Supersymmetry and Some of its Experimental Tests

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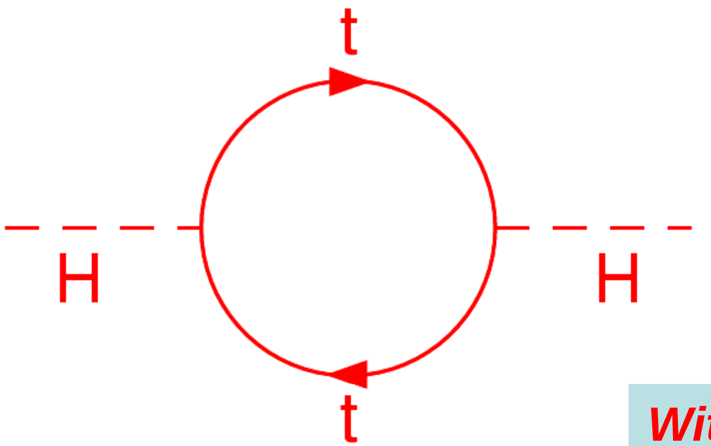
Outline

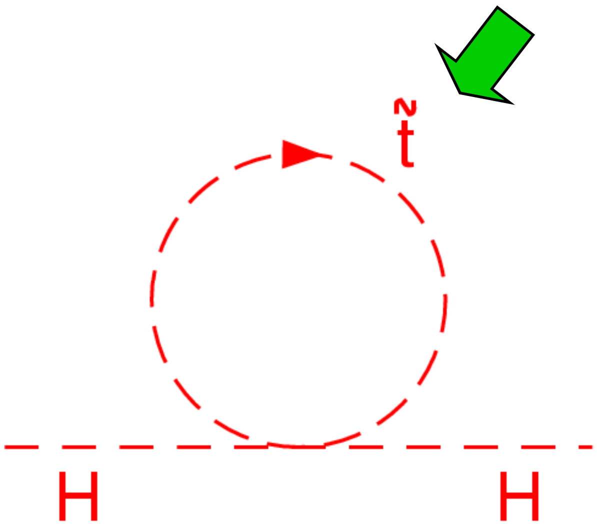
- **Motivations**
- **Supersymmetry Breaking**
- **Direct Tests at Colliders**
- **Indirect Tests**
  - *Rare B Decays*
  - *Dipole Moments*
  - *Lepton Flavor Violation*
- **SUSY GUTs and Proton Decay**
- **Conclusions**

Stability of Higgs Mass



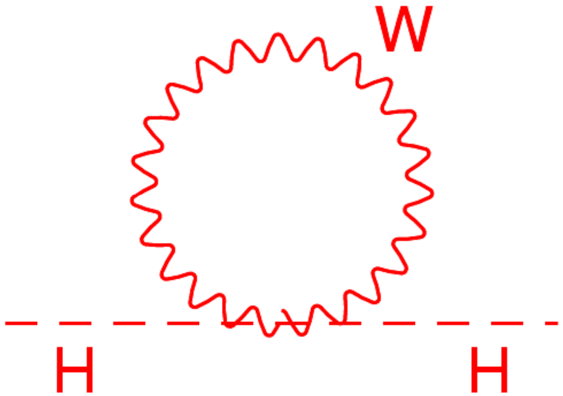
$$\Delta m_H^2 = -\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

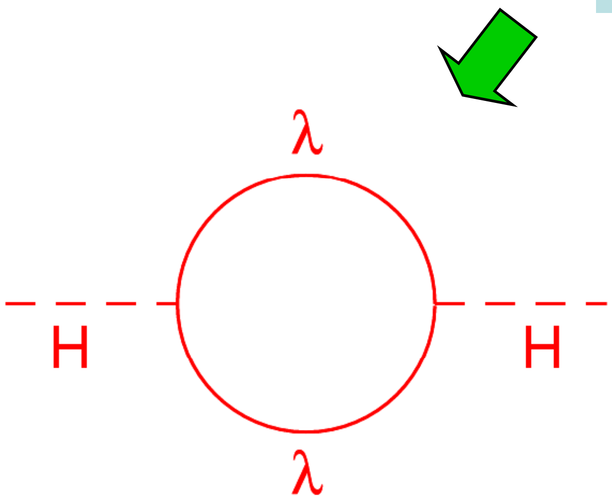
With SUSY, Quadratic Divergence Cancels



$$\Delta m_H^2 = +\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

$$m_{\tilde{t}}^2 - m_t^2 \lesssim (\mathrm{TeV})^2$$





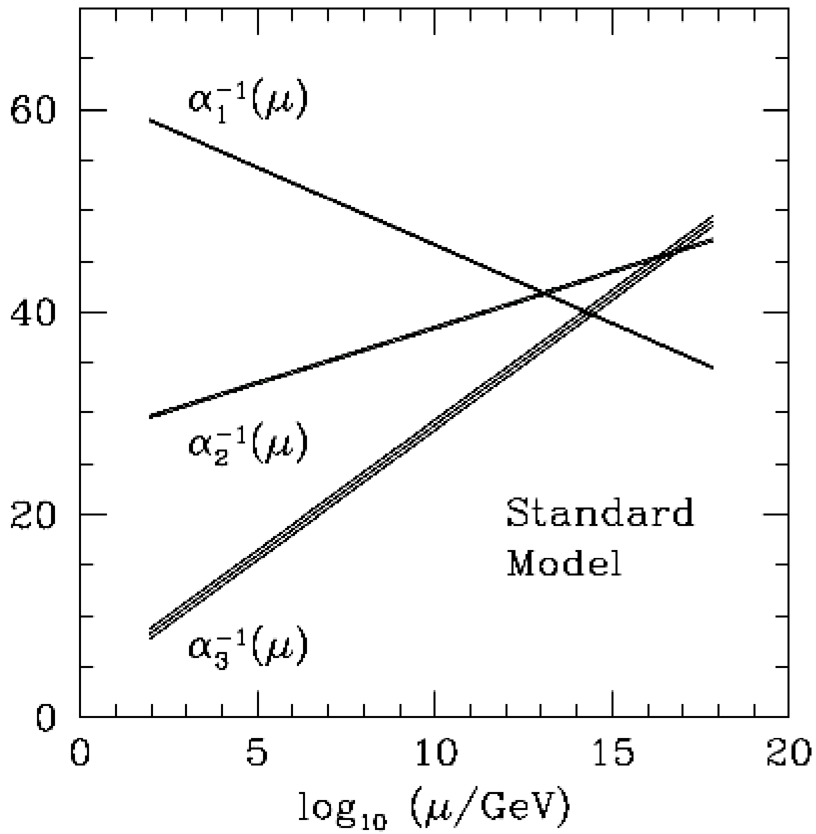
With SUSY, gauge boson contribution is cancelled by gaugino contribution.

SUSY Spectrum

	SM Particles	SUSY Partners	
Spin = 1/2	Q	$\tilde{Q}$	Spin = 0
	u^c	$\tilde{u}^c$	
	d^c	$\tilde{d}^c$	
	L	$\tilde{L}$	
	e^c	$\tilde{e}^c$	
Spin = 0	H_u	$\tilde{H}_u$	Spin = 1/2
	H_d	$\tilde{H}_d$	
Spin = 1	g	$\tilde{g}$	Spin = 1/2
	W	$\tilde{W}$	
	B	$\tilde{B}$	

$$R = (-1)^{3B+L+2S}$$

Evolution of Gauge Couplings In Standard Model



Evolution of Gauge Couplings in six-Higgs-doublet SM

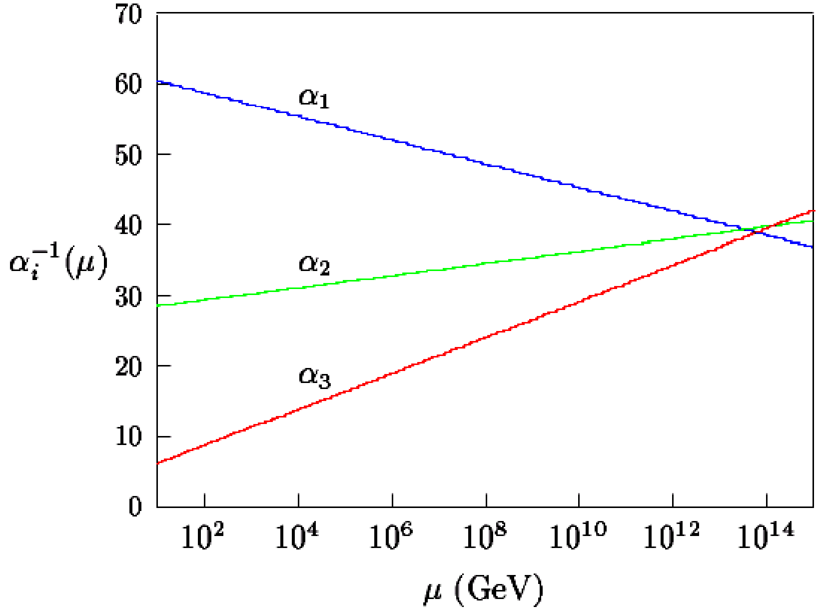
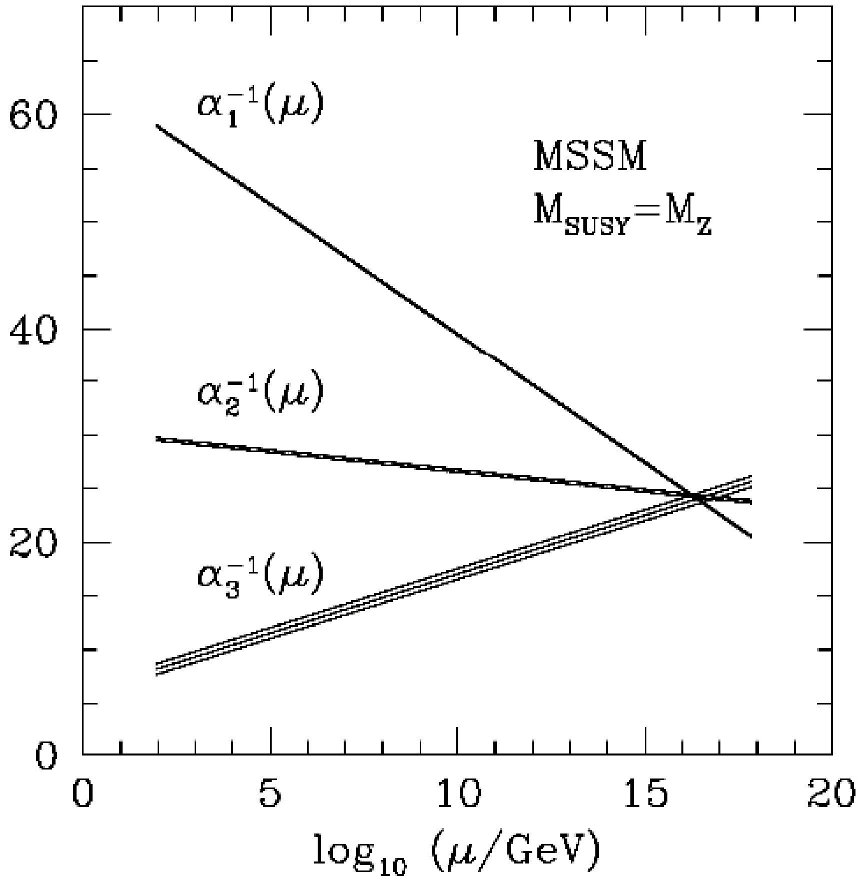


Figure 1: Leading-order evolution of the gauge couplings from their low-energy values to the unification scale in the six-Higgs-doublet standard model. The couplings meet around 10^{14} GeV, within the accuracy of a leading-order calculation.

