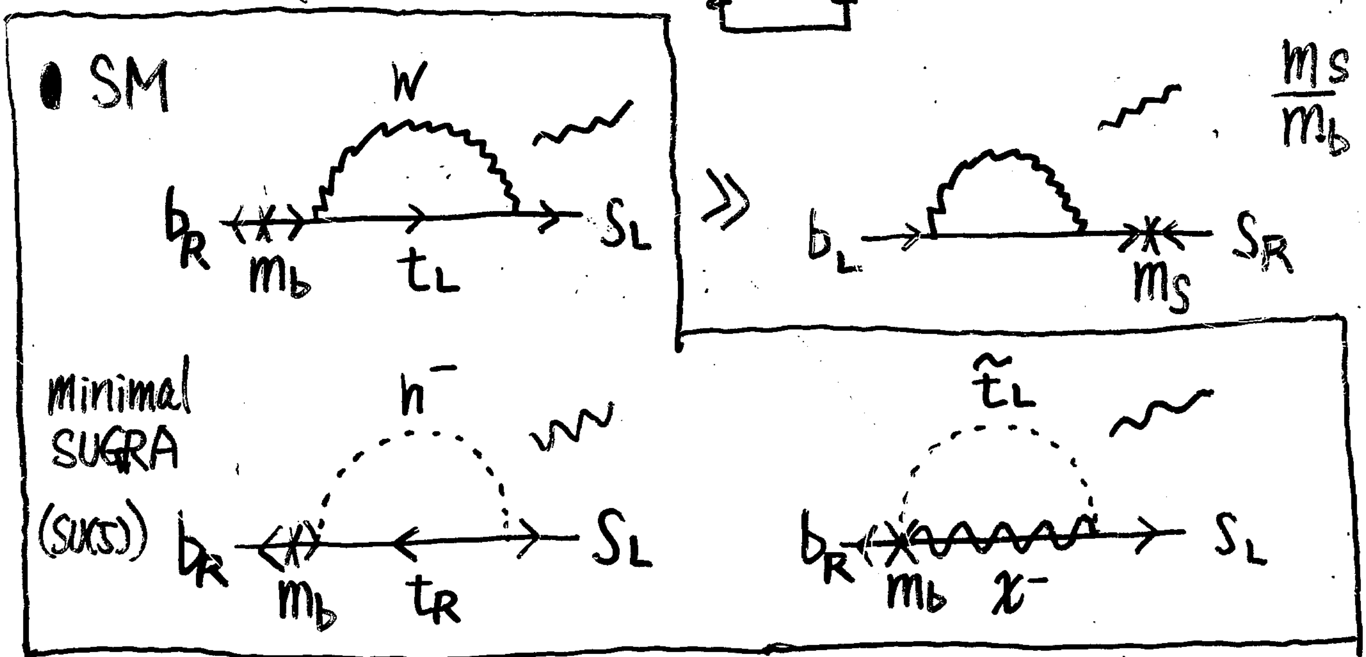
$$A = \frac{|A_L^{21}|^2 - |A_R^{21}|^2}{|A_L^{21}|^2 + |A_R^{21}|^2}$$

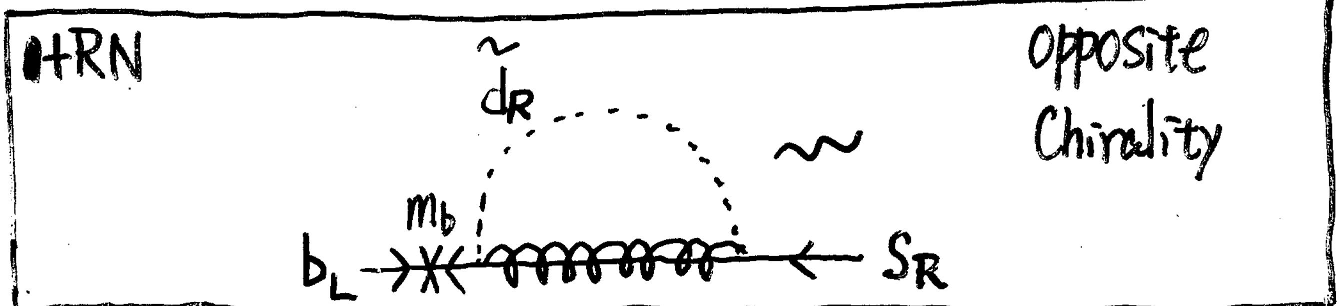
- $b \to s\gamma$

  ↳ used as a constraint for the parameter space

Chirality flip

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} m_b \left[C_7 \bar{s}_L \sigma_{\mu\nu} b_R + C_7' \bar{s}_R \sigma_{\mu\nu} b_L\right] F^{\mu\nu} + h.c.$$





- time-dependent CP asymmetry D.Atwood M.Gronau A.Soni PRL 79 (1997) 185

$$\begin{array}{ccccc} B & \longrightarrow & B & \xrightarrow{C_7} & M_s\,\gamma \\ (\bar{B}) & \searrow & \bar{B} & \nearrow_{C_7'^*} & \end{array}$$

M_s ↳ CP eigenstate $\xi = \begin{cases} +1 & \text{even} \\ -1 & \text{odd} \end{cases}$

$$A(t) = \frac{\Gamma(B^0(t)\to M_s^0\gamma) - \Gamma(\bar{B}^0(t)\to M_s^0\gamma)}{\Gamma(B^0(t)\to M_s^0\gamma) + \Gamma(\bar{B}^0(t)\to M_s^0\gamma)}$$

$$= \xi A_t(B\to M_s^0\gamma)\sin(\Delta m_B t)$$

$$A_t(B\to M_s\gamma) = \frac{2\,\mathrm{Im}(e^{-i\theta_B} C_7 C_7')}{|C_7|^2 + |C_7'|^2} \qquad e^{i\theta_B} = \frac{\langle B_0|H|\bar{B}_0\rangle}{|\langle B_0|H|\bar{B}_0\rangle|}$$

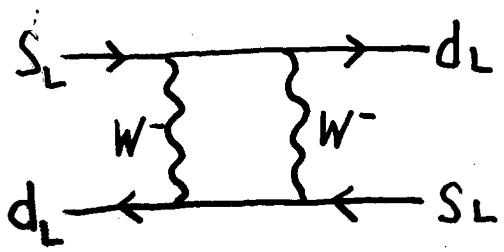
● CP violation parameter of K^0-$\bar{K}^0$ mixing

$$\varepsilon_K = \frac{e^{i\frac{\pi}{4}}}{\sqrt{2}} \frac{\mathrm{Im}\left[\langle K^0 | H_{eff} | \bar{K}^0 \rangle\right]}{2 m_K \Delta m_K}$$

SU(3) Contraction

$$\begin{aligned} H_{eff} = \frac{4G_F}{\sqrt{2}} \Big[& \boxed{g^V_{LL} (\bar{d}\gamma_\mu s_L)(\bar{d}\gamma^\mu s_L)} + g^V_{RR} (\bar{d}\gamma_\mu s_R)(\bar{d}\gamma^\mu s_R) \\ & + g^S_{LL} (\bar{d}\, s_L)(\bar{d}\, s_L) + g^S_{RR} (\bar{d}\, s_R)(\bar{d}\, s_R) \\ & + g^{S'}_{LL} (\bar{d}\, s_L)(\bar{d}\, s_L) + g^{S'}_{RR} (\bar{d}\, s_R)(\bar{d}\, s_R) \\ & + \boxed{2 g^S_{LR} (\bar{d}\, s_L)(d\, s_R) + 2 g^{S'}_{LR} (\bar{d}\, s_L)(d\, s_R)} \end{aligned}$$

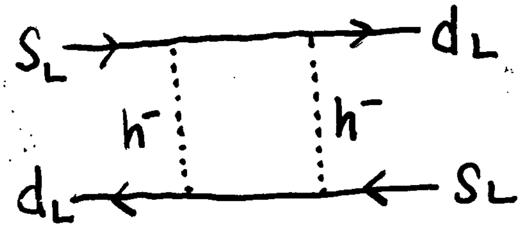
SM

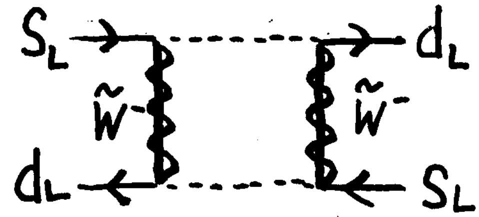


$$\langle K^0 | \bar{d}\gamma_\mu s_L \cdot \bar{d}\gamma^\mu s_L | \bar{K}^0 \rangle = \frac{4}{3} m_K^2 F_K^2 B_K$$

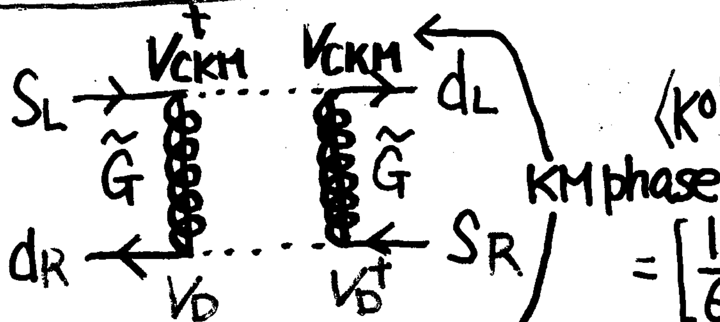
Bag parameter ~10% ambiguity

mSUGRA MSSM (SU(5))



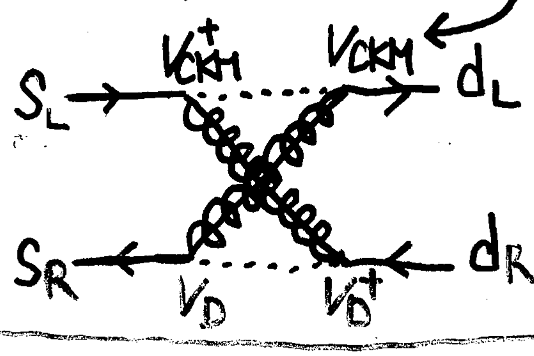


+RN



$$\langle K^0 | (\bar{d} s_L)(\bar{d} s_R) | \bar{K}^0 \rangle = \left[\frac{1}{6} + \left(\frac{m_K}{m_s + m_d} \right)^2 \right] m_K^2 F_K^2 B'_K$$

matrix element enhancement



• $B^0_d - \bar B^0_d$ ($B^0_s - \bar B^0_s$) mixing

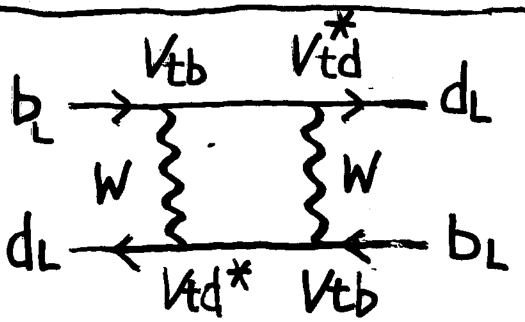
$$\Delta m_{B_d} = \frac{|\langle B^0_d|\mathcal{H}_{eff}|\bar B^0_d\rangle|}{m_B}$$

$$\begin{aligned}\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}}\Big[&\boxed{g^V_{LL}(\bar d\gamma_\mu b_L)(\bar d\gamma^\mu b_L)} + \boxed{g^V_{RR}(\bar d\gamma_\mu b_R)(\bar d\gamma^\mu b_R)}\\
&+ g^S_{LL}(\bar d b_L)(\bar d b_L) + g^S_{RR}(\bar d b_R)(\bar d b_R)\\
&+ g^{S'}_{LL}(\bar d b_L)(\bar d b_L) + g^{S'}_{RR}(\bar d b_R)(\bar d b_R)\\
&+\boxed{2g^S_{LR}(\bar d b_L)(\bar d b_R) + 2g^{S'}_{LR}(\bar d b_L)(\bar d b_R)} + \text{H.c.}\Big]\end{aligned}$$

