Supersymmetry and Its Experimental Tests

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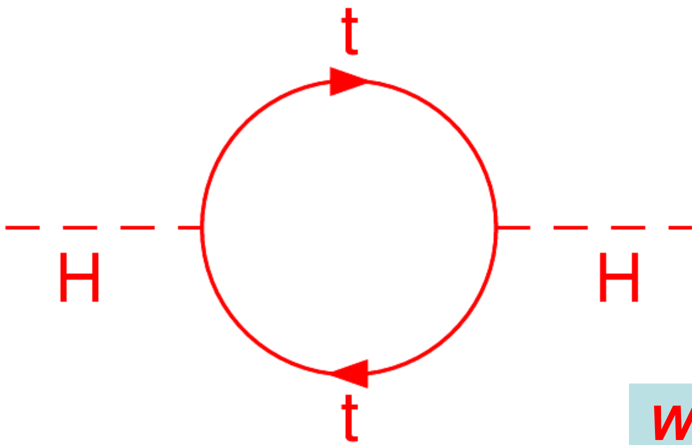
Outline

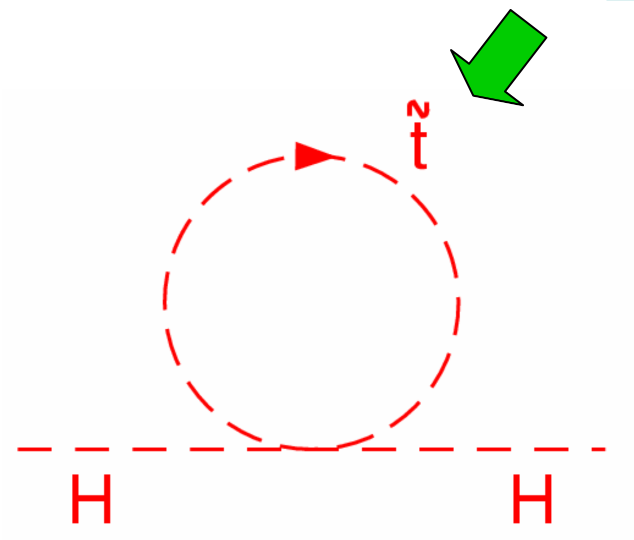
- ☆ Motivations
- ☆ Supersymmetry Breaking
- ☆ Direct Tests at Colliders
- ☆ Indirect Tests
  - *Rare B Decays*
  - *Dipole Moments*
  - *Lepton Flavor Violation*
- ☆ SUSY GUTs and Proton Decay
- ☆ Conclusions

Stability of Higgs Mass



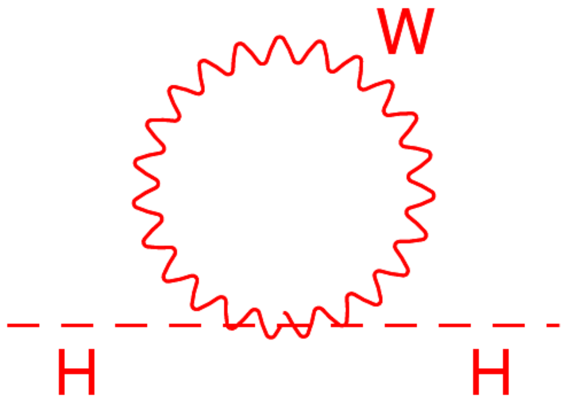
$$\Delta m_H^2 = -\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