S. Willenbrock, hep-ph/0302168

Gauge Coupling Unification in MSSM



Structure of Matter Multiplets

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = (u_1^c \quad u_2^c \quad u_3^c) \sim (\overline{3}, 1, \frac{-2}{3})$$

$$d^c = (d_1^c \quad d_2^c \quad d_3^c) \sim (\overline{3}, 1, \frac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

$$e^c \sim (1, 1, +1)$$

$$\nu^c \sim (1, 1, 0)$$

u_1	:	$\vert\uparrow\downarrow\uparrow\uparrow\downarrow>$
u_2	:	$\vert\uparrow\downarrow\uparrow\downarrow\uparrow>$
u_3	:	$\vert\uparrow\downarrow\downarrow\uparrow\uparrow>$
d_1	:	$\vert\downarrow\uparrow\uparrow\uparrow\downarrow>$
d_2	:	$\vert\downarrow\uparrow\uparrow\downarrow\uparrow>$
d_3	:	$\vert\downarrow\uparrow\downarrow\uparrow\uparrow>$
u_1^c	:	$\vert\downarrow\downarrow\uparrow\downarrow\downarrow>$
u_2^c	:	$\vert\downarrow\downarrow\downarrow\uparrow\downarrow>$
u_3^c	:	$\vert\downarrow\downarrow\downarrow\downarrow\uparrow>$
d_1^c	:	$\vert\uparrow\uparrow\uparrow\downarrow\downarrow>$
d_2^c	:	$\vert\uparrow\uparrow\downarrow\uparrow\downarrow>$
d_3^c	:	$\vert\uparrow\uparrow\downarrow\downarrow\uparrow>$
ν	:	$\vert\uparrow\downarrow\downarrow\downarrow\downarrow>$
e	:	$\vert\downarrow\uparrow\downarrow\downarrow\downarrow>$
e^c	:	$\vert\downarrow\downarrow\uparrow\uparrow\uparrow>$
ν^c	:	$\vert\uparrow\uparrow\uparrow\uparrow\uparrow>$

MSSM Lagrangian

$$W = Qu^cH_u + Qd^cH_d + Le^cH_d + L\nu^cH_u + M_R\nu^c\nu^c + \mu H_uH_d$$

$\mu \sim 10^2$ GeV

R-parity Violation: Potentially Dangerous Proton Decay

$$W_{R-V} = LLe^c + QLd^c + u^cd^cd^c + \mu' LH_u$$

Soft SUSY Breaking:

$$\mathcal{L}_{SUSY} = \Sigma m_\phi^2 \phi^\dagger \phi + A_u\tilde{Q}\tilde{u}^cH_u + A_d\tilde{Q}\tilde{d}^cH_d + A_l\tilde{L}\tilde{e}^cH_d + A_\nu\tilde{L}\tilde{\nu}^cH_u + B\mu H_uH_d + \Sigma M_\lambda\lambda\lambda$$

Generic soft breaking leads to large flavor violation

($K^0 - \bar{K}^0$ Mixing, $\mu \to e\gamma$ etc.)

Natural R-parity and μ-term

Discrete gauge symmetries can protect μ-term and act as R-parity.

Q	u^c	d^c	L	e^c	ν^c	H_u	H_d	θ
1	*1*	*1*	*1*	*1*	*1*	*0*	*0*	*1*

Z_4 Model **K.S. Babu, I. Gogoladze, K. Wang, Nucl. Phys. B660, 322 (2003)**

Anomalies

$$A_2 = [SU(2)_L]^2 \times Z_4 = 3$$

$$A_3 = [SU(3)_C]^2 \times Z_4 = 1$$

L. Krauss, F. Wilczek, (1989)

L. Ibanez. G. Ross, (1991)

T. Banks, M. Dine, (1992)

Green-Schwarz Anomaly Cancellation Mechanism For Z_N

$$A_3 = A_2 + p\frac{N}{2} \qquad p \in Z$$

Guidice-Masiero Mechanism

$$\mathcal{L}_{\mu-term} = \int d^4\theta H_u H_d \frac{Z^*}{M_{pl}}$$

SUSY Breaking Scenarios

- **Gravity Mediated**
  - **mSUGRA**
  - **Anomaly Mediation**
  - **Flavor Symmetry**
- **Gauge Mediated**

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mSUGRA

Neutralino LSP Stable

(Dark Matter)

$$\{ m_0, m_{1/2}, \mu, A_0, B_0 \}$$

GMSB

$$\{ \Lambda, M, \mu, n \}$$

LSP : Gravitino

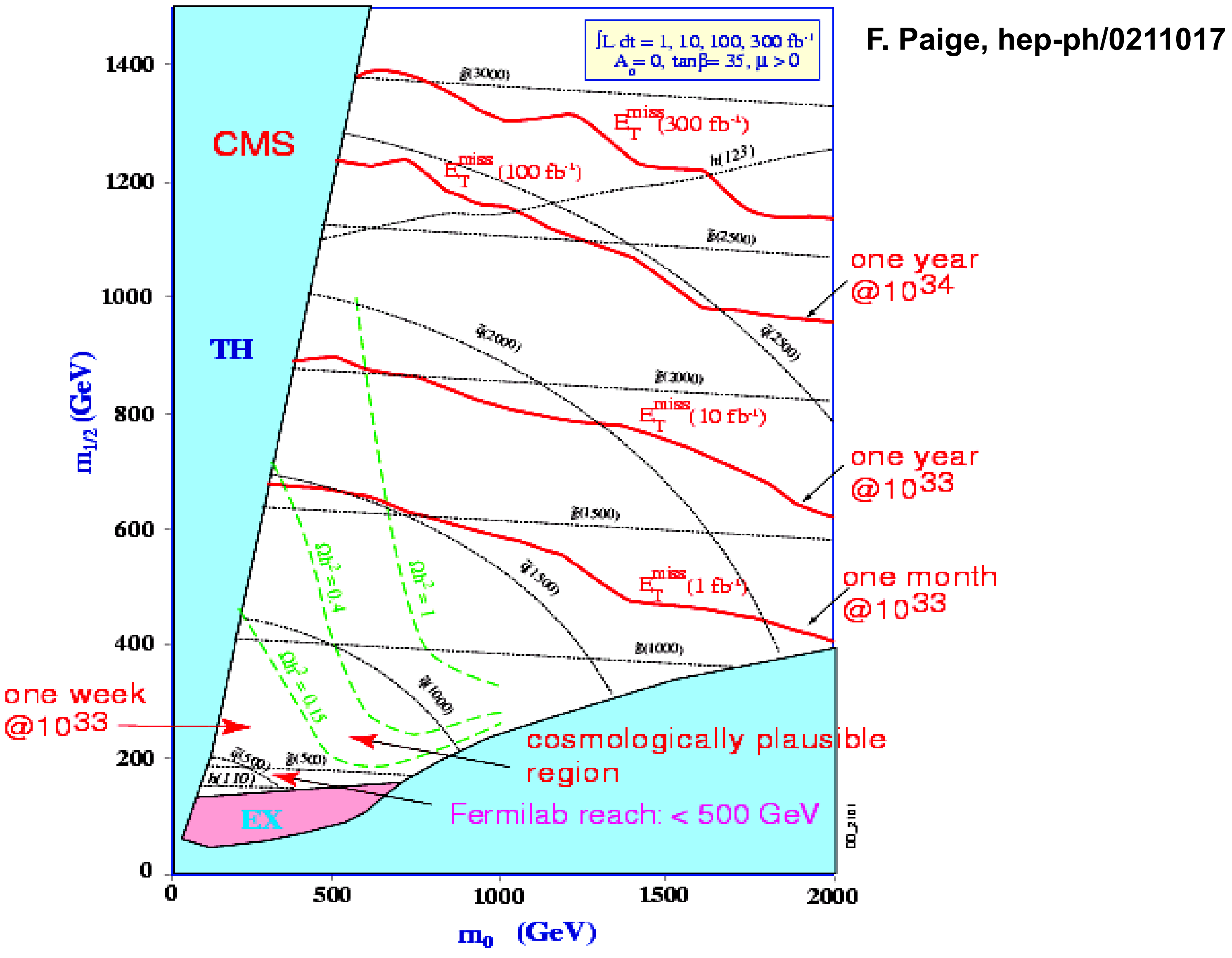


Figure 1: Plot of 5σ reach in jets + $\not{E}_T$ channel for mSUGRA model .

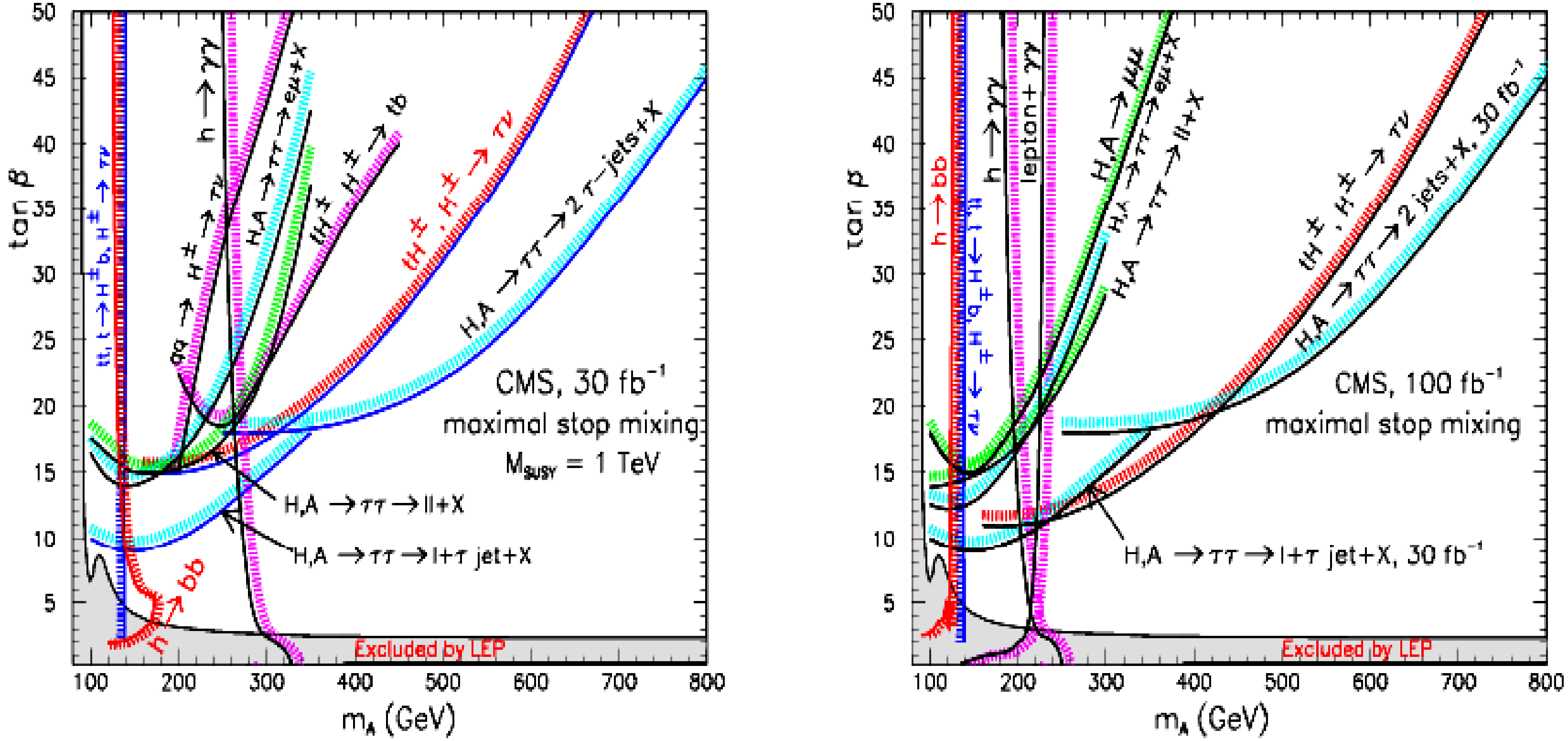


Fig. 6. Expected 5σ discovery limits of various MSSM Higgs signals at LHC for luminosities of 30 fb^{-1} and 100 fb^{-1}.