No matrix-element enhancement

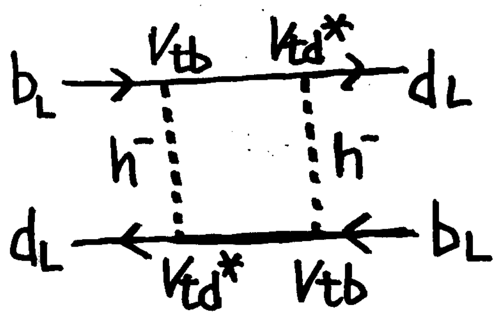
$$\frac{m_B}{m_b} \sim 1$$

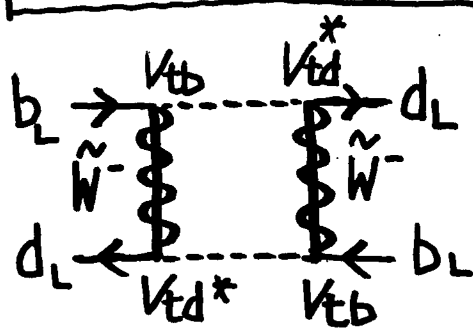
SM



$$\langle B^0_d|\bar d\gamma_\mu b_L \cdot \bar d\gamma^\mu b_L|\bar B^0_d\rangle = \frac{4}{3} m_B^2 F_{B_d}^2 B_d$$

mSUGRA MSSM (SU(5))



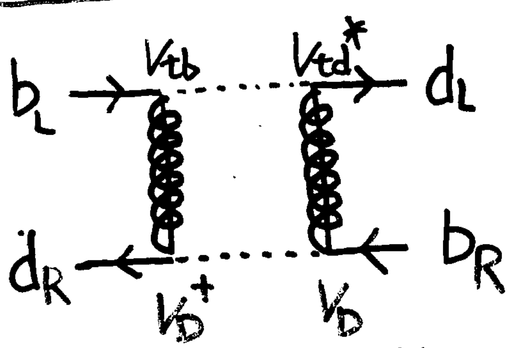


$$\frac{\Delta m_{B_s}}{\Delta m_{B_d}} \frac{F^2_{B_s}B_{B_s}}{F^2_{B_d}B_{B_d}} \frac{|V_{ts}|}{|V_{td}|}$$

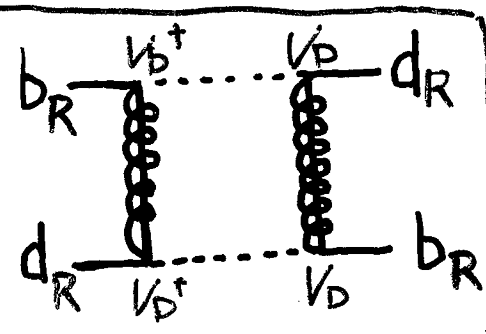
Less ambiguity

Same for SM and SU5

+RN



+ cross



+ cross

For $B^0_s - \bar B^0_s$ mixing $d \to s$ $V_{td} \to V_{ts}$

IV Results of numerical calculations

- We solved renormalization group equations numerically from M_P to M_W considering all sources of flavor mixing
- We assumed radiative EW symmetry breaking.
- Constraints from
  - direct SUSY search (LEP, Tevatron)
  - Higgs boson search (LEP)
  - $b \to s\gamma$
  - eEDM nEDM
  - neutral LSP, CCB
- We calculate

  a_μ, $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to e\gamma$,
  $b \to s\gamma$, ε_K, Δm_{B_d}, Δm_{B_s}
  $A^{CP}(b \to M_s\gamma)$, $A^{CP}(B \to J/\psi K_S)$
  eEDM, nEDM

Input parameters

- Planck scale

  $m_0 \quad M_0 \quad A_0 \quad \Delta A_0$

- GUT scale

  θ_D, θ_E

- M_R scale

  $M_{\nu\, ij}$

- EW scale

  $\tan\beta$ $\quad$ sign(μ_H) $\quad$ $V_{CKM}(\delta_{13})$

- low energy

  m_{ν_1}, $\quad V_{MNS}$ $\quad$ (MSW LMA, SMA)

Neutrino parameters

For simplicity

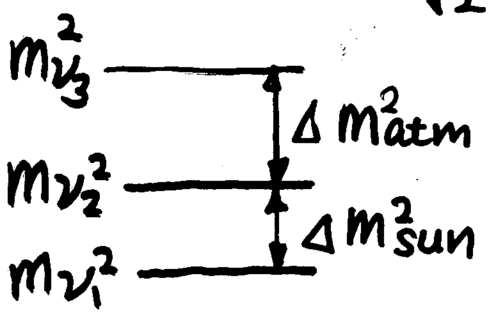
$$M_{\nu\, ij} = M_R \delta_{ij}$$

$$m_{\nu\, ij} = \hat{y}_{\nu_i} \frac{1}{M_R} \hat{y}_{\nu_i} \delta_{ij} \langle h_u^0 \rangle^2$$