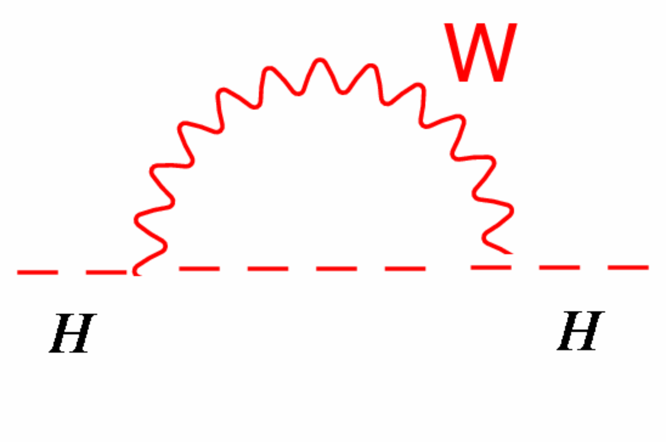
With SUSY, Quadratic Divergence Cancels



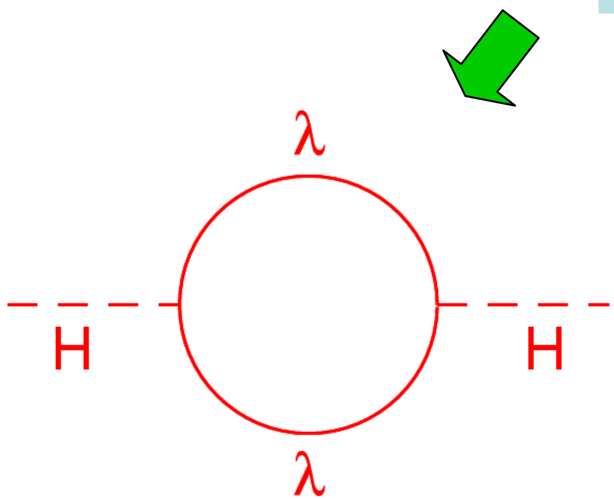
$$\Delta m_H^2 = +\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