D. Denegri et al, CMS NOTE 2001/032 [hep-ph/0112045].

$B \to \mu^+ \mu^-$ Decay in Supersymmetry

K.S. Babu, C. Kolda, Phys. Rev. Lett. 84, 228 (2000)

$$-\mathcal{L}_{eff} = \bar{D}_R Y_D Q_L H_d + \bar{D}_R Y_D \left[\epsilon_g + \epsilon_u Y_U^\dagger Y_U\right] Q_L H_u^* + h.c. + \ldots$$

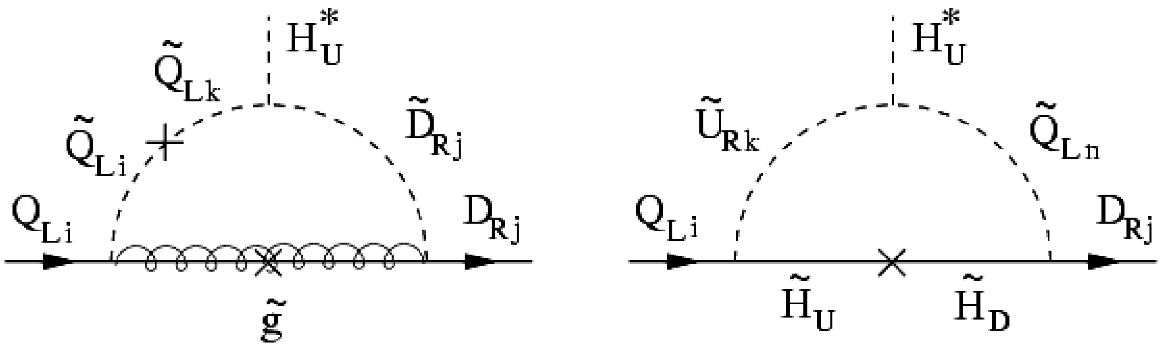
MSSM is a general two-Higgs-doublet model.

$$\Longrightarrow \quad \bar{y}_b \simeq y_b \left[1 + (\epsilon_g + \epsilon_u y_t^2) \tan\beta\right]$$

$$V_{ub} \simeq V_{ub}^0 \left[\frac{1+\epsilon_g \tan\beta}{1+(\epsilon_g+\epsilon_u y_t^2)\tan\beta}\right]$$

$$\tan\beta \equiv \frac{<H_u>}{<H_d>}$$

Hall, Rattazzi, Sarid (1993)



Leading contributions to ϵ_g and ϵ_u. Indices i, j, k, n label flavors

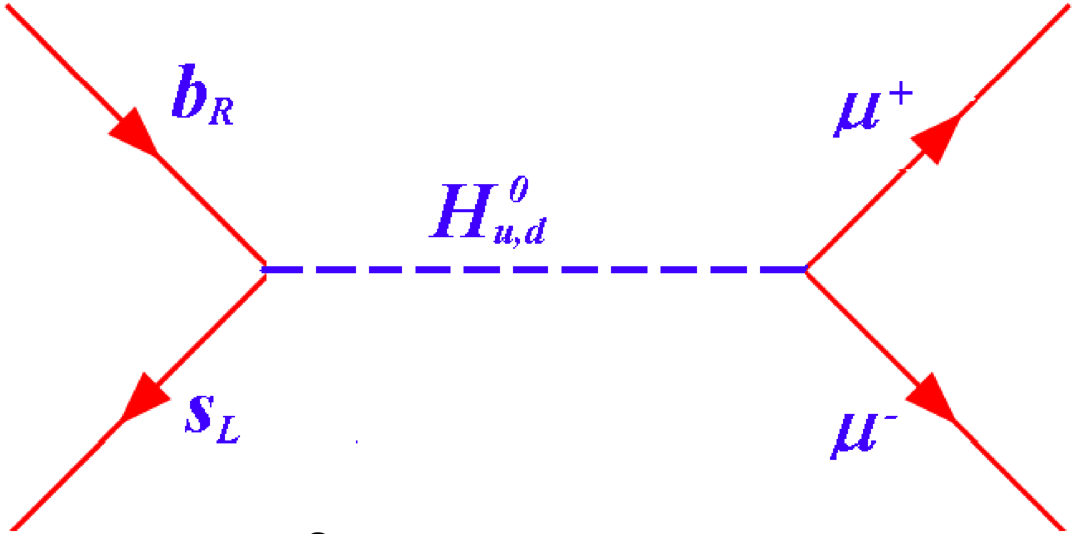
$$\epsilon_g \simeq \frac{2\alpha_3}{3\pi}(\mu^* M_3 f(M_3^2, M_{\tilde{Q}_L}^2, M_{\tilde{d}_R}^2)$$

$$\epsilon_u \simeq \frac{1}{16\pi^2}(\mu^* A_u f(\mu^2, M_{\tilde{Q}_L}^2, M_{\tilde{u}_R}^2)$$

For $\tan\beta \simeq 50 - 60$, $m_A \simeq 100 - 400$ GeV

$Br(B \to \mu^+\mu^-) \sim 10^{-7} - 10^{-8}$

$$\mathcal{L}_{FCNC} = \frac{\bar{y}_b V_{tb}^*}{\sin\beta} \chi_{FC} \left[V_{td} \bar{b}_R d_L + V_{ts} \bar{b}_R s_L \right] \left(\cos\beta H_u^{0*} - \sin\beta H_d^0 \right) + h.c.$$



$$\Gamma(B^0_{(d,s)} \to \mu^+\mu^-) = \frac{\eta^2_{QCD}}{128\pi} m_B^3 f_B^2 \, \bar{y}_b^2 y_\mu^2 \, |V^*_{t(d,s)} V_{tb}|^2 \, \chi^2_{FC} (a_1^2 + a_2^2)$$

$$\chi_{FC} = \frac{-\epsilon_u y_t^2 \tan\beta}{(1+\epsilon_g \tan\beta)[1+(\epsilon_g+\epsilon_u y_t^2)\tan\beta]}$$

$$a_1^2 + a_2^2 \simeq 2/m_A^4$$

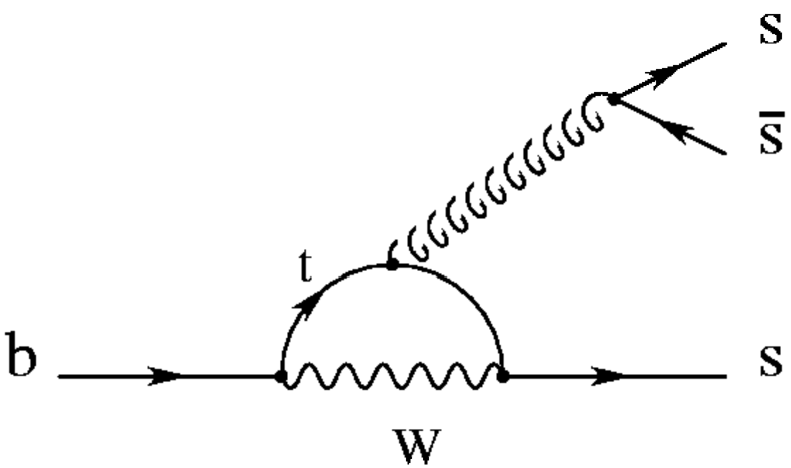
SUSY CP Violation in $B_d \to \phi K_s$ Decay

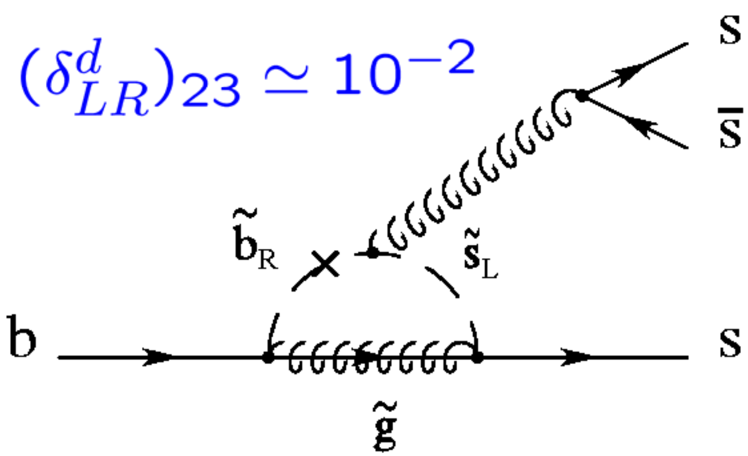
Observable	BaBar	Belle	Average	SM prediction
Br (in 10^{-6})	$8.1^{+3.1}_{-2.5} \pm 0.8$	$8.7^{+3.8}_{-3.0} \pm 1.5$	$8.4^{+2.5}_{-2.1}$	$\simeq 5$ (see text)
$S_{\phi K_S}$	$-0.19^{+0.52}_{-0.50} \pm 0.09$	$-0.73 \pm 0.64 \pm 0.18$	-0.39 ± 0.41	0.734 ± 0.054

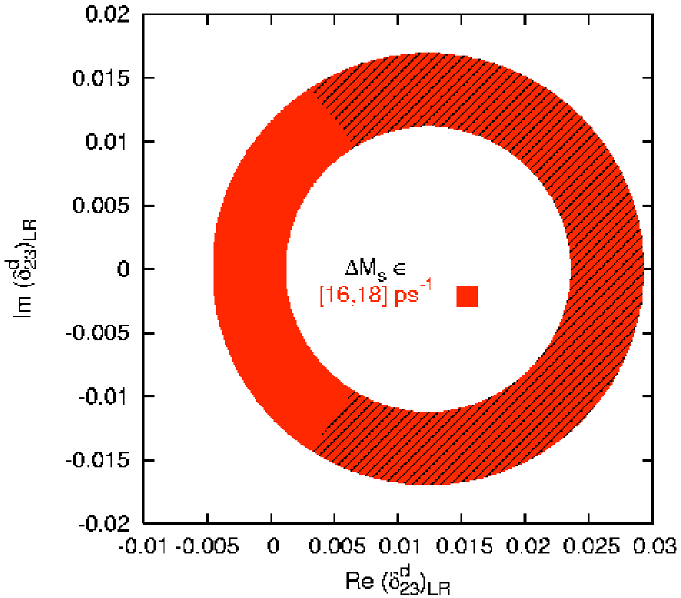
$$
\begin{aligned}
\mathcal{A}_{\phi K}(t) &\equiv \frac{\Gamma(\overline{B}^0_{\rm phys}(t) \to \phi K_S) - \Gamma(B^0_{\rm phys}(t) \to \phi K_S)}{\Gamma(\overline{B}^0_{\rm phys}(t) \to \phi K_S) + \Gamma(B^0_{\rm phys}(t) \to \phi K_S)} \\
&= -C_{\phi K} \cos(\Delta m_B t) + S_{\phi K} \sin(\Delta m_B t),
\end{aligned}
$$

$$
C_{\phi K} = \frac{1 - |\lambda_{\phi K}|^2}{1 + |\lambda_{\phi K}|^2}; \quad S_{\phi K} = \frac{2\, {\rm Im}\lambda_{\phi K}}{1 + |\lambda_{\phi K}|^2};
$$

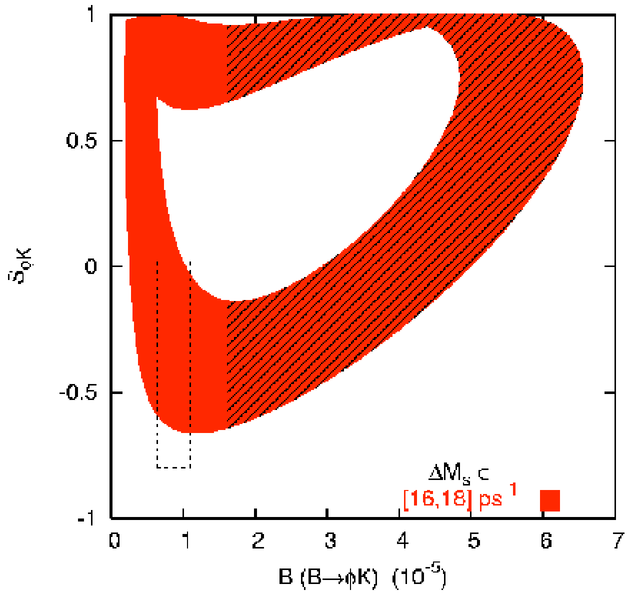
$$
\lambda_{\phi K} \equiv -e^{-2i(\beta+\theta_d)} \frac{\overline{A}(B^0 \to \phi K_S)}{A(\overline{B}^0 \to \phi K_S)}.
$$







(a) Allowed region for the LR insertion



(b) $S_{\phi K}$ vs. $B(B \to \phi K)$

Kane, *et al*, hep-ph/0212092

Lepton Dipole Moments

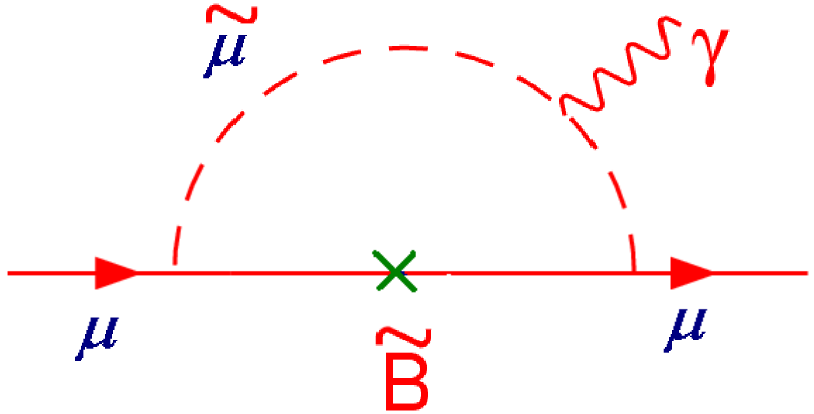
$$\mathcal{L}_{eff} = \frac{a_\mu}{2m_\mu}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$$