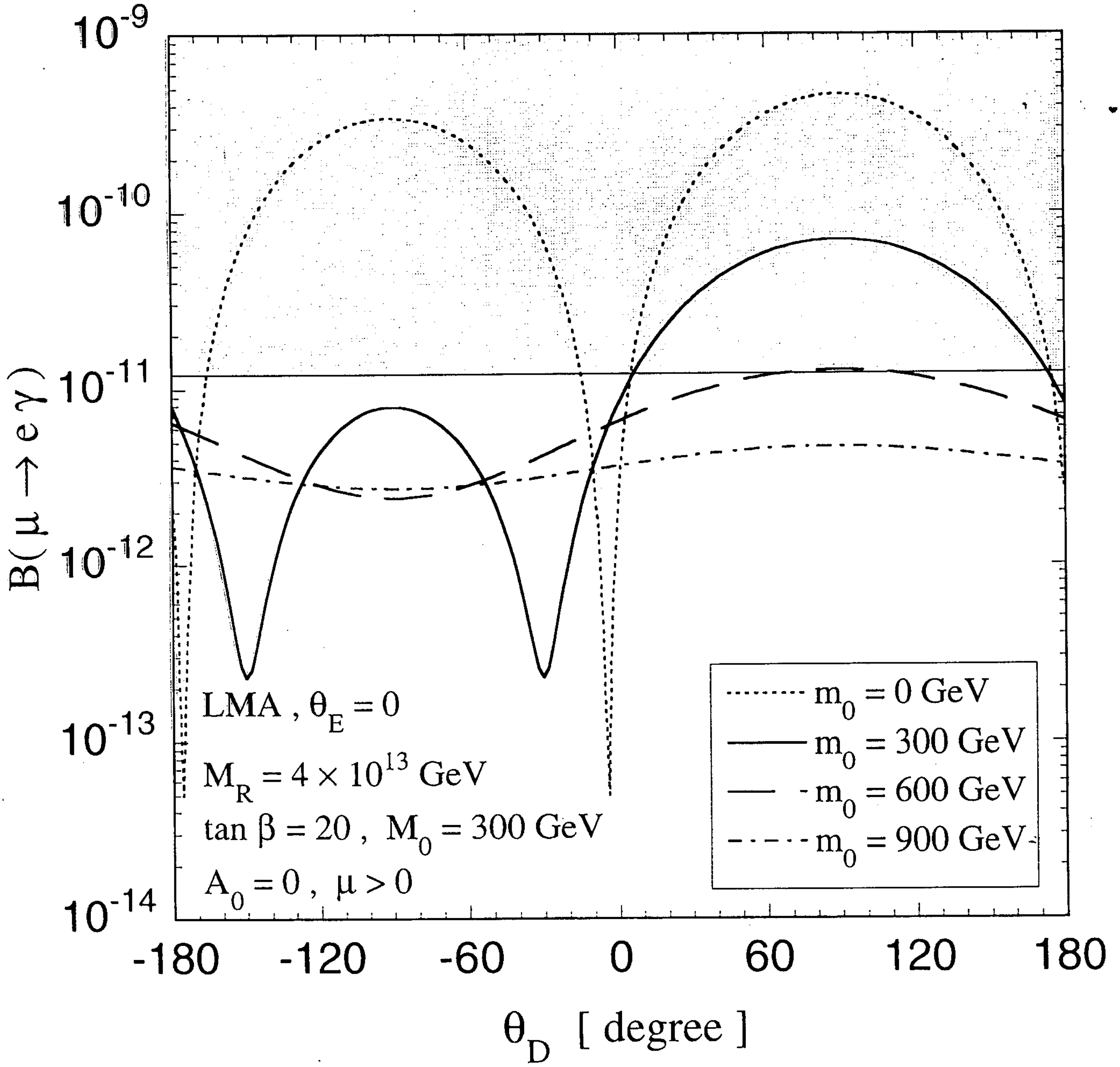
← diagonal

$$y_e = V_E^T \hat{y}_e \underbrace{V_L}_{= V_{MNS}}$$

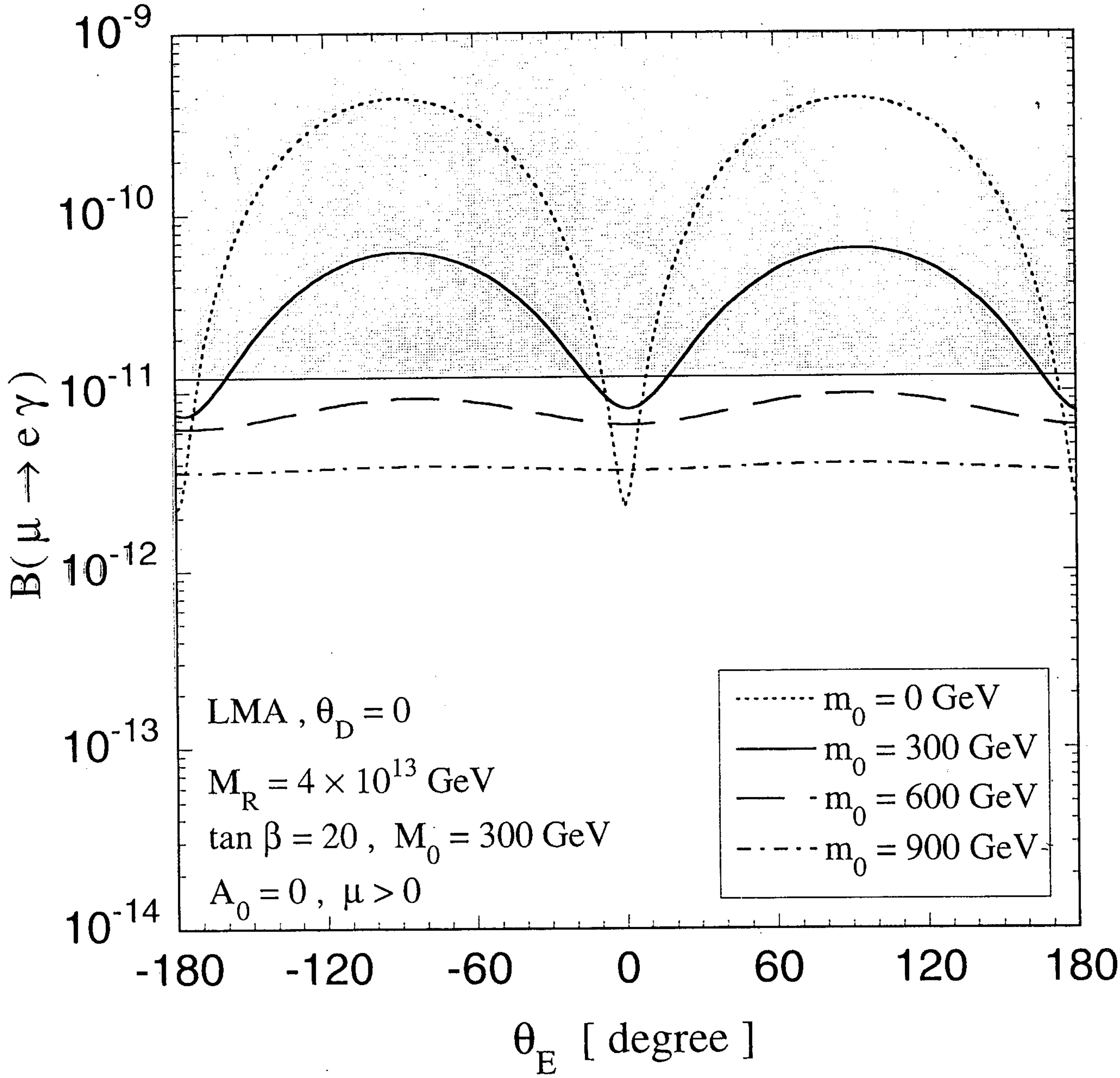
$$V_{MNS} = \begin{bmatrix} \cos\theta_{sun} & \sin\theta_{sun} & 0 \\ -\frac{\sin\theta_{sun}}{\sqrt{2}} & \frac{\cos\theta_{sun}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\theta_{sun}}{\sqrt{2}} & -\frac{\cos\theta_{sun}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$



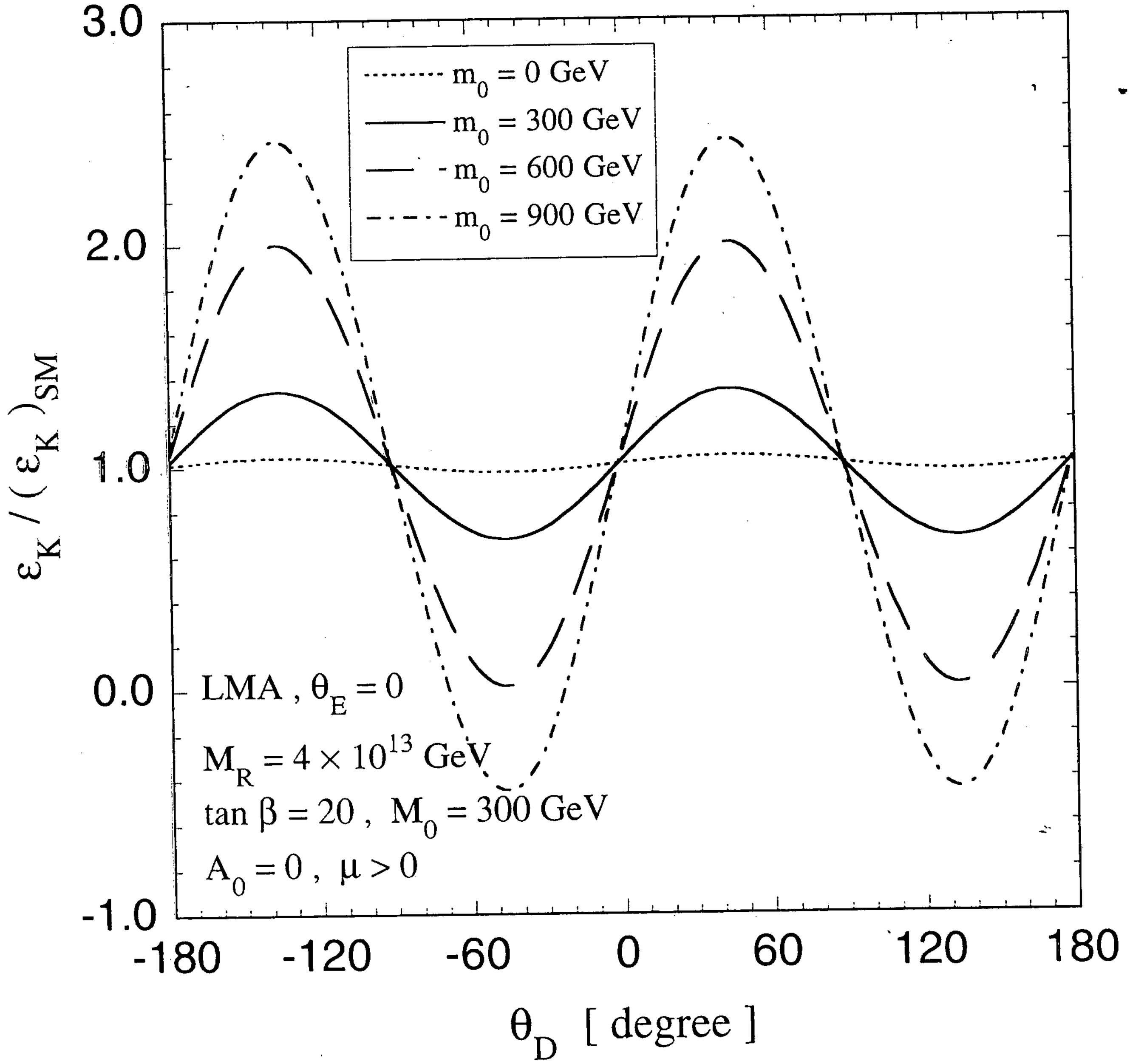
	Δm^2_{atm} (eV^2)	Δm^2_{sun} (eV^2)	m_{ν_1} (eV)	$\sin^2\theta_{sun}$
LMA	3.5×10^{-3}	1.8×10^{-5}	4.0×10^{-3}	1
SMA	3.5×10^{-3}	5.0×10^{-6}	2.2×10^{-3}	5.5×10^{-3}



10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$B(\mu \to e\gamma)$
-180
-120
-60
0
60
120
180
θ_D [degree]
LMA , $\theta_E = 0$
$M_R = 4 \times 10^{13}$ GeV
$\tan\beta = 20$, $M_0 = 300$ GeV
$A_0 = 0$, $\mu > 0$
$m_0 = 0$ GeV
$m_0 = 300$ GeV
$m_0 = 600$ GeV
$m_0 = 900$ GeV

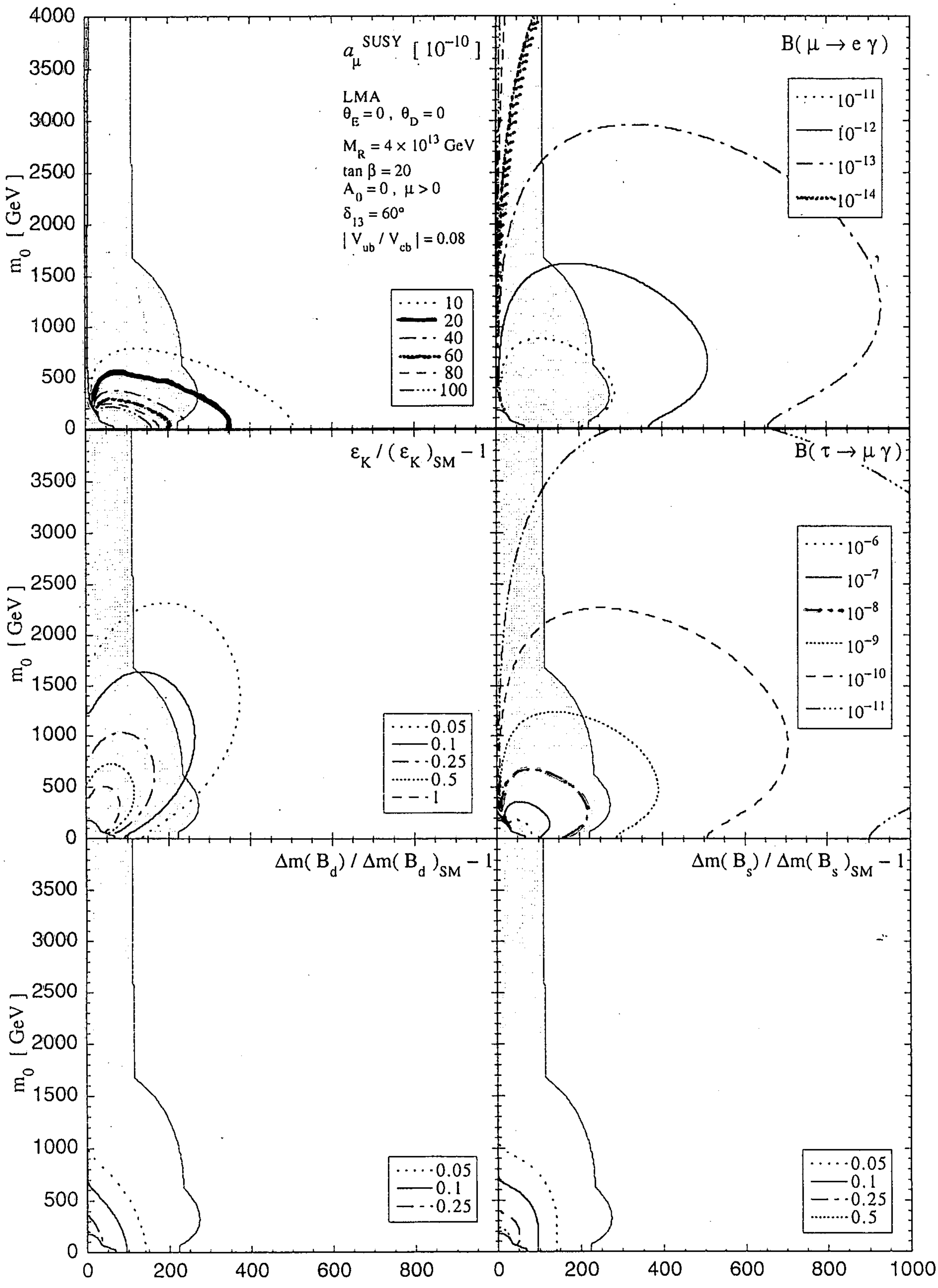


B(μ → e γ)
θ_E [degree]
LMA , θ_D = 0
M_R = 4 × 10^13 GeV
tan β = 20 , M_0 = 300 GeV
A_0 = 0 , μ > 0
m_0 = 0 GeV
m_0 = 300 GeV
m_0 = 600 GeV
m_0 = 900 GeV