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





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

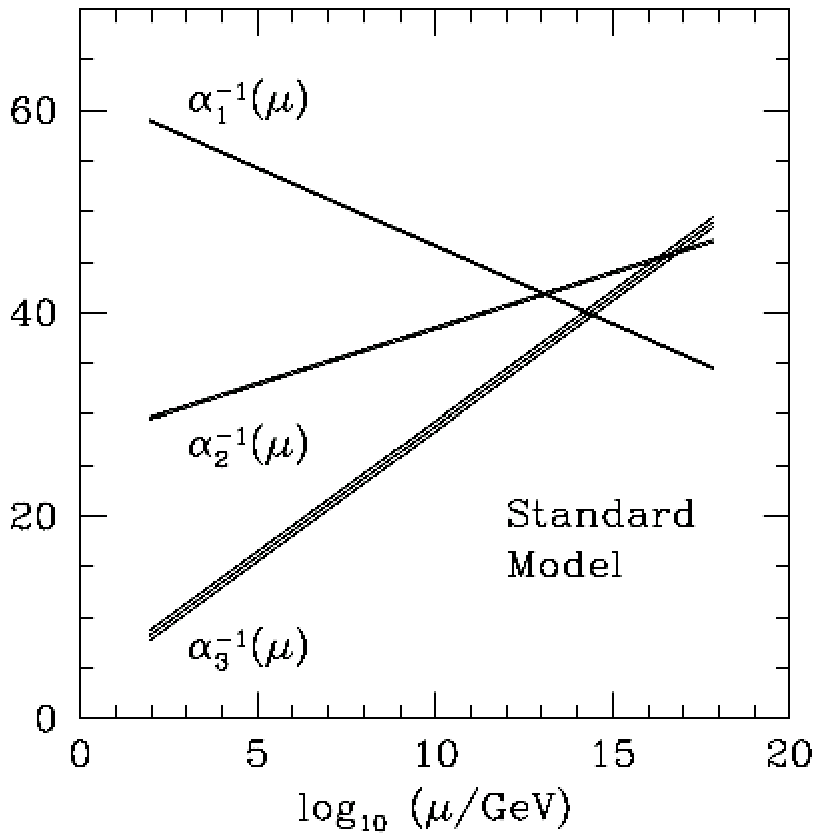


SUSY Spectrum

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

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

Evolution of Gauge Couplings In Standard Model



Evolution of Gauge Couplings in six-Higgs-doublet SM

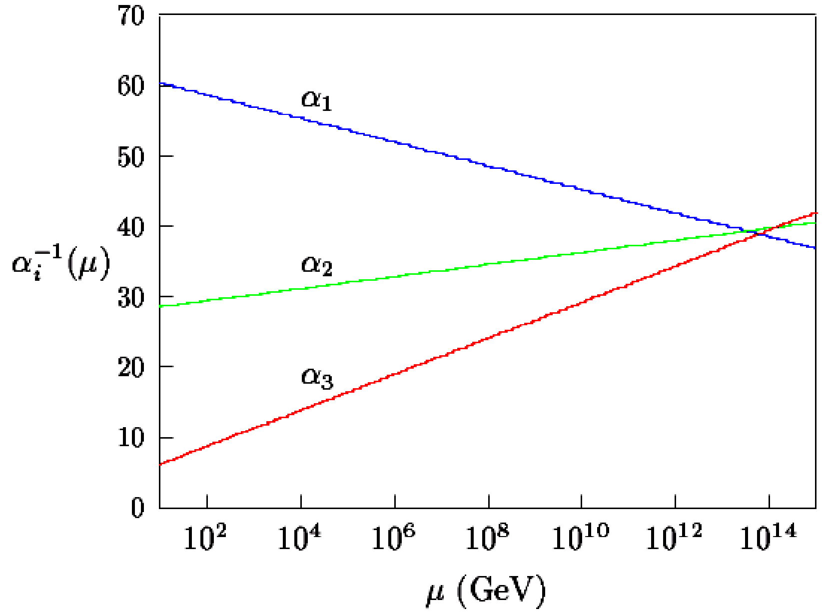
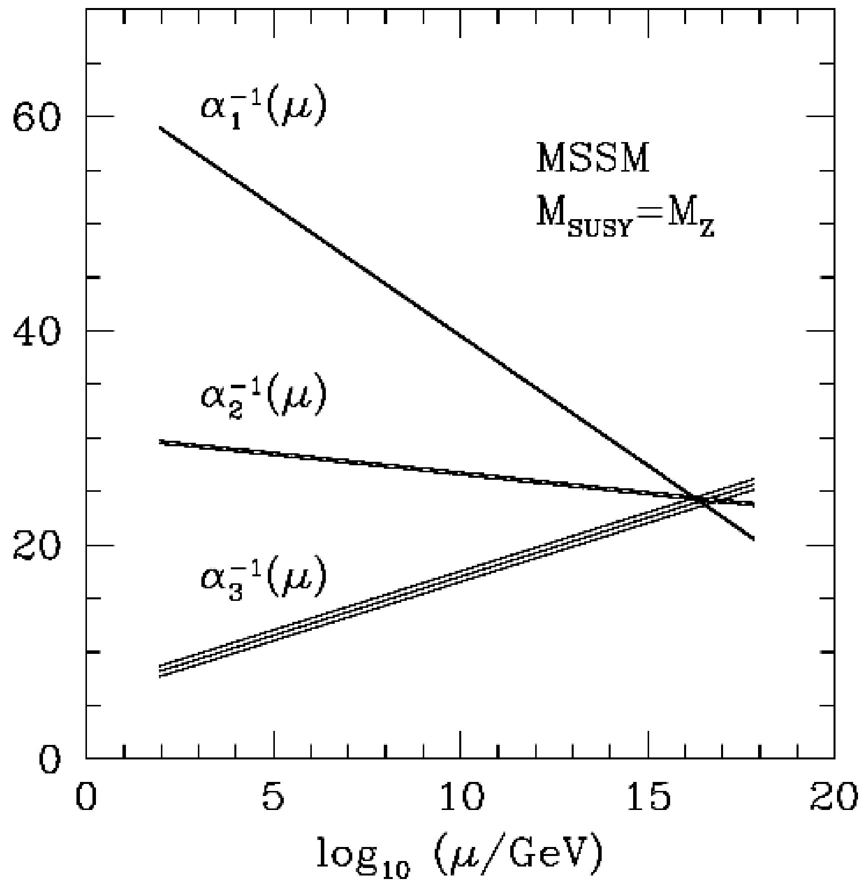