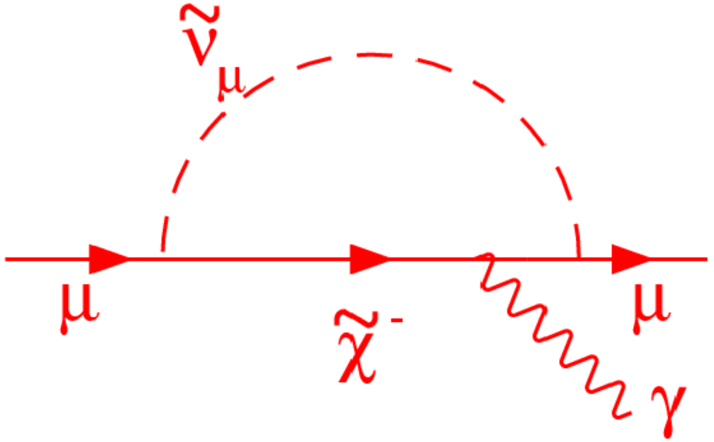
$$a_\mu(SM) = 11\ 659\ 182.1(7.2) \times 10^{-10}$$

$$a_\mu(EXP) = 11\ 659\ 203(8) \times 10^{-10}$$

$$\delta a_\mu = 21(11) \times 10^{-10}$$

SUSY Contributions:

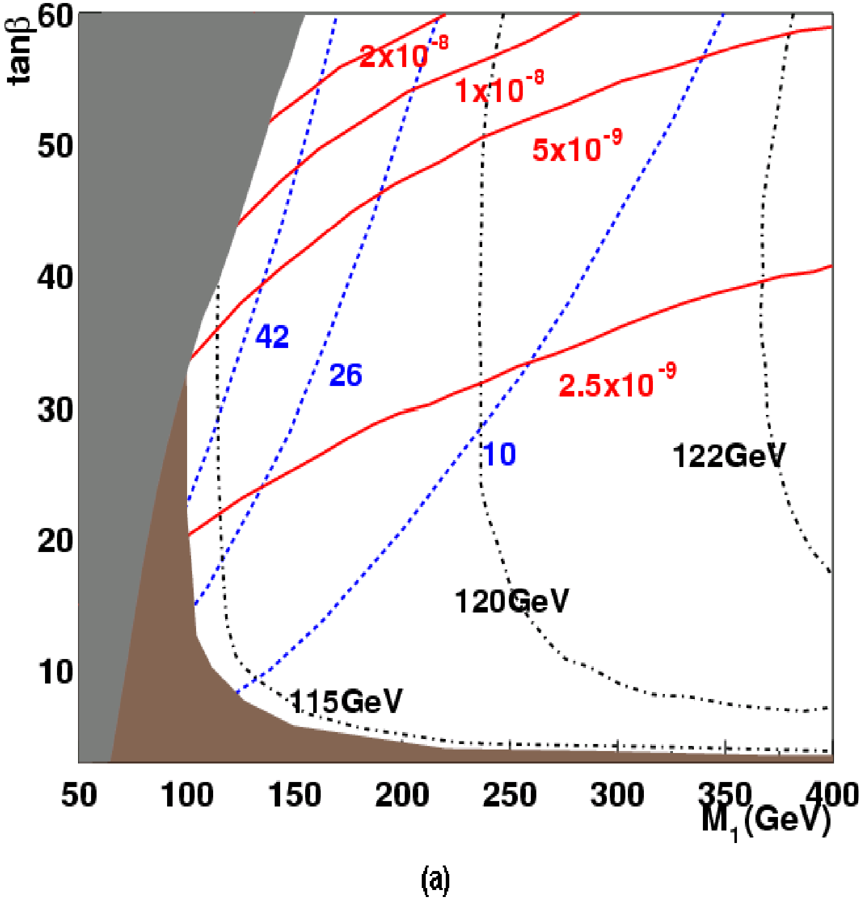




$$\delta a_\mu \simeq \frac{\alpha_2}{8\pi}\frac{m_\mu^2}{M_{SUSY}^2}\tan\beta$$

$$\sim \text{few } \times 10^{-10} \text{ if } M_{SUSY} \lesssim 500 \text{ GeV}$$

S. Baek, P. Ko, W. Song, hep-ph/0210373



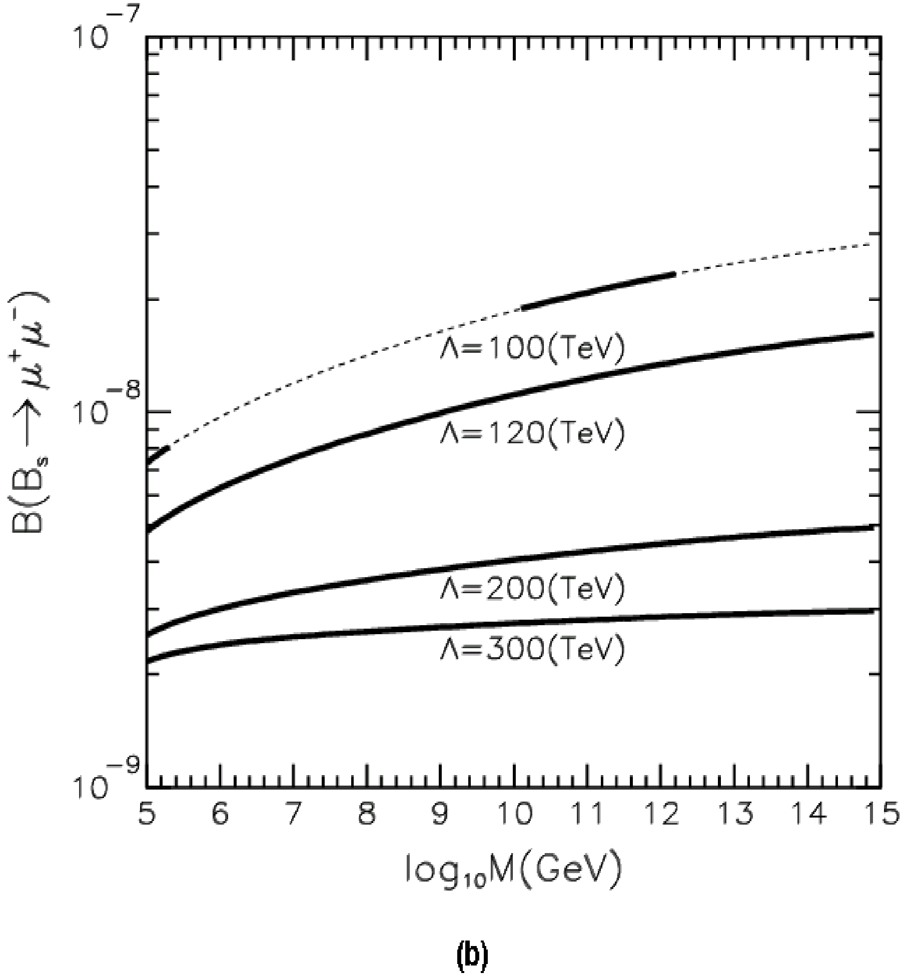


FIG. 2: (a) The contour plots for the $a_\mu^{\rm SUSY}$, m_{h^0}, and $B(B_s \to \mu^+\mu^-)$ with $N = 1$ and $M = 10^6$ GeV. (b) The branching ratio for $B_s \to \mu^+\mu^-$ as a function of the messenger scale M in the GMSB with $N = 1$ for various Λ's with a fixed $\tan\beta = 50$. The dashed parts are excluded by the direct search limits on the Higgs and SUSY particle masses.

Electric Dipole Moments

$$\mathcal{L}_{eff} = -\frac{i}{2} d_f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

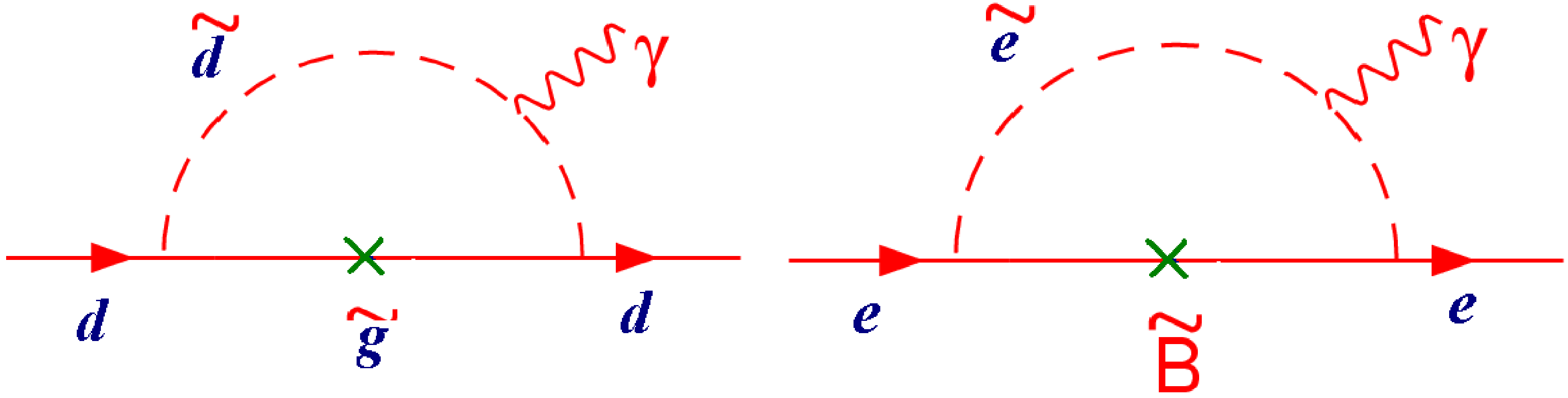
Violates CP

Electron: $d_e(Exp) \leq 2.1 \times 10^{-27}$ e-cm

Neutron: $d_n(Exp) \leq 6.3 \times 10^{-26}$ e-cm

Phases in SUSY breaking sector contribute to EDM.

SUSY Contributions:



A, B are complex in MSSM

$$d_n \sim (\sin\phi)\ 10^{-23}\ \text{e-cm}$$

$$d_e \sim (\sin\phi)\ 10^{-24}\ \text{e-cm}$$

$$\Rightarrow \quad \phi \simeq 10^{-2} - 10^{-1}$$

Effective SUSY Phase

If parity is realized asymptotically,

$$Y_U,\ Y_D,\ Y_E \quad \text{HERMITIAN}$$
$$A_U,\ A_D,\ A_E \quad \text{HERMITIAN}$$

EDM will arise only through non-hermiticity induced by RGE.

$$d_e \simeq 10^{-28} - 10^{-27} \text{ e-cm;}$$
$$d_n \simeq 10^{-26} - 10^{-27} \text{ e-cm}$$

Subject to experimental tests

$$d_\mu = 10^{-22} - 10^{-23} \text{ e-cm}$$

Dutta, Mohapatra, KB (2001)

Lepton Flavor Violation and Neutrino Mass

Seesaw mechanism naturally explains small ν–mass.

$$\mathcal{L} = \bar{\nu}_L M_D \nu_R + \frac{1}{2} {\nu_R}^T M_R \nu_R + h.c.$$

$$M_\nu = -M_D M_R^{-1} M_D^T$$

Current neutrino-oscillation data suggests

$$M_R \sim (10^{12} - 10^{15})\ \mathrm{GeV}$$

Flavor change in neutrino-sector

⇒ **Flavor change in charged leptons**

In standard model with Seesaw, leptonic flavor changing is very tiny.

$$Br(\mu \to e\gamma) \propto \frac{1}{M_{Pl}^4} \sim 10^{-50}$$

In Supersymmetric Standard model

$$Br(\mu \to e\gamma) \propto \frac{1}{M_{SUSY}^4} \sim 10^{-10}$$

For $M_R \leq \mu \leq M_{Pl}$ ν_R **active**

⇨ **flavor violation in neutrino sector Transmitted to Sleptons**

Borzumati, Masiero (1986)

Hall, Kostelecky, Raby (1986)

Hisano, et al (1995)

SUSY Seesaw Mechanism

$$\mathcal{W} = f\nu^c\nu^c\Delta + Y_\nu \nu^c L H_u$$

$$M_D = Y_\nu v_u \;;\; M_R = f v_{B-L}$$

If *B-L* is gauged, M_R must arise through Yukawa couplings.