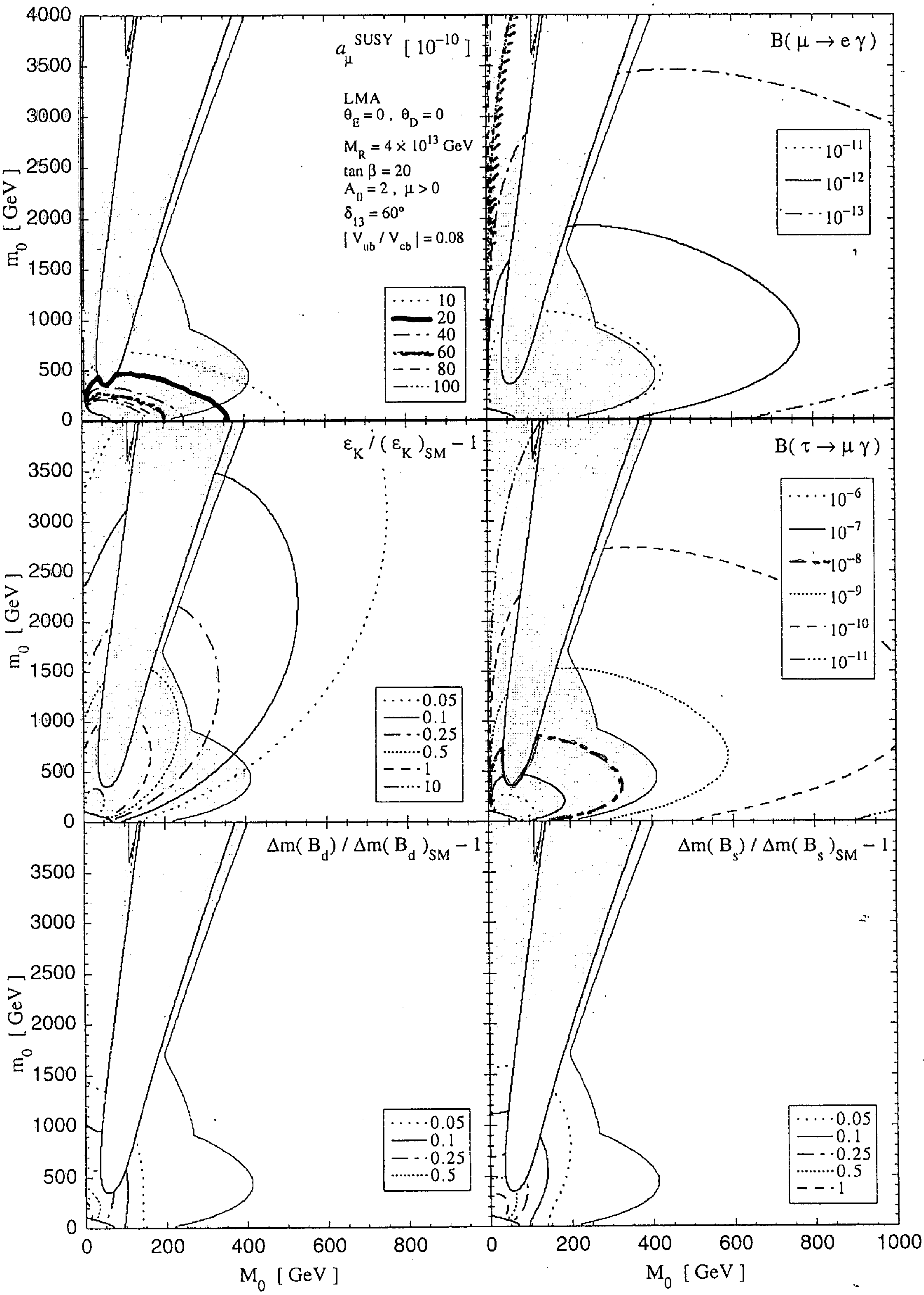


m0 = 0 GeV
m0 = 300 GeV
m0 = 600 GeV
m0 = 900 GeV
LMA , θE = 0
MR = 4 × 10^13 GeV
tan β = 20 , M0 = 300 GeV
A0 = 0 , μ > 0
3.0
2.0
1.0
0.0
-1.0
-180
-120
-60
0
60
120
180
εK / (εK)SM
θD [degree]

LMA $\theta_E = \theta_D = 0$ $M_R = 4\times10^{13}$ GeV
$\tan\beta = 20$ $A_0 = 0$

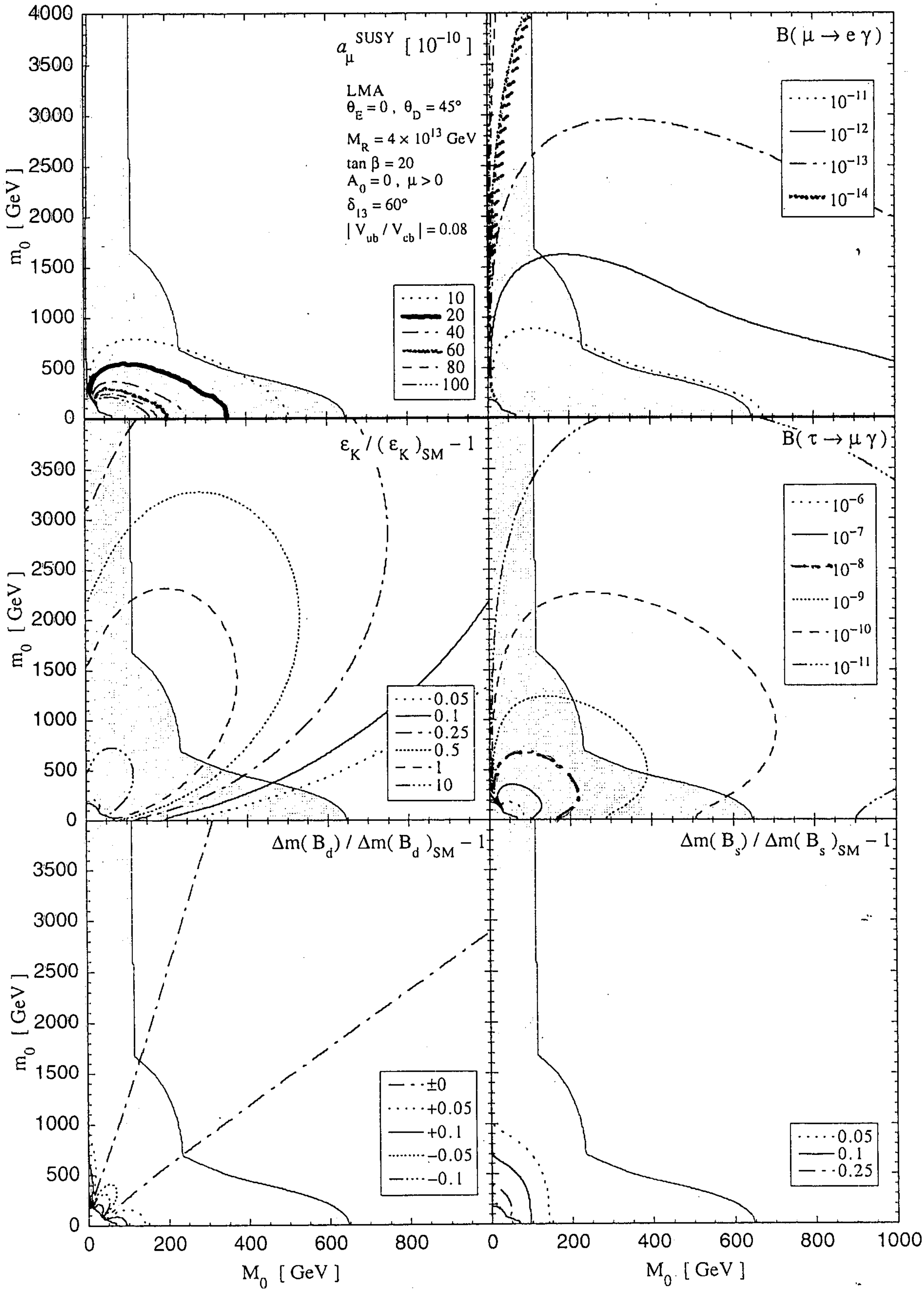


$A_0 = 2$



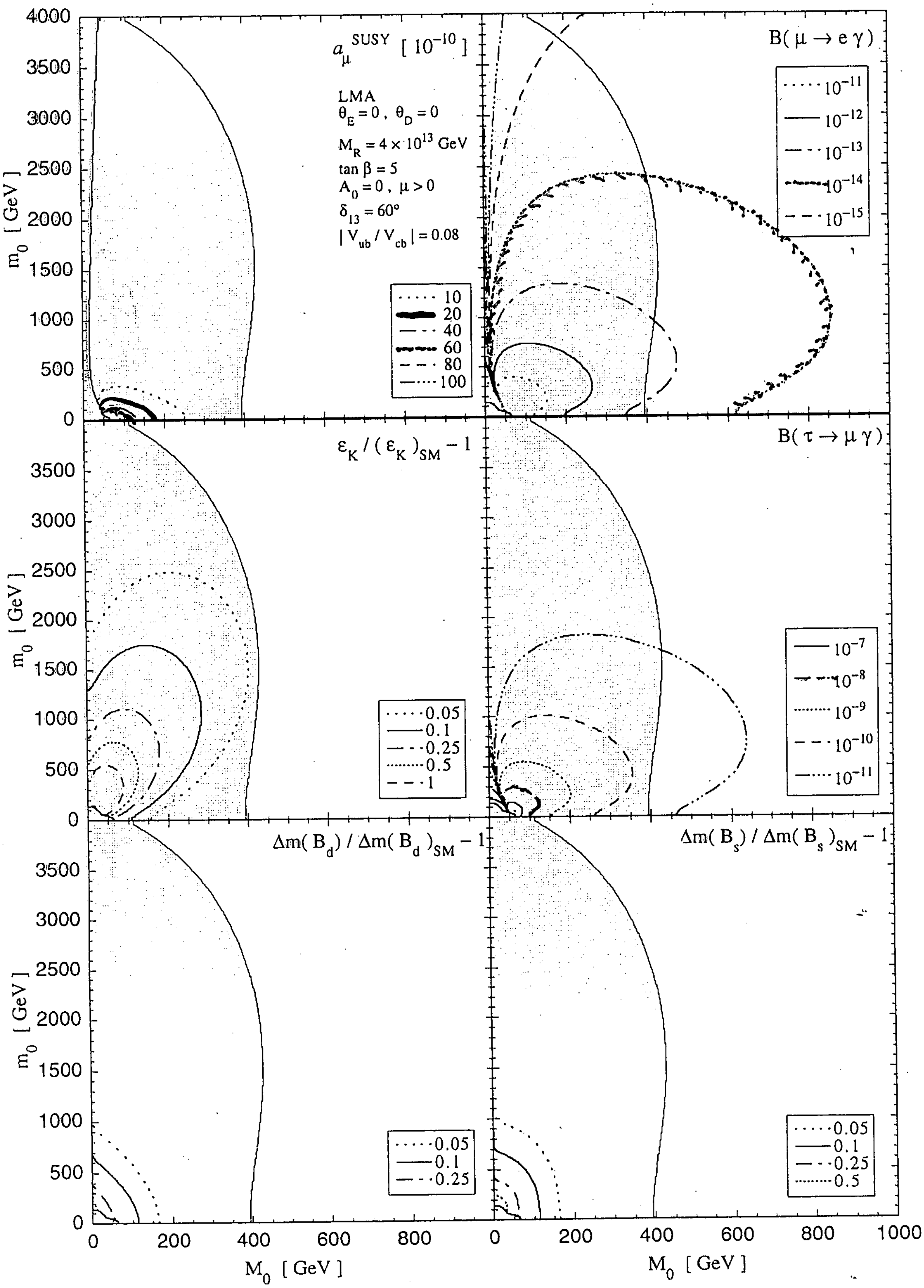
a_μ^{SUSY} [10^{-10}]
LMA
$\theta_E = 0$, $\theta_D = 0$
$M_R = 4 \times 10^{13}$ GeV
$\tan\beta = 20$
$A_0 = 2$, $\mu > 0$
$\delta_{13} = 60°$
$|V_{ub} / V_{cb}| = 0.08$
10
20
40
60
80
100
B($\mu \to e\gamma$)
10^{-11}
10^{-12}
10^{-13}
$\varepsilon_K / (\varepsilon_K)_{SM} - 1$
0.05
0.1
0.25
0.5
1
10
B($\tau \to \mu\gamma$)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\Delta m(B_d) / \Delta m(B_d)_{SM} - 1$
0.05
0.1
0.25
0.5
$\Delta m(B_s) / \Delta m(B_s)_{SM} - 1$
0.05
0.1
0.25
0.5
1
m_0 [GeV]
M_0 [GeV]