Figure 1: Leading-order evolution of the gauge couplings from their low-energy values to the unification scale in the six-Higgs-doublet standard model. The couplings meet around 10^{14} GeV, within the accuracy of a leading-order calculation.

S. Willenbrock, hep-ph/0302168

Gauge Coupling Unification in MSSM



Structure of Matter Multiplets

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

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

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

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

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

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

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

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

I. Gogoladze, K. Wang, KB hep-ph/0212245

Z_4 Model

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

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

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

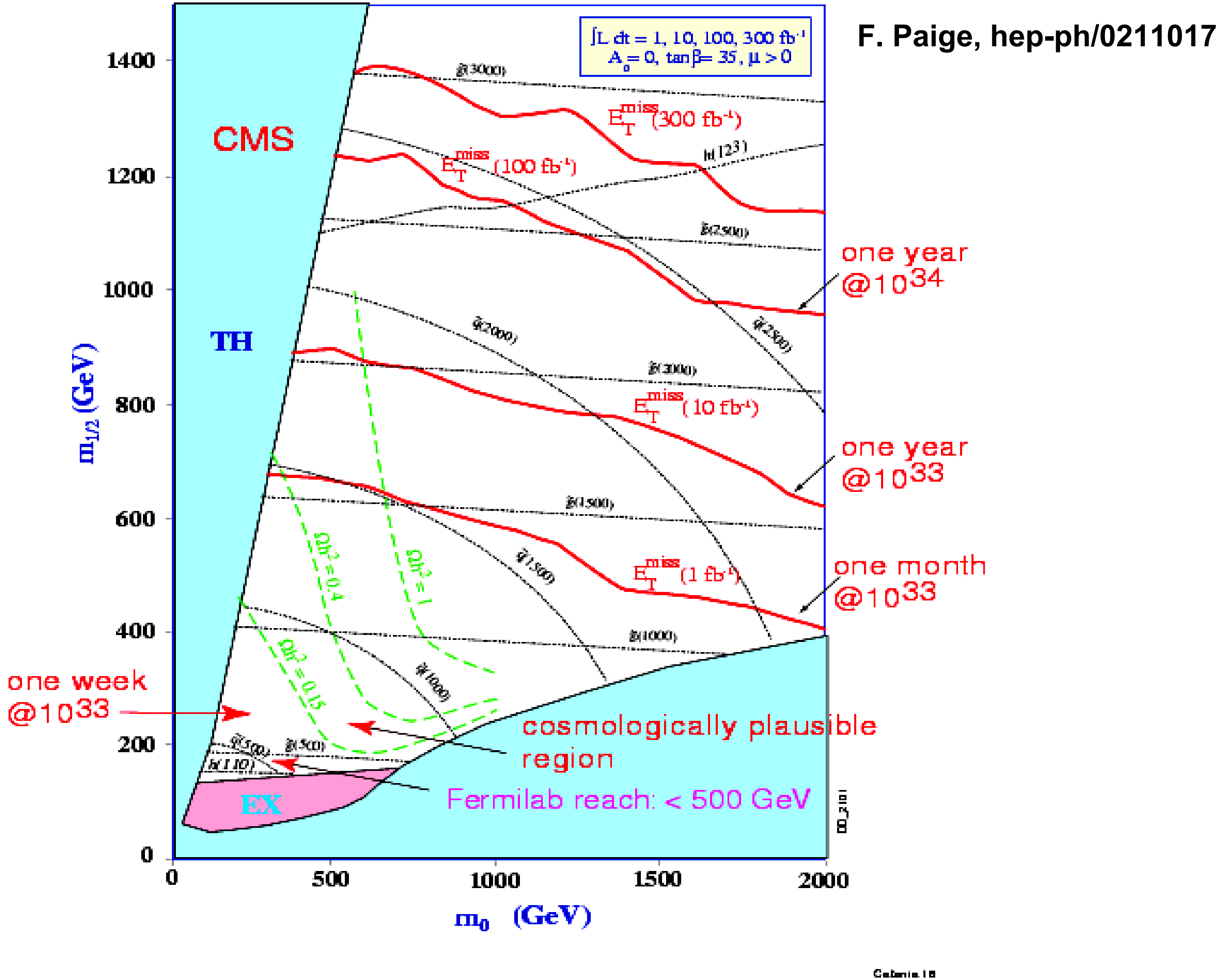


Figure 1: Plot of 5σ reach in jets + $\not{E}_T$ channel for mSUGRA model .