Flavor violation may reside entirely in f or entirely in Y_ν

If flavor violation occurs only in Dirac Yukawa Y_ν (with mSUGRA)

$$\Delta m^2_{ij}(i \neq j) \simeq -\frac{1}{8\pi^2}(3m_0^2+A_0^2)(Y_\nu^\dagger Y_\nu)_{ij}\left(\ell n\frac{M_{Pl}}{M_{B-L}}\right)$$

If flavor violation occurs only in *f* (Majorana LFV)

$$A_{\ell ij}(i \neq j) \simeq \frac{-3}{64\pi^4}[A_\ell(Y_\nu^\dagger Y_\nu f^\dagger f + f^\dagger f Y_\nu^\dagger Y_\nu)]_{ij}\left(\ell n\frac{M_{P\ell}}{M_{B-L}}\right)^2$$

$$\Delta m^2_{ij}(i \neq j) \simeq \frac{-3(m_0^2+A_0^2)}{32\pi^4}[Y_\nu^\dagger Y_\nu f^\dagger f + f^\dagger f Y_\nu^\dagger Y_\nu]_{ij}\left(\ell n\frac{M_{P\ell}}{M_{B-L}}\right)^2$$

LFV in the two scenarios are comparable.

More detailed study is needed.

Neutrino Fit

For Majorana LFV scenario, take

Dutta, Mohapatra, KB 2002

$$m_d \propto diag[c\epsilon^3,\ \epsilon,\ 1] \qquad \epsilon \sim 1/10$$

$$\mathcal{M}_\nu = m_0 \begin{pmatrix} e\epsilon^n & h\epsilon^m & d\epsilon \\ h\epsilon^m & 1+a\epsilon & 1 \\ d\epsilon & 1 & 1+b\epsilon \end{pmatrix}$$

$$f = \frac{m_{D,3}^2}{d^2 m_0 v_{B-L}} \begin{pmatrix} (a+b)c^2\epsilon^5 & cd\epsilon^3 & -cd\epsilon^2 \\ cd\epsilon^3 & -d^2\epsilon^2 & dh\epsilon^2 \\ -cd\epsilon^2 & dh\epsilon^2 & (e-h^2)\epsilon^2 \end{pmatrix}$$

$$v_{B-L} = 2 \times 10^{12}\ \text{GeV},\ M_D \propto M_{l+}$$

$$f = \begin{pmatrix} -1.1 \times 10^{-4} & -0.015 & 0.29 \\ -0.015 & 0.50 & -0.57 \\ 0.29 & -0.57 & 0.104 \end{pmatrix}$$

$$(m_1,\ m_2,\ m_3) = (-2.7 \times 10^{-3},\ 6.4 \times 10^{-3},\ 8.6 \times 10^{-2})\ \text{eV}$$

$$\mathbf{U} = \begin{pmatrix} 0.85 & -0.52 & -0.053 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{pmatrix}$$

For Dirac LFV scenario

$$M_R = (9 \times 10^{13}\ GeV) \times (\text{Identity Matrix})$$

$$Y_\nu = \begin{pmatrix} 0.04 + 0.074i & -0.073 + 0.029i & 0.025 - 0.034i \\ -0.073 + 0.029i & -0.22 + 0.011i & -0.35 - 0.013i \\ 0.025 - 0.034i & -0.35 - 0.013i & -0.24 + 0.016i \end{pmatrix}$$

⇨ **Same neutrino oscillation parameters as in Majorona LFV**

The two scenarios differ in predictions for

$$\mu \longrightarrow e\gamma$$
$$\tau \longrightarrow \mu\gamma$$
$$\tau \longrightarrow e\gamma$$

Dirac LFV

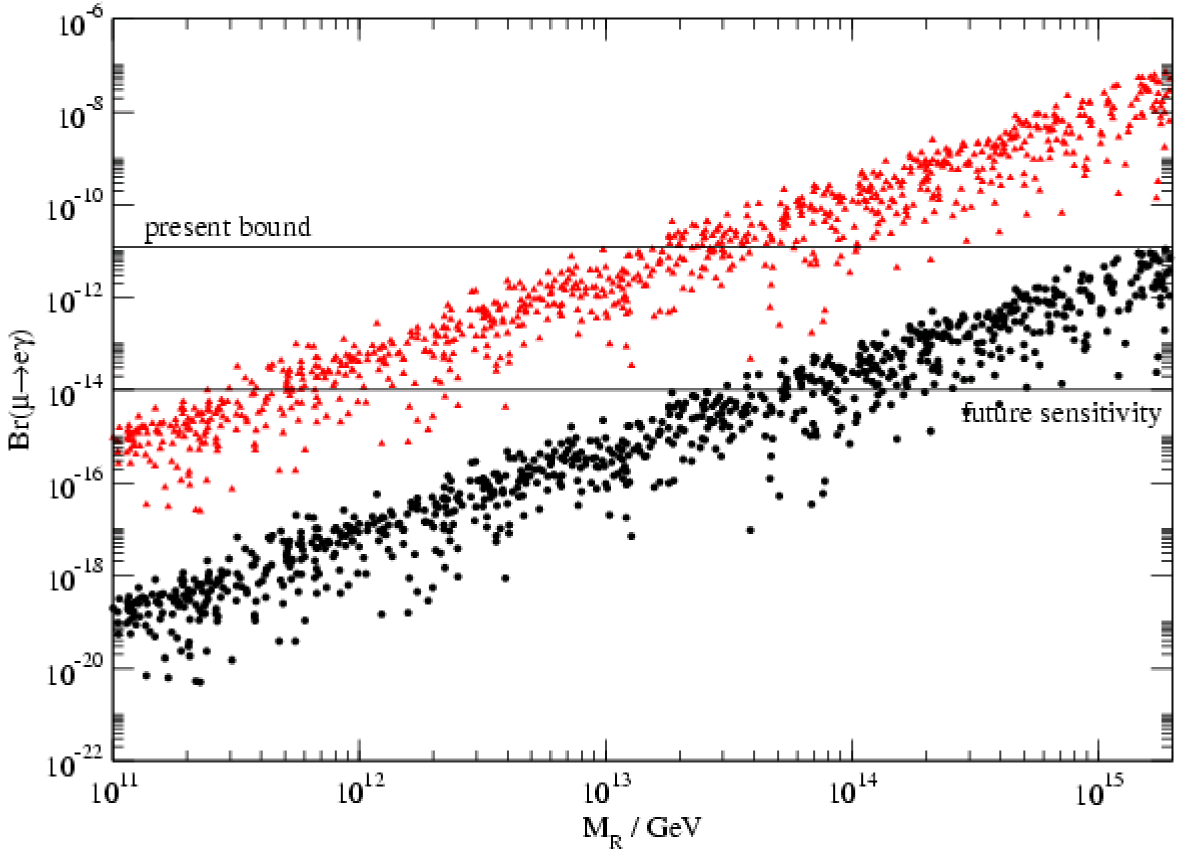
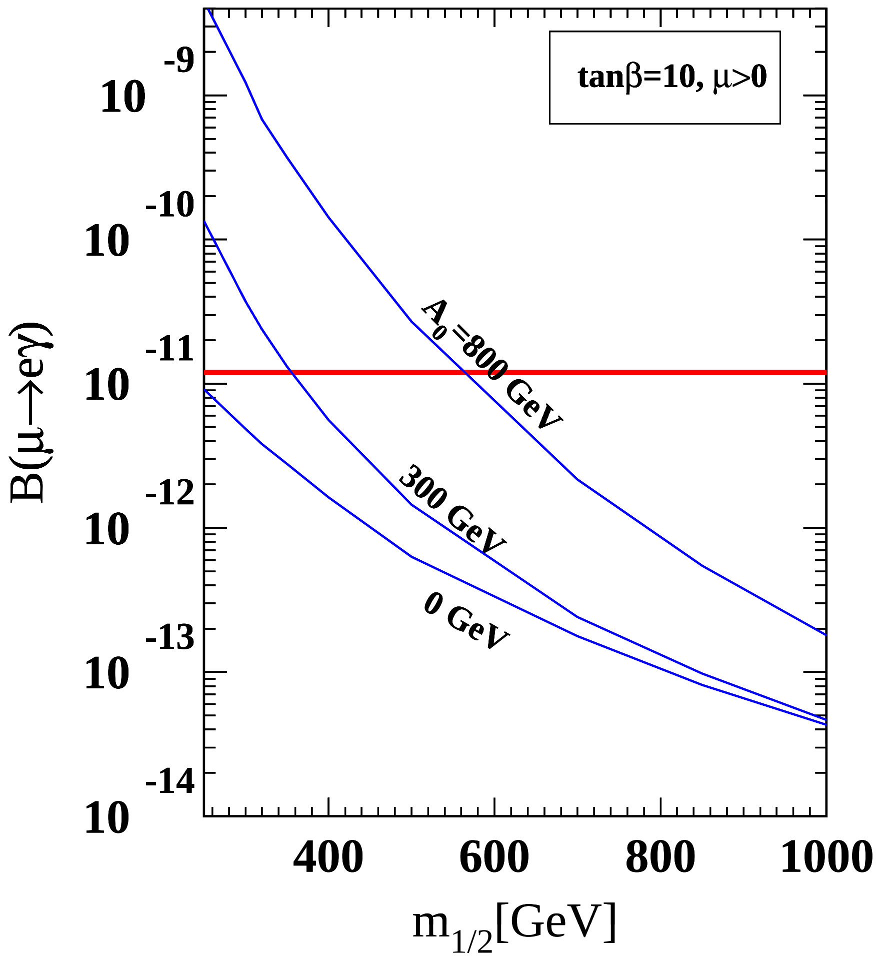
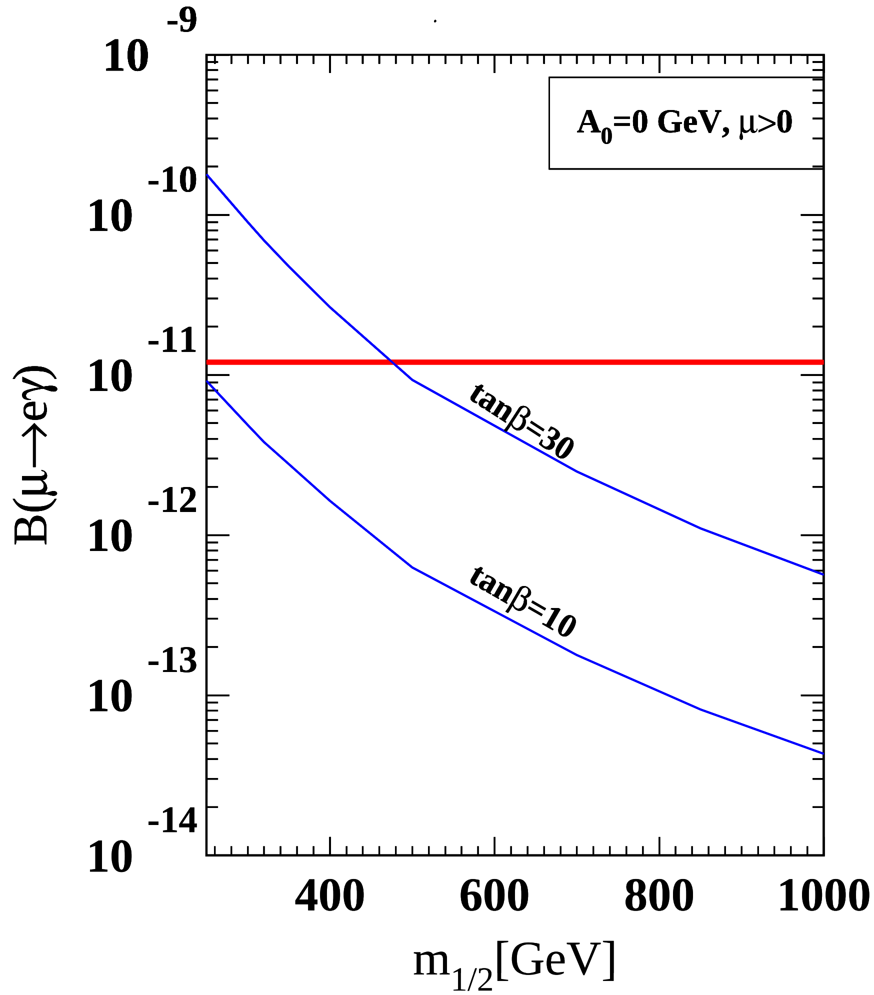


Figure 3: Branching ratio of $\mu \to e\gamma$ for hierarchical neutrinos and uncertainties of future neutrino experiments in the mSUGRA scenarios leading to the largest (L, upper) and the smallest (H, lower) LFV rates.