$\theta_D = 45°$



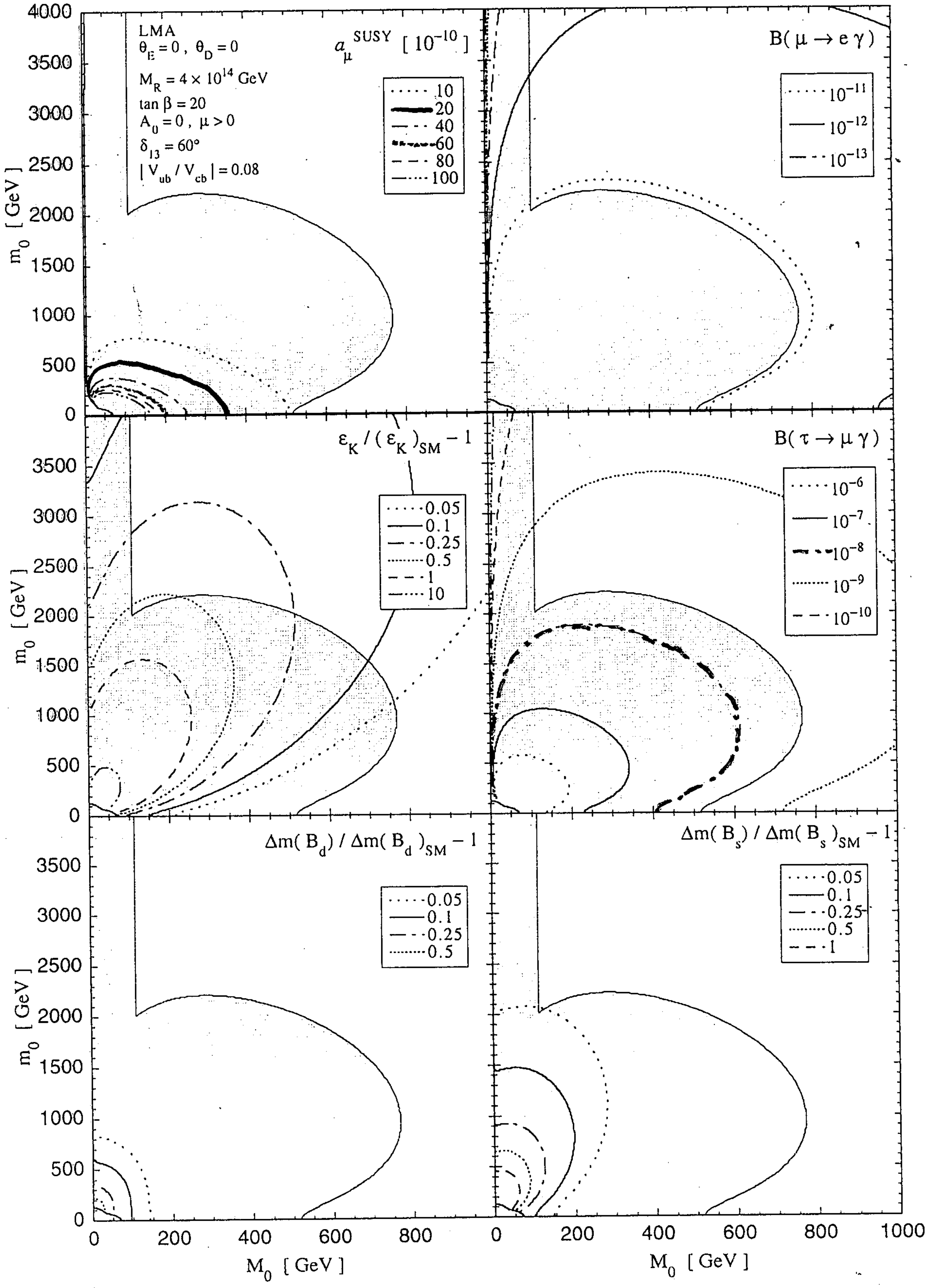
a_μ^{SUSY} [10^{-10}]
LMA
$\theta_E = 0$, $\theta_D = 45°$
$M_R = 4 \times 10^{13}$ GeV
$\tan\beta = 20$
$A_0 = 0$, $\mu > 0$
$\delta_{13} = 60°$
$|V_{ub}/V_{cb}| = 0.08$
10
20
40
60
80
100
B($\mu \to e\gamma$)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$\varepsilon_K / (\varepsilon_K)_{SM} - 1$
0.05
0.1
0.25
0.5
1
10
B($\tau \to \mu\gamma$)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\Delta m(B_d) / \Delta m(B_d)_{SM} - 1$
±0
+0.05
+0.1
−0.05
−0.1
$\Delta m(B_s) / \Delta m(B_s)_{SM} - 1$
0.05
0.1
0.25
m_0 [GeV]
M_0 [GeV]
0
500
1000
1500
2000
2500
3000
3500
4000
0
200
400
600
800
1000

tanβ = 5

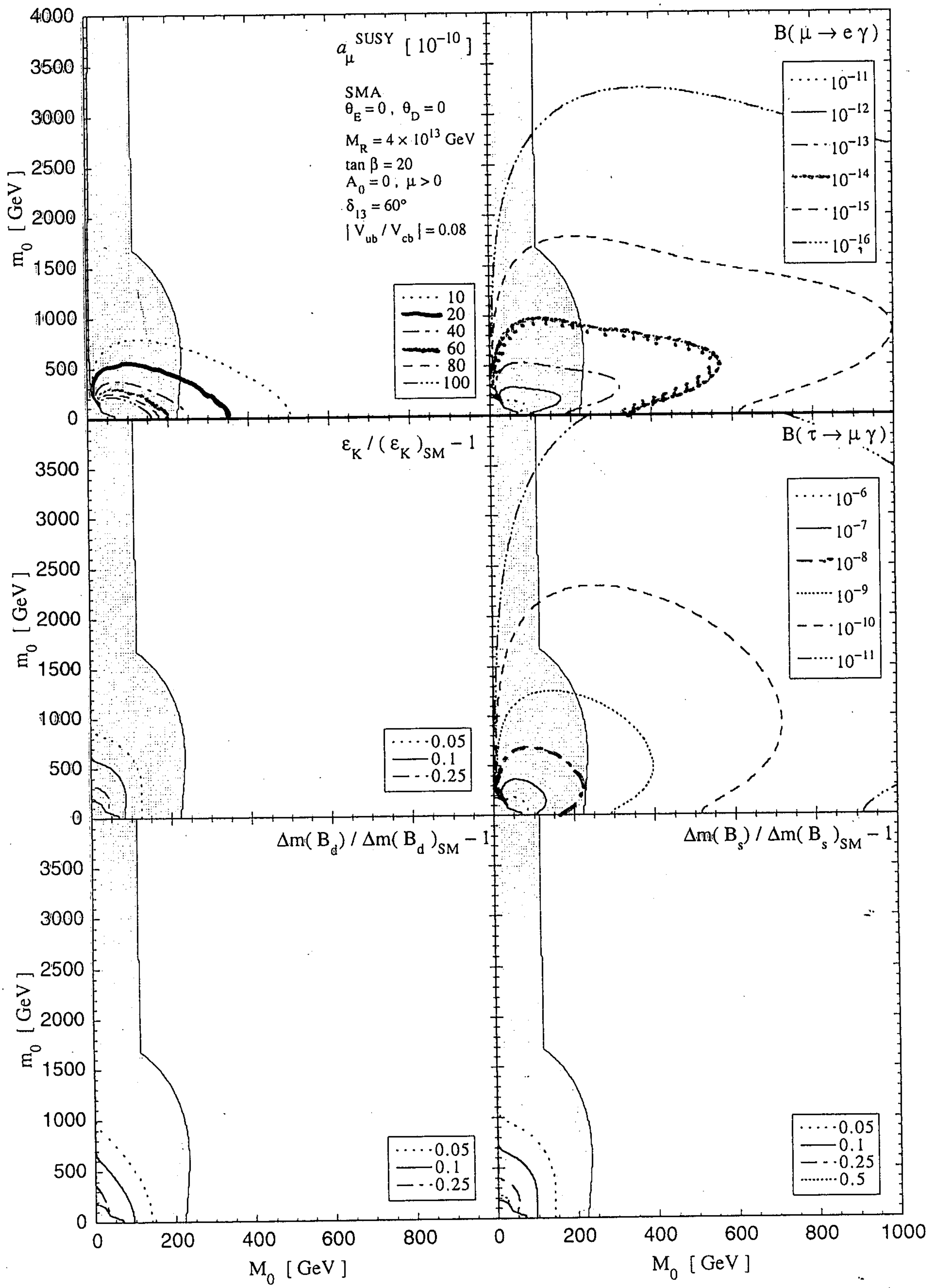


a_μ^{SUSY} [10^{-10}]
LMA
$\theta_E = 0$, $\theta_D = 0$
$M_R = 4 \times 10^{13}$ GeV
tan β = 5
$A_0 = 0$, μ > 0
$\delta_{13} = 60°$
$|V_{ub}/V_{cb}| = 0.08$
10
20
40
60
80
100
B(μ → e γ)
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$\varepsilon_K / (\varepsilon_K)_{SM} - 1$
0.05
0.1
0.25
0.5
1
B(τ → μ γ)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\Delta m(B_d) / \Delta m(B_d)_{SM} - 1$
0.05
0.1
0.25
$\Delta m(B_s) / \Delta m(B_s)_{SM} - 1$
0.05
0.1
0.25
0.5
m_0 [GeV]
M_0 [GeV]
0
200
400
600
800
1000
500
1000
1500
2000
2500
3000
3500
4000