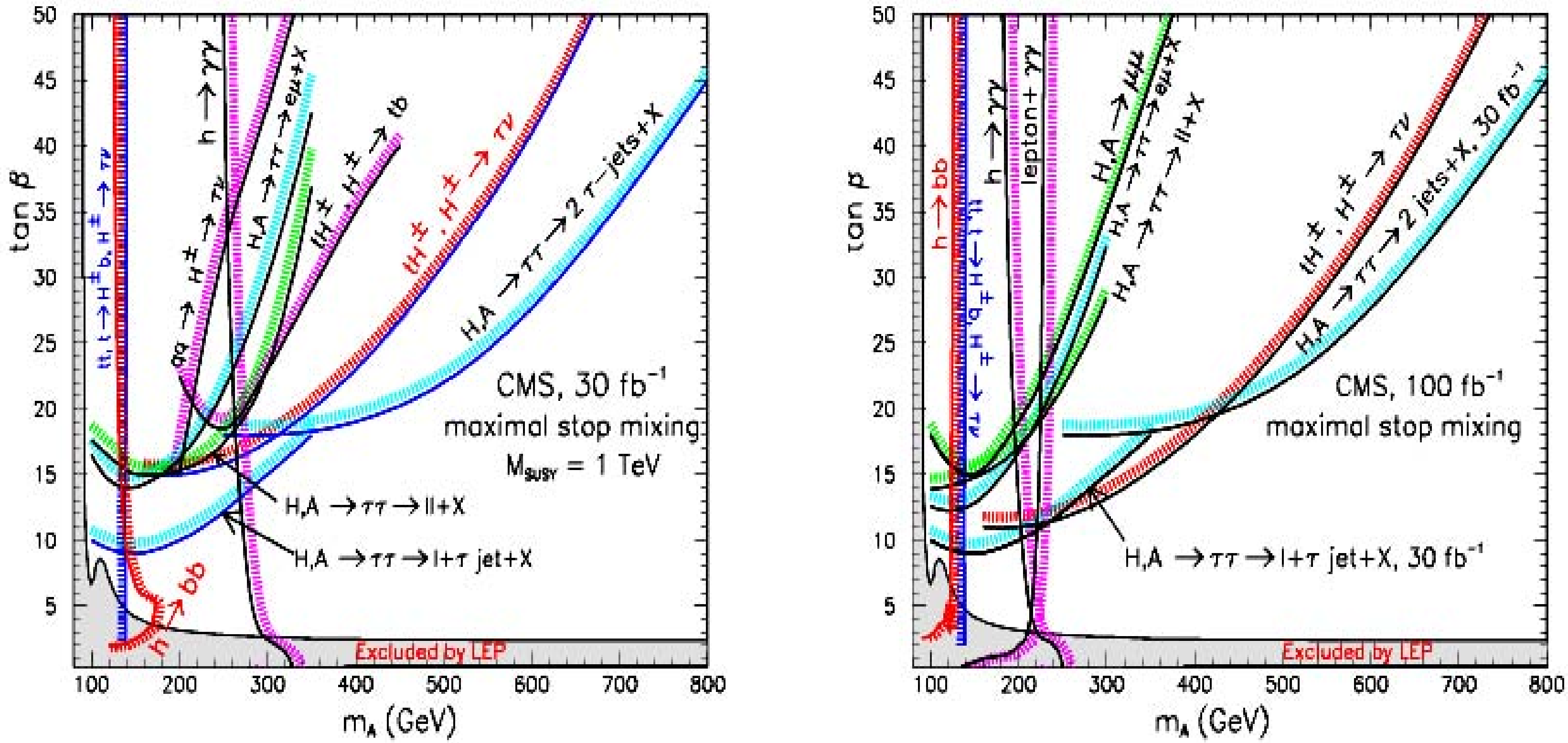


Fig. 6. Expected 5σ discovery limits of various MSSM Higgs signals at LHC for luminosities of 30 fb^{-1} and 100 fb^{-1} .

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

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

Kolda, KB (1999)

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

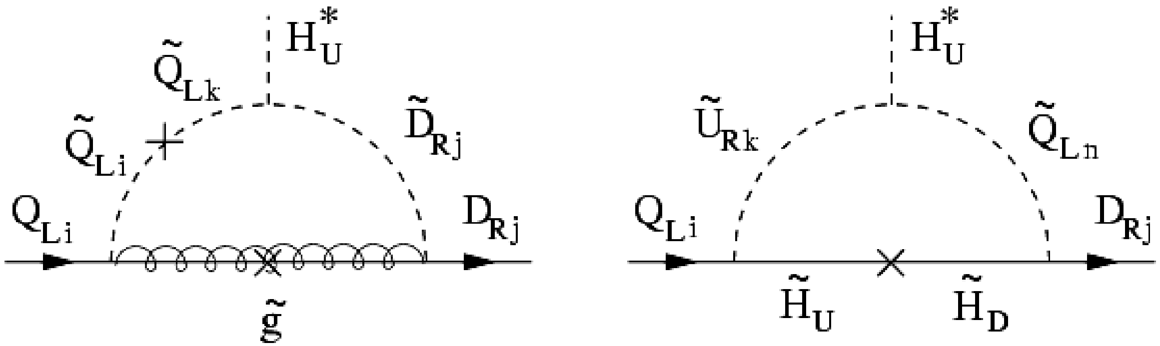
MSSM is a general two-Higgs-doublet model.