F. Deppisch, et al, hep-ph/0206122

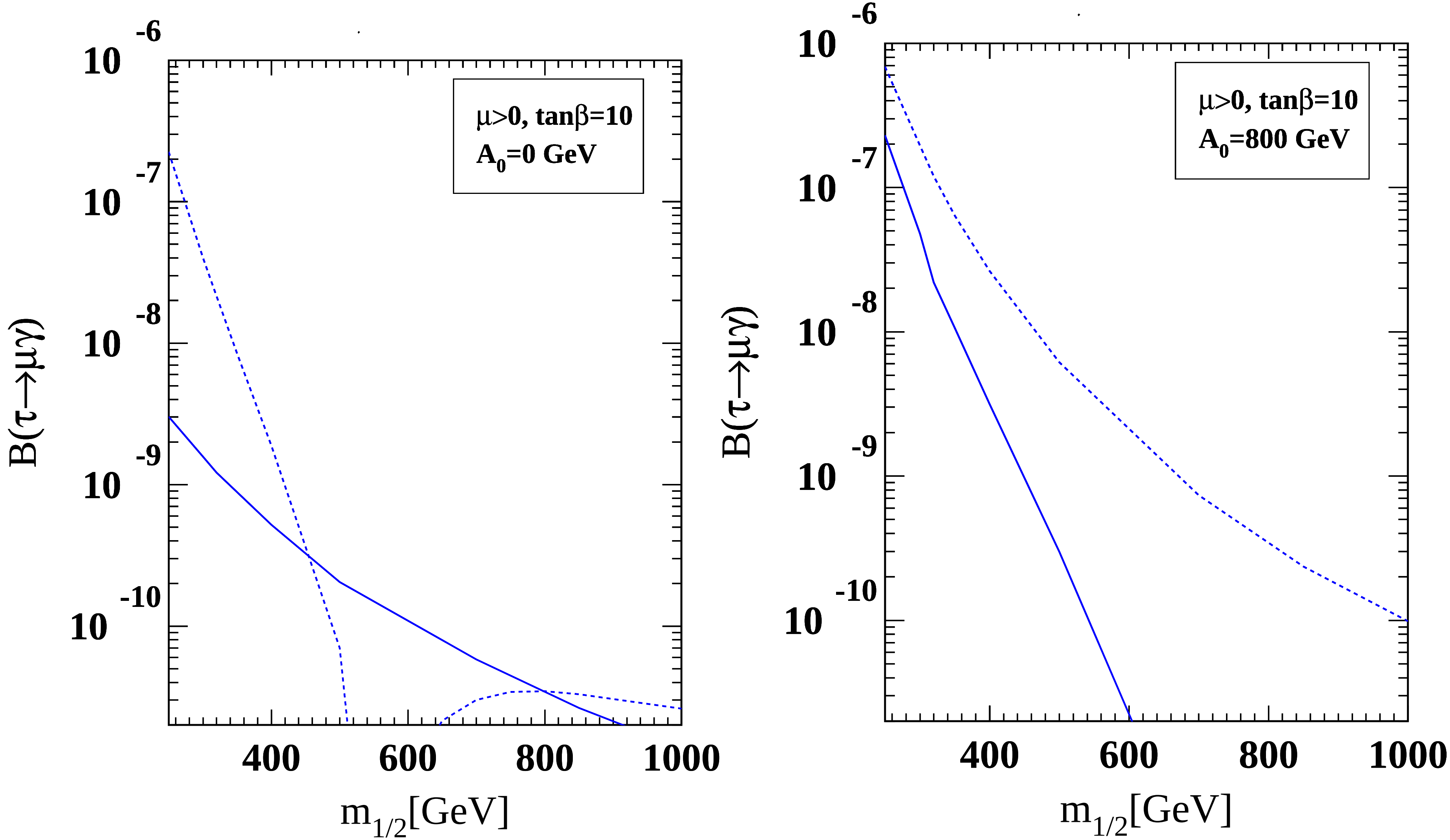
$\mu \to e\gamma$ Majorana LFV





Dutta, Mohapatra, KB (2002)

$\tau \to \mu\gamma$



Flavor Symmetry and Fermion Mass Hierarchy

- Complex Yukawa couplings. ~~SUSY~~ in mSUGRA with real universal soft parameters.
- Fermion mass matrices:

$$M_u \sim \langle H_u\rangle \begin{pmatrix} \epsilon^8 & \epsilon^6 & \epsilon^4 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix} \qquad M_d \sim \langle H_d\rangle \epsilon^p \begin{pmatrix} \epsilon^5 & \epsilon^4 & \epsilon^4 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & 1 \end{pmatrix},$$

$$M_e \sim \langle H_d\rangle \epsilon^p \begin{pmatrix} \epsilon^5 & \epsilon^3 & \epsilon \\ \epsilon^4 & \epsilon^2 & 1 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix} \qquad M_{\nu_D} \sim \langle H_u\rangle \epsilon^s \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix},$$

$$M_{\nu^c} \sim M_R \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \quad \text{See-Saw} \Rightarrow \quad M_\nu^{light} \sim \frac{\langle H_u\rangle^2}{M_R}\epsilon^{2s} \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}.$$

Here small parameter $\epsilon \simeq .2$ and $p = (0,\ 1,\ 2)$ for $\tan\beta = (50,\ 20,\ 5)$

- This experimental fact motivates a generation dependent $U(1)$ symmetry.

U(1) flavor charge assignment

Field	$U(1)_A$ Charge	Charge notation
Q_1, Q_2, Q_3	$4,\ 2,\ 0$	q_i^Q
L_1, L_2, L_3	$1+s,\ s,\ s$	q_i^L
u_1^c, u_2^c, u_3^c	$4,\ 2,\ 0$	q_i^u
d_1^c, d_2^c, d_3^c	$1+p,\ p,\ p$	q_i^d
e_1^c, e_2^c, e_3^c	$4+p-s,\ 2+p-s,\ p-s$	q_i^e
$\nu_1^c, \nu_2^c, \nu_3^c$	$1,\ 0,\ 0$	q_i^ν
H_u, H_d, S	$0,\ 0,\ -1$	$(h, \bar{h}, q_s)$

The value of Yukawa couplings at M_F from low energy data through two–loop RGE ($\tan\beta = 5$)

$$Y^u = \begin{pmatrix} (1.45 + 1.60\,i)\,\epsilon^8 & (-0.563 - 1.24\,i)\,\epsilon^6 & (1.50 - 0.397\,i)\,\epsilon^4 \\ (-0.769 - 0.584\,i)\,\epsilon^6 & (0.765 - 0.109\,i)\,\epsilon^4 & (-0.255 - 0.261\,i)\,\epsilon^2 \\ (-0.282 - 0.204\,i)\,\epsilon^4 & (0.274 - 0.44 \times 10^{-1}\,i)\,\epsilon^2 & 0.554 - 2.80 \times 10^{-5}\,i \end{pmatrix}$$

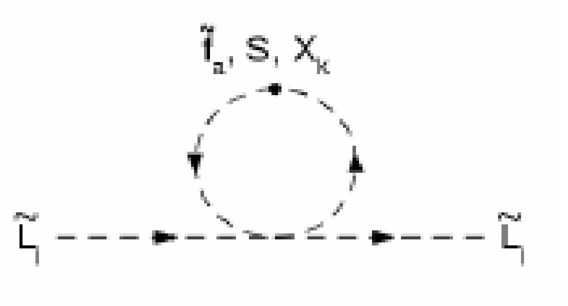
$$Y^d = \epsilon^2 \begin{pmatrix} (1.87 - 1.69\,i)\,\epsilon^5 & (1.93 + 0.849\,i)\,\epsilon^4 & (1.29 + 0.957\,i)\,\epsilon^4 \\ (-0.404 - 0.248\,i)\,\epsilon^3 & (0.5542 + 1.54 \times 10^{-2}\,i)\,\epsilon^2 & (0.702 - 0.546\,i)\,\epsilon^2 \\ (-0.152 - 0.435\,i)\,\epsilon & 0.312 - 0.314\,i & 0.543 - 4.74 \times 10^{-4}\,i \end{pmatrix}$$

$$Y^e = \epsilon^2 \begin{pmatrix} (3.52 \times 10^{-2} + 0.480\,i)\,\epsilon^5 & (-1.85 - 1.74\,i)\,\epsilon^3 & (-0.539 - 0.579\,i)\,\epsilon \\ (-0.170 - 0.612\,i)\,\epsilon^4 & (1.15 + 4.65 \times 10^{-2}\,i)\,\epsilon^2 & 0.319 - 0.321\,i \\ (0.538 - 0.421\,i)\,\epsilon^4 & (-0.419 - 0.536\,i)\,\epsilon^2 & 0.784 + 9.74 \times 10^{-5}\,i \end{pmatrix}$$

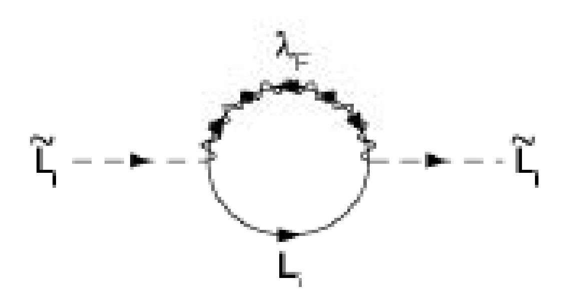
$$Y^\nu = \epsilon^2 \begin{pmatrix} (0.232 - 0.190\,i)\,\epsilon^2 & (0.217 - 6.09 \times 10^{-2}\,i)\,\epsilon & (-0.206 - 0.637\,i)\,\epsilon \\ (0.638 - 0.652\,i)\,\epsilon & -7.82 \times 10^{-2} + 0.537\,i & 0.804 + 0.296\,i \\ (0.305 - 0.392\,i)\,\epsilon & -4.41 \times 10^{-3} + 0.277\,i & 0.404 - 3.89 \times 10^{-2}\,i \end{pmatrix}$$

Anomalous U(1) Symmetry and Lepton Flavor Violation

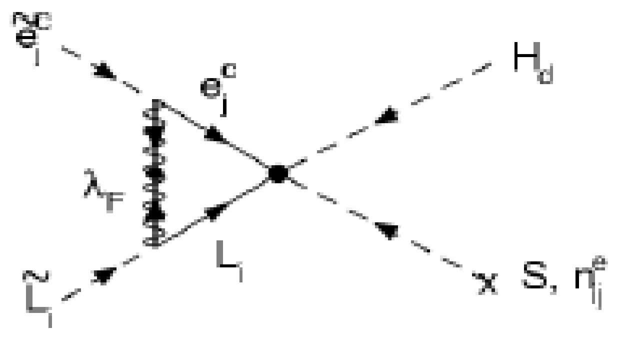
Enkhbat, Gogoladze, KSB (2003)



$$\delta\left(\tilde{m}^2_L\right)^A_{ij} \simeq -q^L_i |q_s| g^2_F \delta_{ij} m^2_0 \mathrm{Tr}(Q) \frac{\ln\left(M_{st}/M_F\right)}{8\pi^2}$$