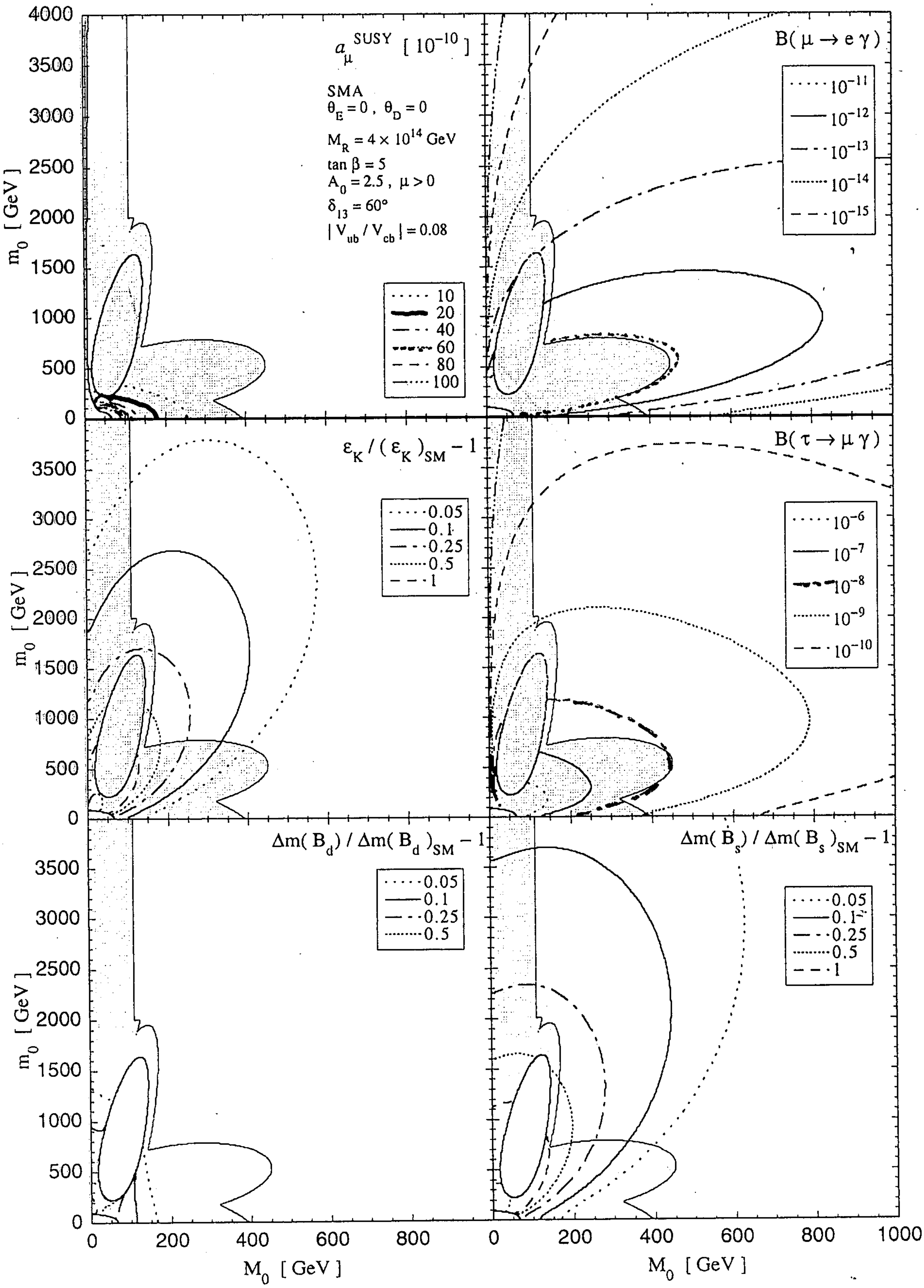
$M_R = 4 \times 10^{14}$ GeV



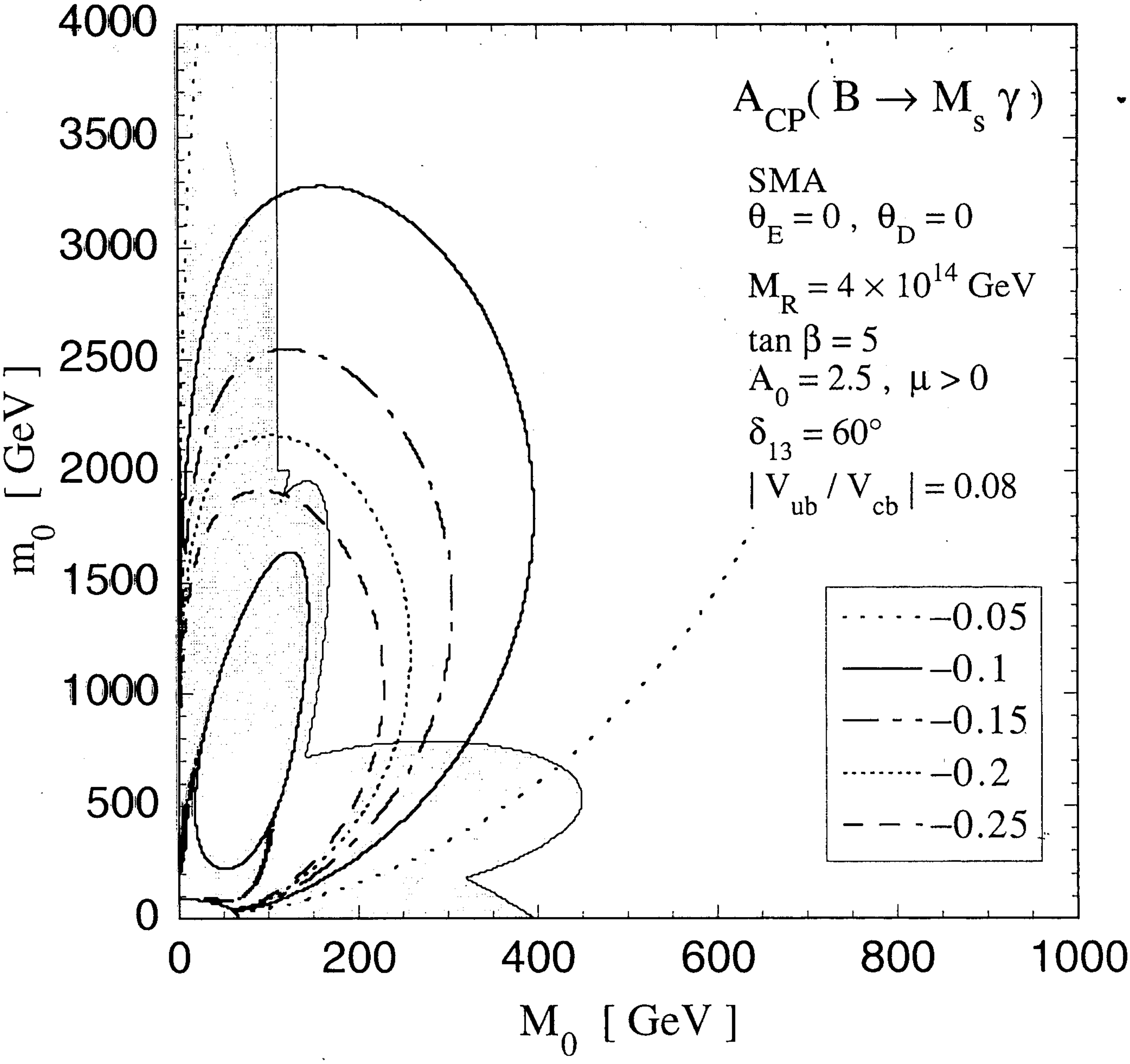
SMA



a_μ^{SUSY} [10^{-10}]
SMA
$\theta_E = 0$, $\theta_D = 0$
$M_R = 4 \times 10^{13}$ GeV
$\tan\beta = 20$
$A_0 = 0$, $\mu > 0$
$\delta_{13} = 60°$
$|V_{ub}/V_{cb}| = 0.08$
10
20
40
60
80
100
$B(\mu \to e\gamma)$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
$\varepsilon_K / (\varepsilon_K)_{SM} - 1$
0.05
0.1
0.25
$B(\tau \to \mu\gamma)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\Delta m(B_d) / \Delta m(B_d)_{SM} - 1$
0.05
0.1
0.25
$\Delta m(B_s) / \Delta m(B_s)_{SM} - 1$
0.05
0.1
0.25
0.5
m_0 [GeV]
M_0 [GeV]
0
500
1000
1500
2000
2500
3000
3500
4000
0
200
400
600
800
1000