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

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

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

Hall, Rattazzi, Sarid (1993)



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

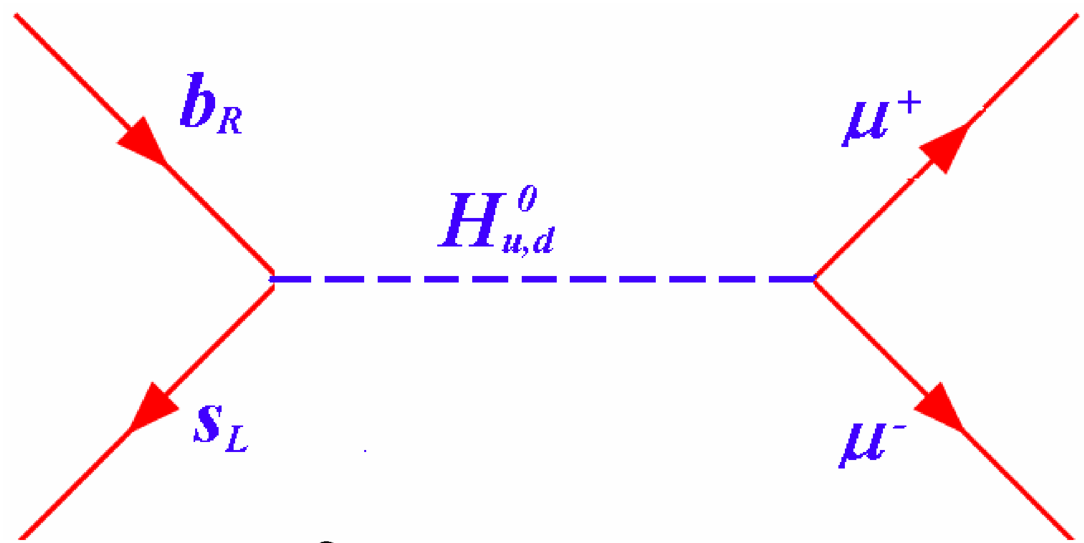
$$\epsilon_g \simeq \frac{2\alpha_3}{3\pi}(\mu^* M_3 f(M_3^2, M_{\tilde{Q}_L}^2, M_{\tilde{d}_R}^2)$$