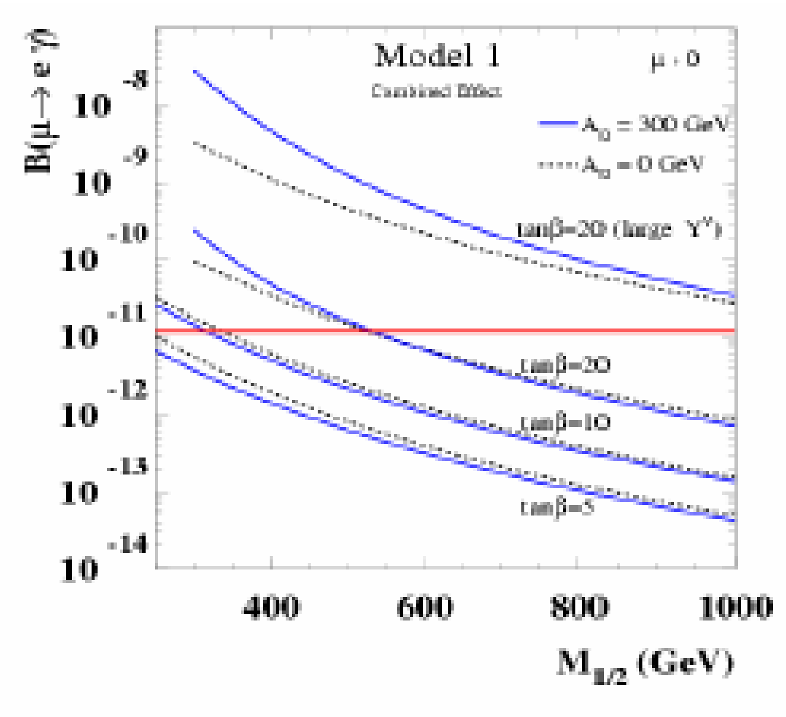


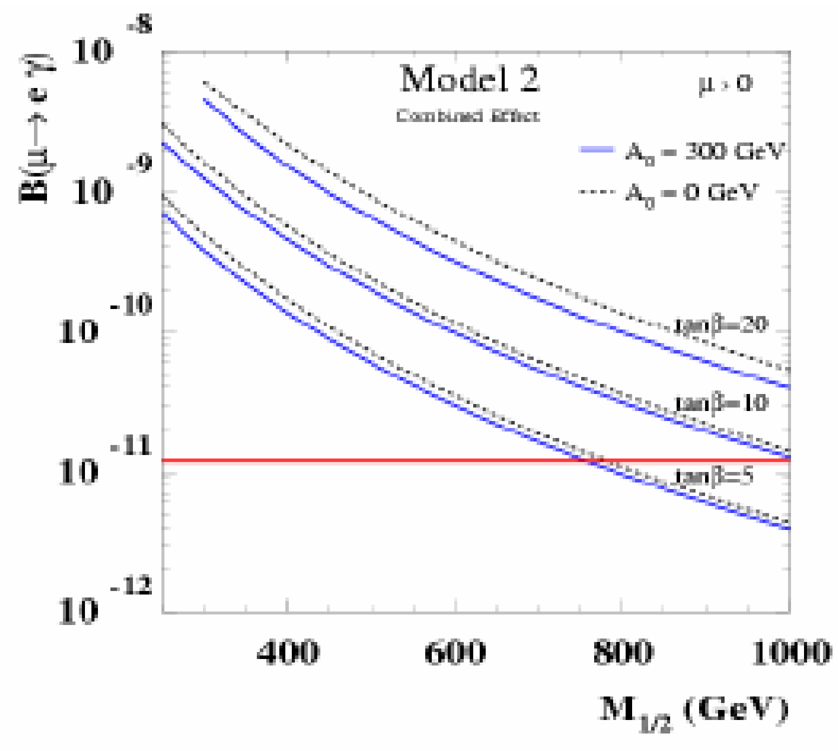
$$\delta\left(\tilde{m}^2_L\right)^G_{ij} \simeq \left(q^L_i\, g_F\right)^2 \delta_{ij} \left(M_{\lambda_F}\right)^2 \frac{\ln\left(M_{st}/M_F\right)}{2\pi^2}$$



$$\delta A^e_{ij} \simeq -M_{\lambda_F} {g_F}^2 Y^e_{ij} Z^e_{ij} \frac{\ln\left(M_{st}/M_F\right)}{4\pi^2}$$

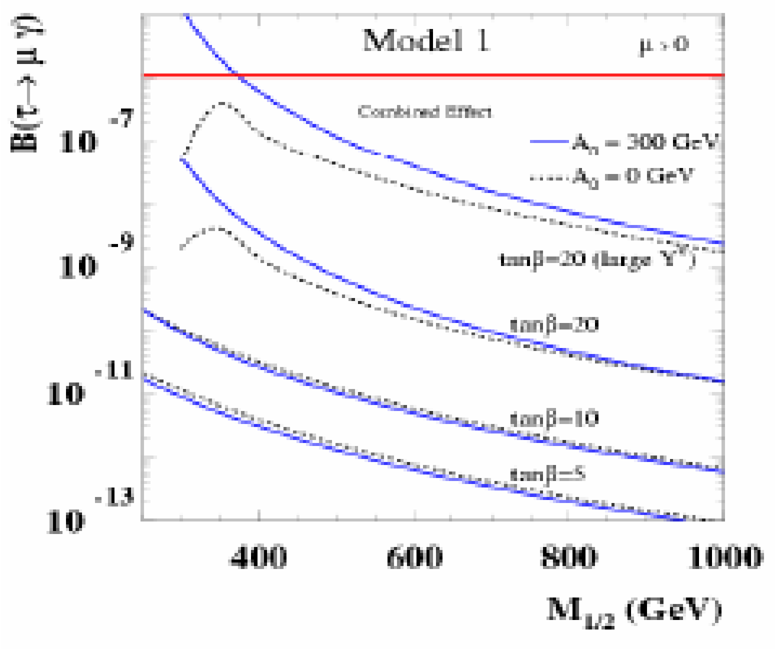
$\mu \to e\gamma$ in Anomalous $U(1)$ Models

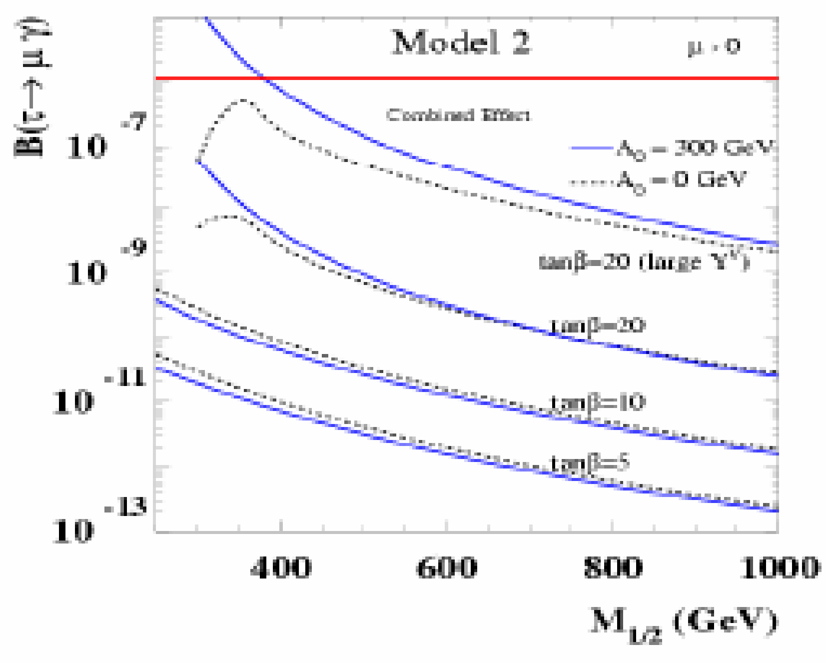




Enkhbat, Gogoladze, KSB (2003)

$\tau \to \mu\gamma$ in Anomalous $U(1)$ Models





Enkhbat, Gogoladze, KSB (2003)

EDM from Flavor Symmetry

The EDM induced by the $U(1)_A$ flavor gaugino is estimated to be

$$d_e/e \simeq \frac{\alpha v_d M_{\tilde{B}}}{8\pi \cos^2\theta_W} \frac{1}{m_{\tilde{l}}^2} A\left(\frac{M_{\tilde{B}}^2}{m_{\tilde{l}}^2}\right) \frac{(|q_s| g_F)^2 \log(M_{st}/M_F)}{8\pi^2} \sum_{i=2,3} \left[C_i^m + C_i^A\right] \mathrm{Im}\left[\frac{Y_{1i}^e Y_{i1}^e}{Y_{ii}^e}\right],$$

$$C_i^m = \frac{(|q_s| g_F)^2 \log(M_{st}/M_F)}{8\pi^2} \frac{m_0^4 (A_0 - |\mu| \tan\beta)}{m_{\tilde{l}}^6} H_i^L H_i^R,$$

The flavor dependent factors:

$$H_i^L = 4\left(M_{1/2}/m_0\right)^2 \left((q_i^L)^2 - (q_1^L)^2\right) - (q_i^L - q_1^L)\,\mathrm{Tr}(q) \text{ and } H^R = H^L(q^L \to q^e),$$