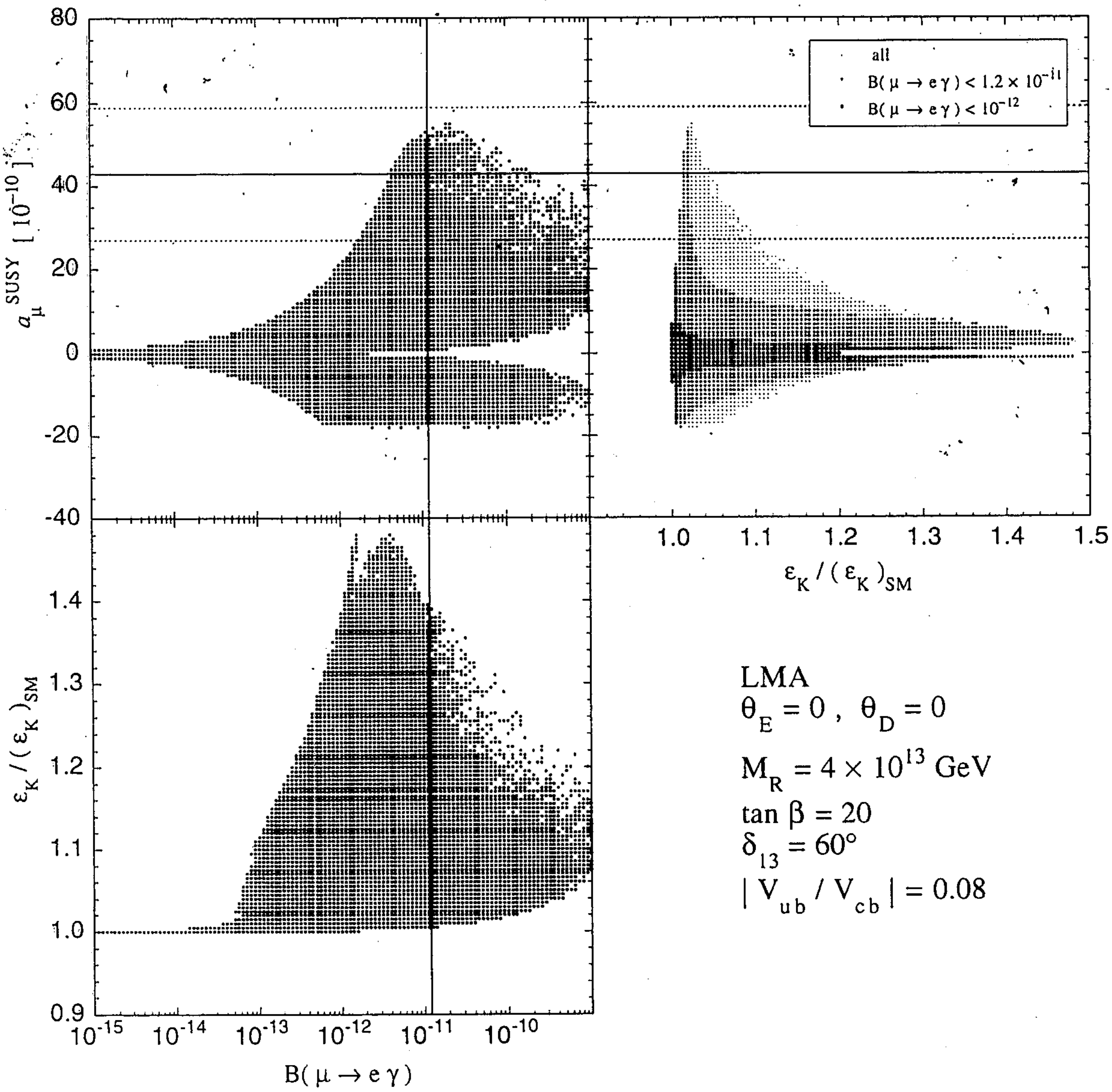


a_μ^{SUSY} [10^{-10}]
SMA
$\theta_E = 0$, $\theta_D = 0$
$M_R = 4 \times 10^{14}$ GeV
$\tan\beta = 5$
$A_0 = 2.5$, $\mu > 0$
$\delta_{13} = 60°$
$|V_{ub}/V_{cb}| = 0.08$
10
20
40
60
80
100
$B(\mu \to e\gamma)$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$\epsilon_K / (\epsilon_K)_{SM} - 1$
0.05
0.1
0.25
0.5
1
$B(\tau \to \mu\gamma)$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\Delta m(B_d) / \Delta m(B_d)_{SM} - 1$
0.05
0.1
0.25
0.5
$\Delta m(B_s) / \Delta m(B_s)_{SM} - 1$
0.05
0.1
0.25
0.5
1
m_0 [GeV]
M_0 [GeV]
0
200
400
600
800
1000
500
1000
1500
2000
2500
3000
3500
4000



$A_{CP}(B \to M_s \gamma)$
SMA
$\theta_E = 0\,,\ \theta_D = 0$
$M_R = 4 \times 10^{14}$ GeV
$\tan\beta = 5$
$A_0 = 2.5\,,\ \mu > 0$
$\delta_{13} = 60°$
$|V_{ub}/V_{cb}| = 0.08$
−0.05
−0.1
−0.15
−0.2
−0.25
0
500
1000
1500
2000
2500
3000
3500
4000
m_0 [GeV]
0
200
400
600
800
1000
M_0 [GeV]

mo, Mo < 3TeV , |Ao| < 5



LMA
$\theta_E = 0$, $\theta_D = 0$
$M_R = 4 \times 10^{13}$ GeV
$\tan\beta = 20$
$\delta_{13} = 60°$
$|V_{ub} / V_{cb}| = 0.08$

- Flavor mixing in A-terms

$$\delta\mathcal{L}_{\cancel{SUSY}} = m_0(A_0 + \Delta A)\frac{1}{M_P}(\widetilde{24}\cdot\tilde{\bar{5}}_i)K_{dij}\,\hat{\widetilde{10}}_j\,\bar{h}$$

proportionality is broken $\quad A_d \propto y_d, \quad A_e \propto y_e \quad \times$.

$$A_d = m_0 A_0 y_d + m_0 \Delta A_0 \frac{2}{5}(y_d - y_e^T)$$

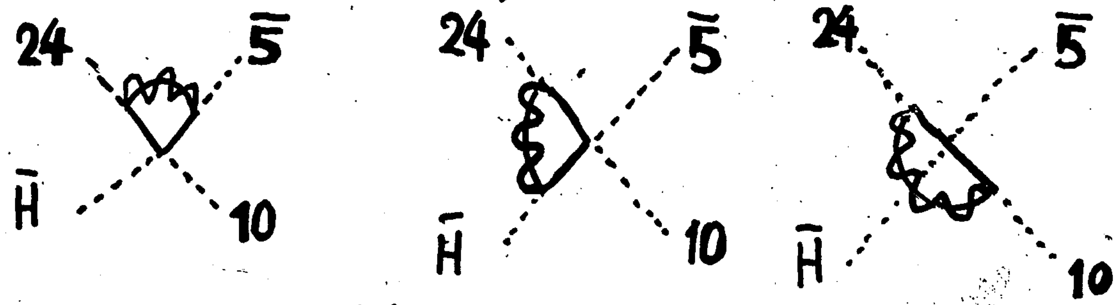
$$A_e = m_0 A_0 y_e - m_0 \Delta A_0 \frac{3}{5}(y_d^T - y_e)$$

$$\boxed{\text{New source of flavor mixing in L-R mixing mass matrices.}}$$

$\tilde{d}_L \cdots\cdots\times\cdots\cdots \tilde{d}_R \qquad\qquad \tilde{e}_L \cdots\cdots\times\cdots\cdots \tilde{e}_R$

$V_E^T \hat{m}_e V_L \qquad\qquad\qquad V_D^T \hat{m}_d V_{CKM}^\dagger$

ΔA is radiatively induced!



$$\Delta A \simeq -20\, g_5^2 \frac{M_0}{m_0}\frac{1}{(4\pi)^2}\ln\left(\frac{M_G}{M_P}\right)$$

IV Summary

- We calculated various LFV and FCNC processes and muon anomalous magnetic moment in SU(5) SUSY GUT with right-handed neutrino.
- We introduced a higher dimensional operator to incoporate realistic mass relations and new mixing angles θ_E, θ_D appeared.
- Large SUSY contributions are possible in $\mu \to e\gamma$ and either a_μ or ε_K. These two cases are distinguished if future experiments observe the deviation.
- $\tau \to \mu\gamma$ and $A^{CP}(b \to M_s \gamma)$ can be enhanced in the MSW SMA case

$\boxed{\text{It is important to combine the results of various experiments to get some insights on the interaction at the GUT and Majorana neutrino mass scale}}$

Constraints for the CKM matrix

$$V_{CKM} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta_{13}} \\ -s_{12}c_{13} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

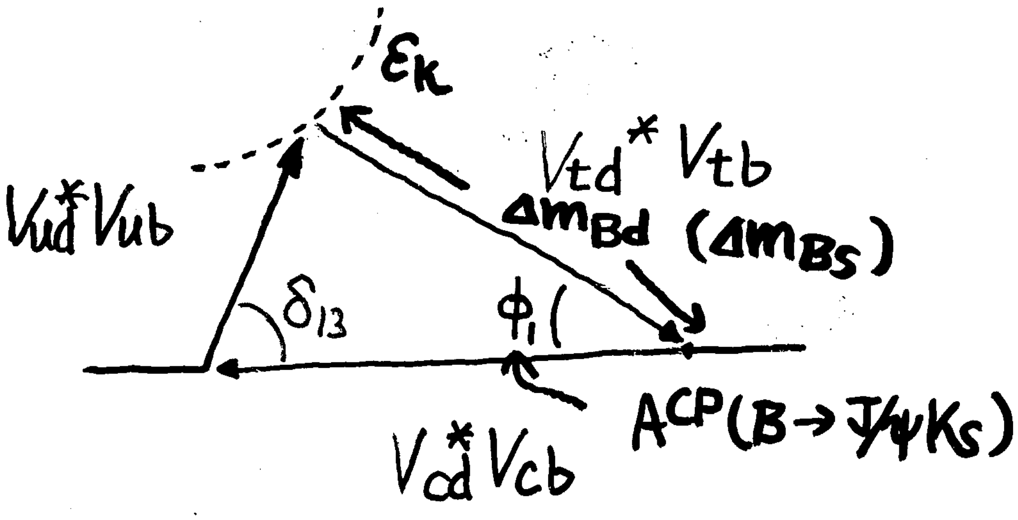
$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

- Three angles θ_{12} θ_{23} θ_{13} $\Rightarrow$ decay processes (tree)

  $|V_{us}| = 0.22 \quad |V_{cb}| = 0.04 \quad |V_{ub}| / |V_{cb}| = 0.08$

- KM phase $\delta_{13} = 60°$

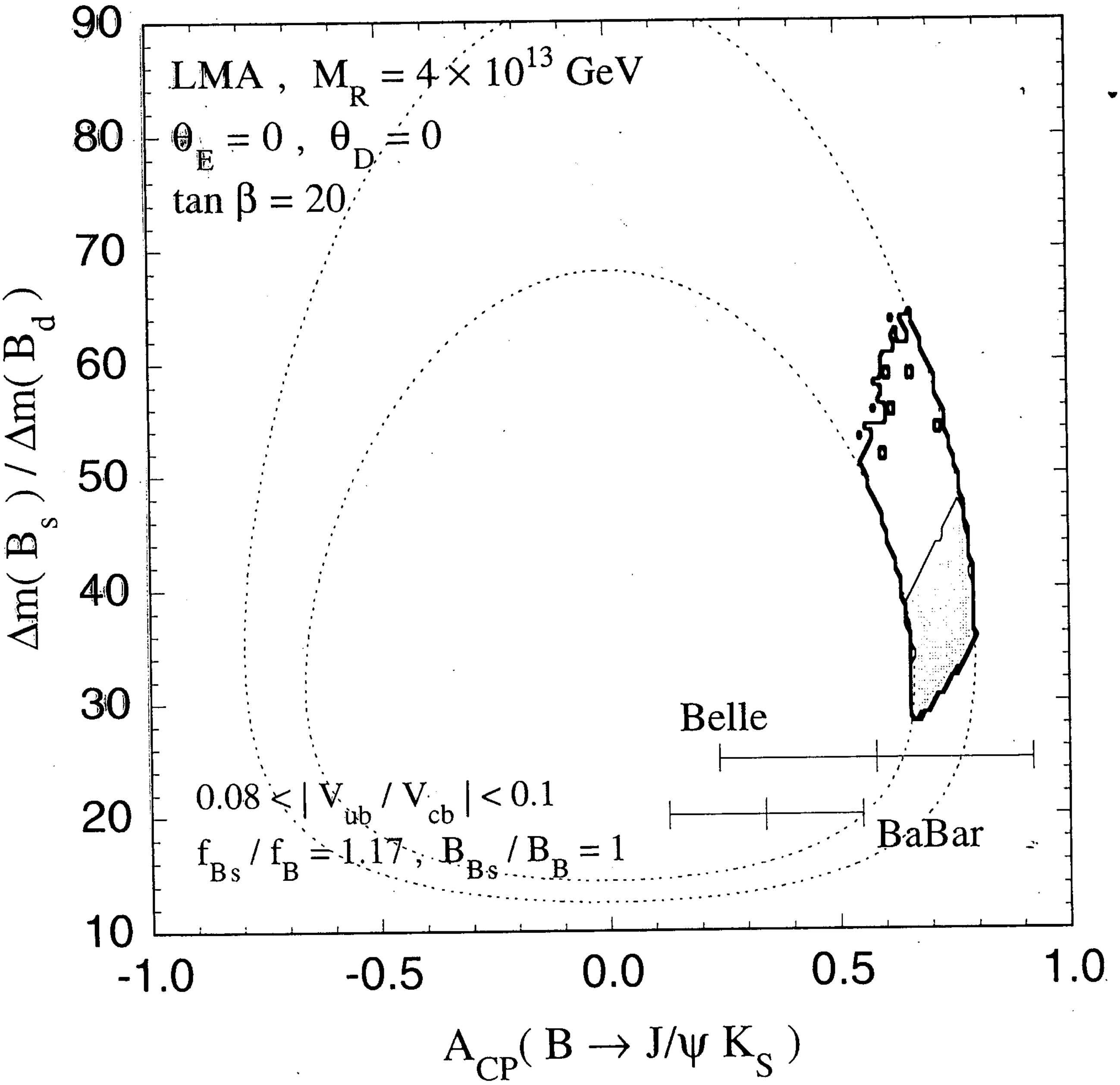
  $\Rightarrow$ constrained from FCNC itself



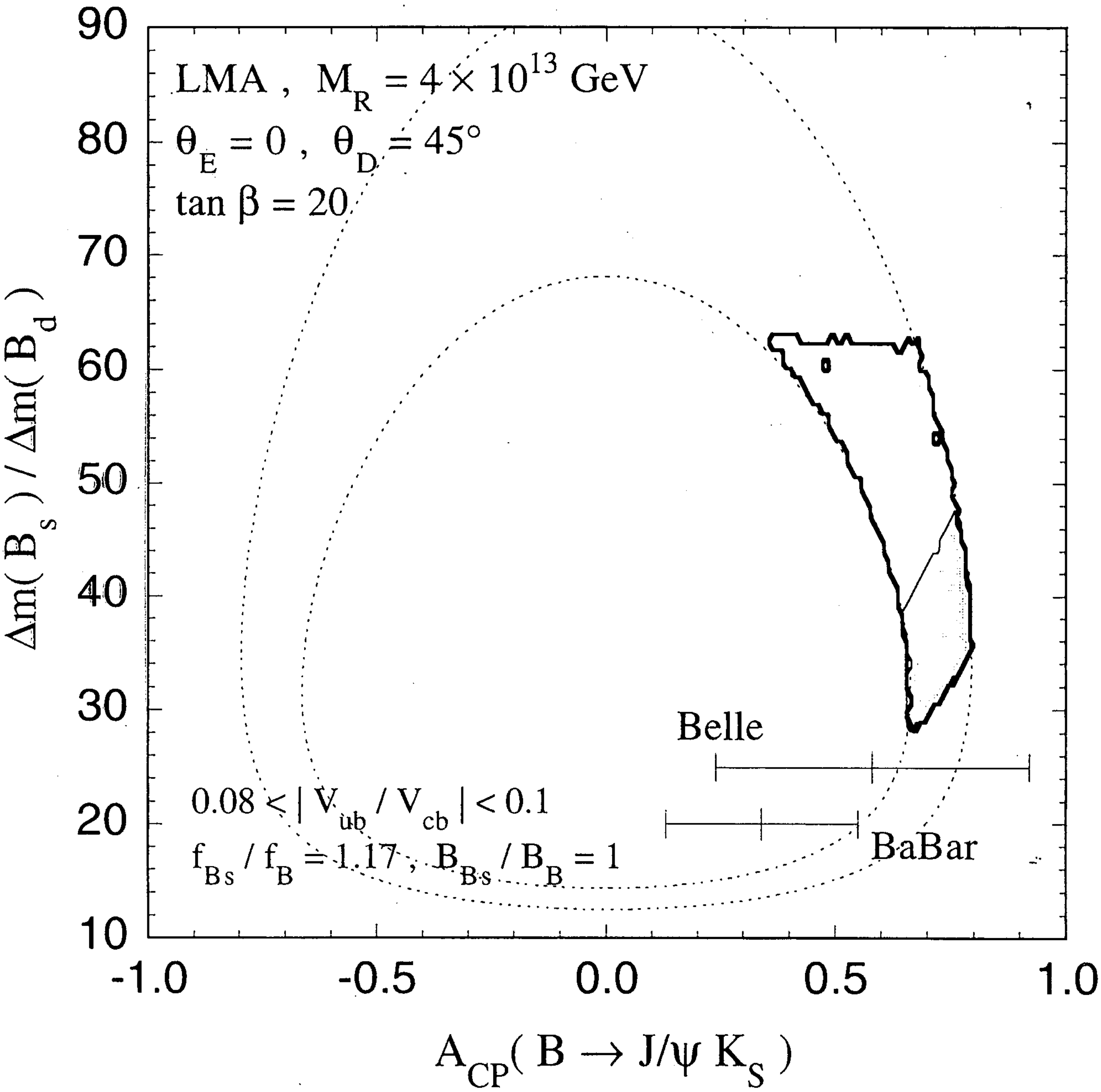
δ_{13} is modified from the SM case.

$\Rightarrow$ deviations in Δm_{Bd}, Δm_{Bs}

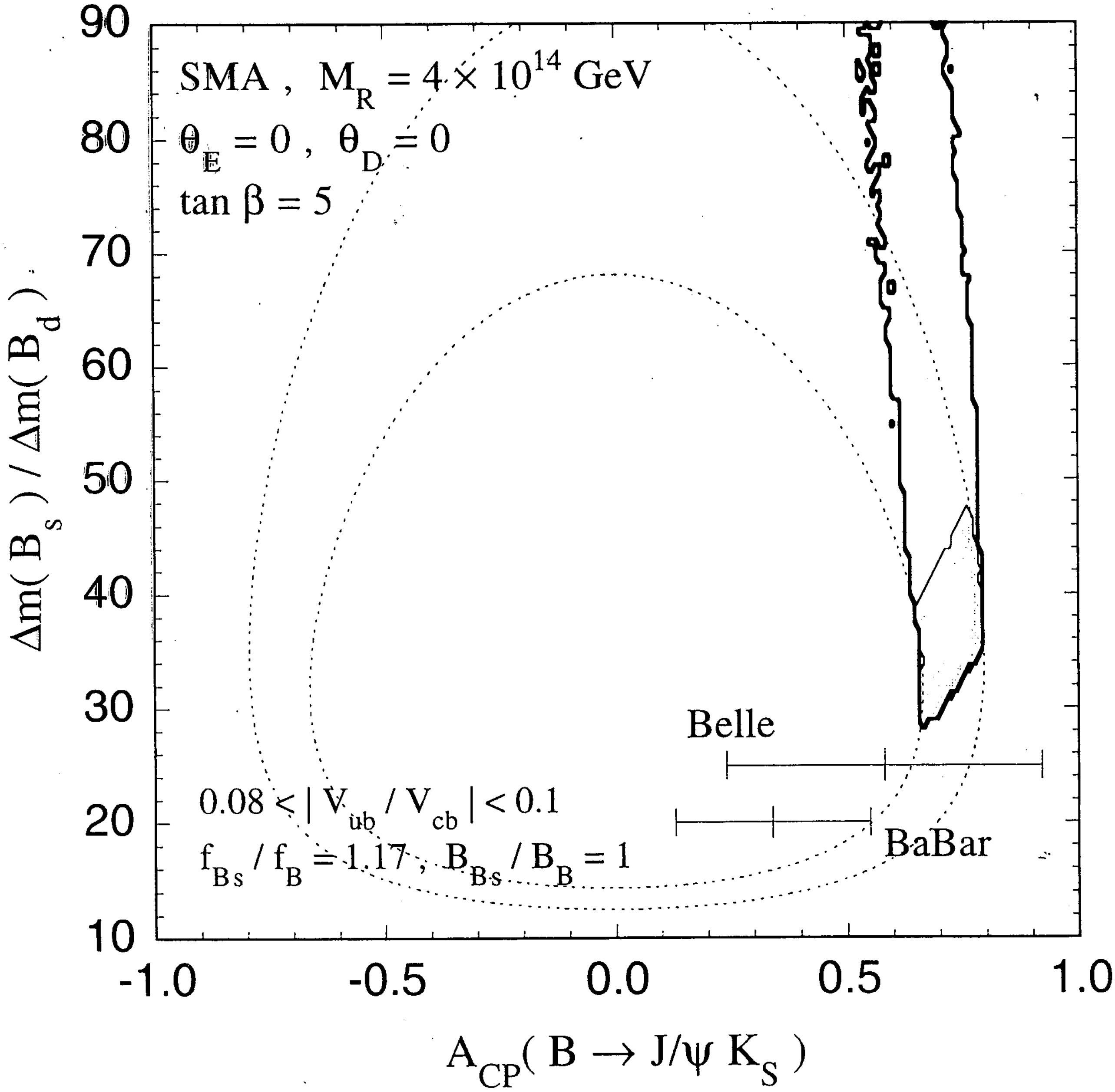
$A^{CP}(B \to J/\psi K_S)$



LMA , $M_R = 4 \times 10^{13}$ GeV
$\theta_E = 0$, $\theta_D = 0$
$\tan\beta = 20$
Belle
BaBar
$0.08 < |V_{ub} / V_{cb}| < 0.1$
$f_{Bs} / f_B = 1.17$, $B_{Bs} / B_B = 1$
$\Delta m(B_s) / \Delta m(B_d)$
$A_{CP}(B \to J/\psi K_S)$



LMA , $M_R = 4 \times 10^{13}$ GeV
$\theta_E = 0$, $\theta_D = 45°$
tan $\beta = 20$
Belle
BaBar
$0.08 < |V_{ub} / V_{cb}| < 0.1$
$f_{Bs} / f_B = 1.17$, $B_{Bs} / B_B = 1$
$\Delta m(B_s) / \Delta m(B_d)$
$A_{CP}(B \to J/\psi K_S)$
90
80
70
60
50
40
30
20
10
-1.0
-0.5
0.0
0.5
1.0


SMA , $M_R = 4 \times 10^{14}$ GeV
$\theta_E = 0$, $\theta_D = 0$
tan $\beta = 5$
$0.08 < |V_{ub} / V_{cb}| < 0.1$
$f_{Bs} / f_B = 1.17$, $B_{Bs} / B_B = 1$
Belle
BaBar
$\Delta m(B_s) / \Delta m(B_d)$
$A_{CP}(B \to J/\psi K_S)$
90
80
70
60
50
40
30
20
10
-1.0
-0.5
0.0
0.5
1.0

V Conclusion

- Large SUSY contributions are possible in $\mu \to e\gamma$, a_μ, ε_K
- Within the constraint of $\mu \to e\gamma$ Large SUSY contribution to a_μ and that of ε_K are incompatible
- a_μ case

  $\Rightarrow$ The result of BNL E821 is saturated
- ε_K case

  KM phase δ_{13} is modified ~~from the SM case~~

  $\Rightarrow$ deviations in Δm_{B_s} and $A^{CP}(B \to J/\psi K_S)$

  (Tevatron, Belle, Babar)
- $\tau \to \mu\gamma$ and $A^{CP}(b \to s\gamma)$ canbe enhanced in the MSW SMA case.