$$C_i^A = 2\frac{M_{1/2}}{m_{\tilde{l}}^2}\left(Z_{i1}^e - Z_{11}^e\right).$$

C^m–soft mass corrections, C^A– A–term corrections

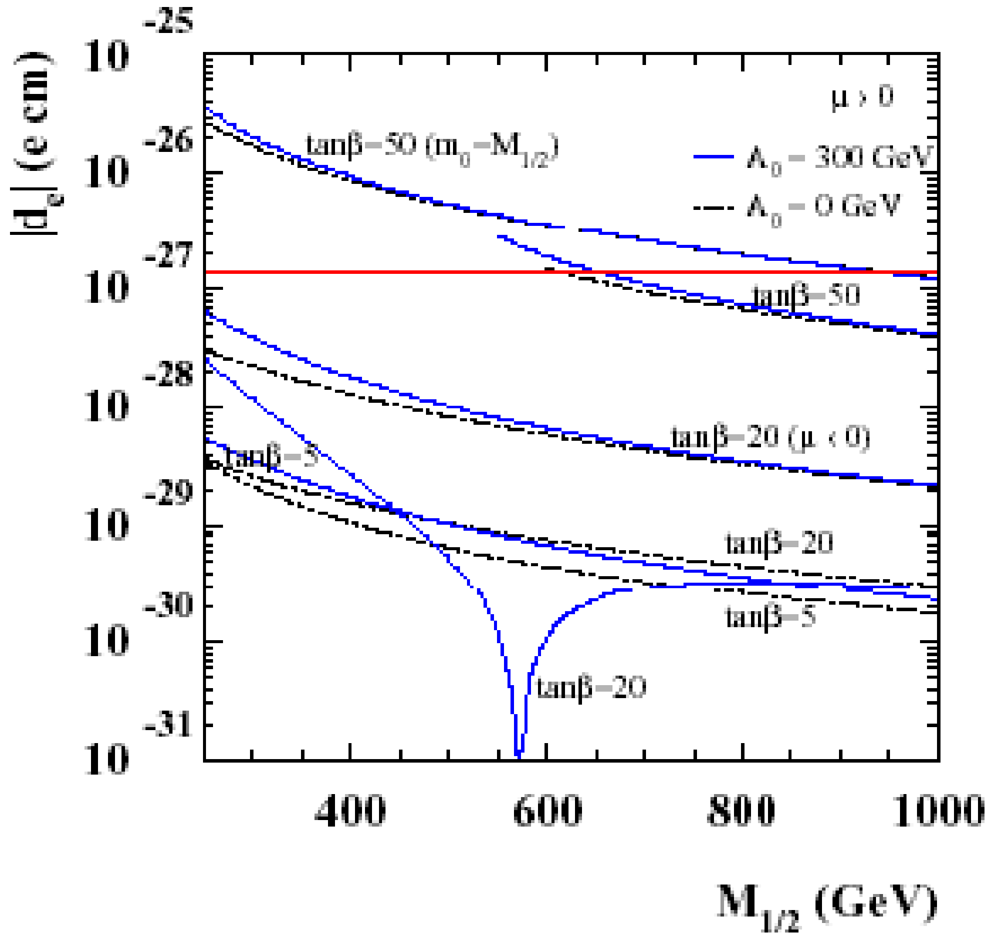


Figure 4: The Electron Electric Dipole Moment. The red line: experimental bound

Ts. Enkhbat, KSB, hep-ph/0406003

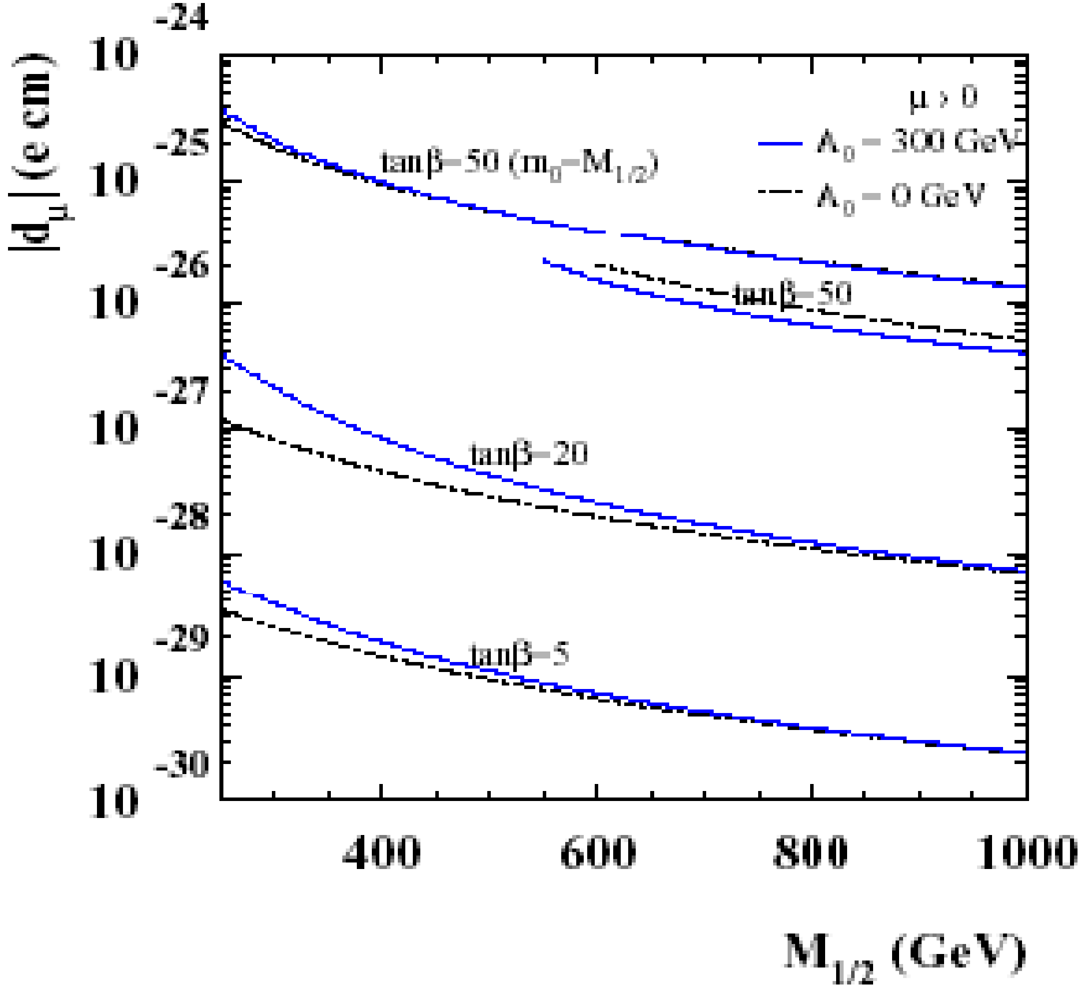


Figure 5: Muon Electric Dipole Moment.

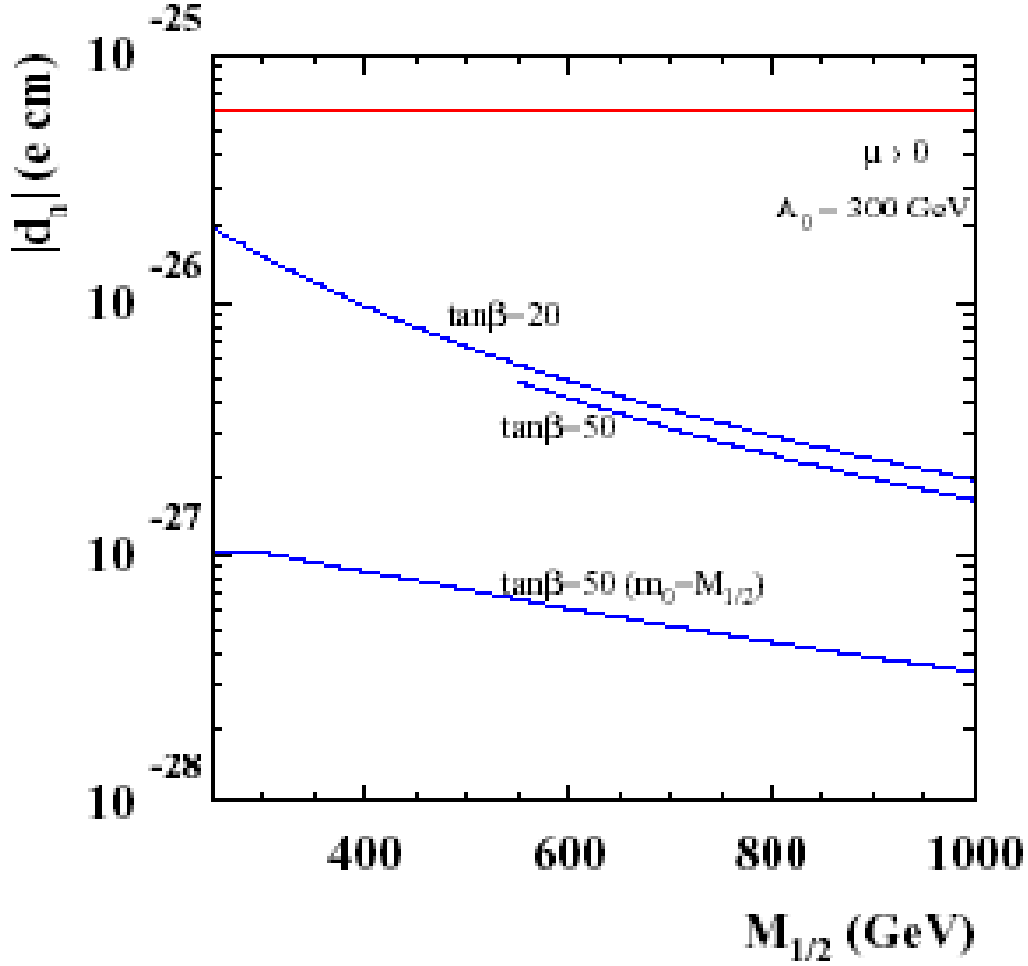


Figure 6: Neutron Electric Dipole Moment.

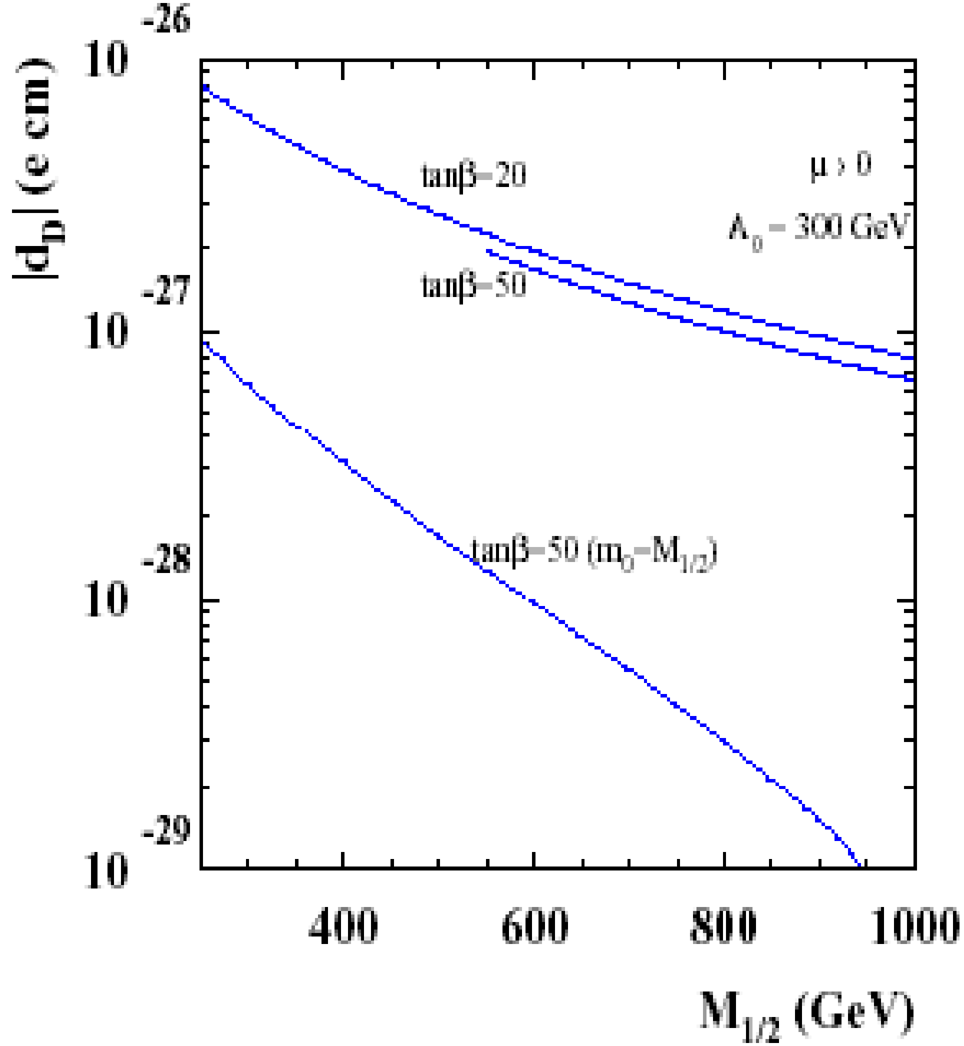


Figure 7: Deuteron Electric Dipole Moment.

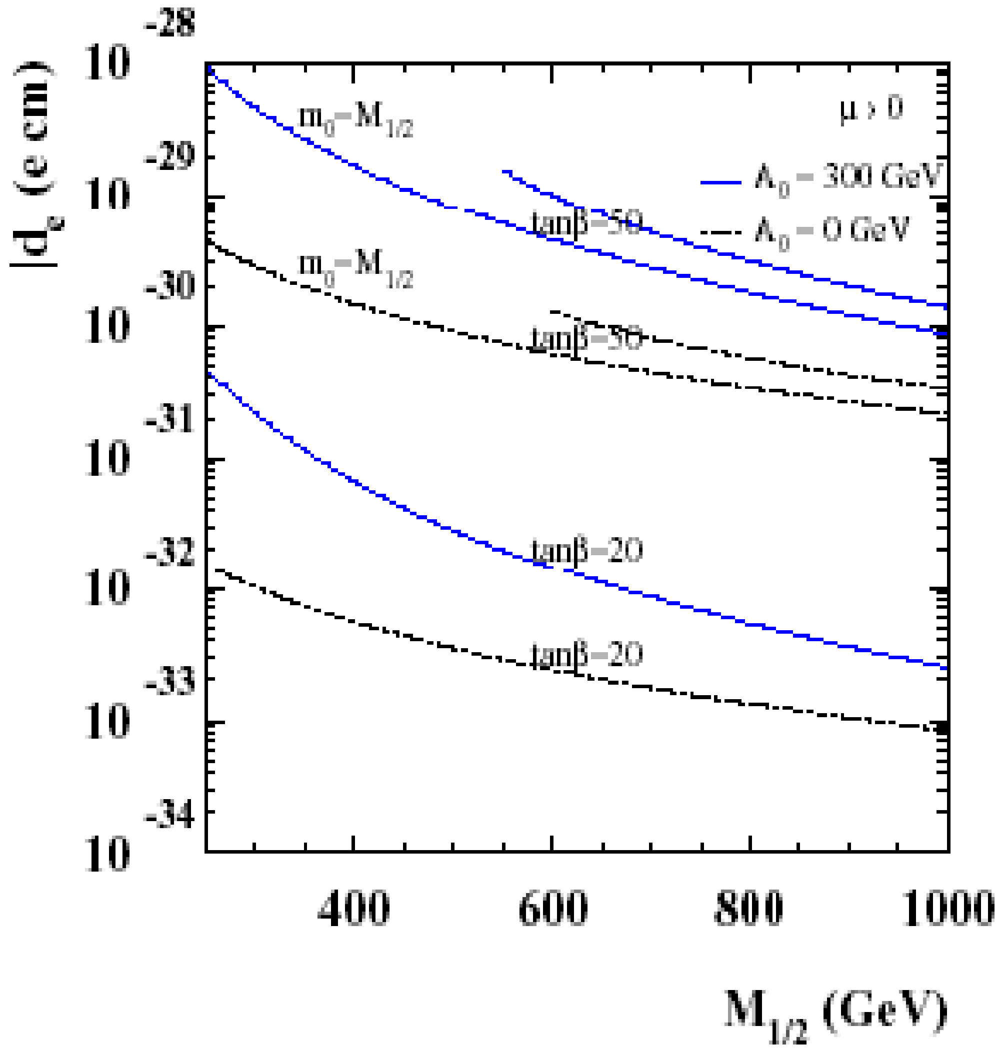


Figure 8: Electron Electric Dipole Moment by purely the neutrino effects.

Conclusions

- **Supersymmetry: attractive candidate to stabilize Higgs mass**
- **Suggested by gauge coupling unification**
- **Before direct discovery, SUSY can show up in:**
  - **Lepton flavor violation ($\mu \to e\gamma$, $\tau \to \mu\gamma$)**
  - **$B_S \to \mu^+ \mu^-$ Decay**
  - **Muon *g-2***
  - **d_e, d_n**
  - **Proton decay**
  - **Dark matter**