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

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

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

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



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

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

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

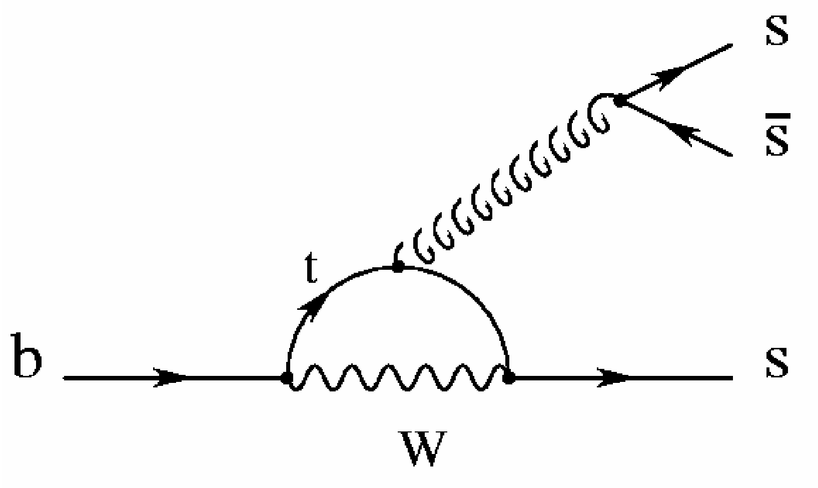
SUSY CP Violation in $B_d \to \phi K_s$ Decay

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

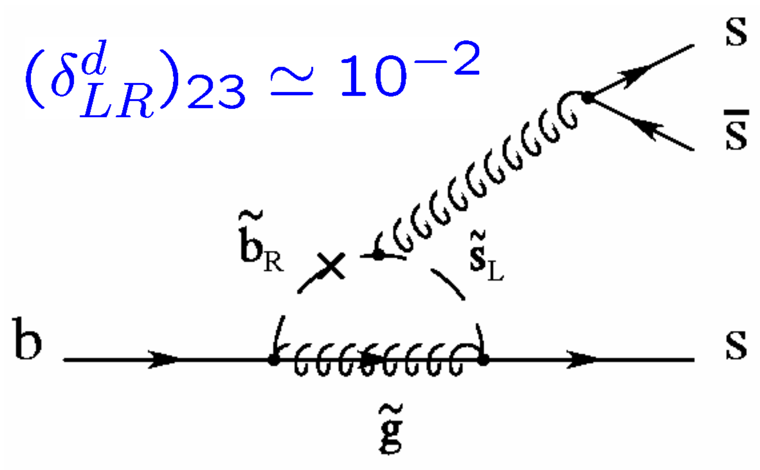
$$\mathcal{A}_{\phi K}(t) \equiv \frac{\Gamma(\overline{B}^0_{\text{phys}}(t) \to \phi K_S) - \Gamma(B^0_{\text{phys}}(t) \to \phi K_S)}{\Gamma(\overline{B}^0_{\text{phys}}(t) \to \phi K_S) + \Gamma(B^0_{\text{phys}}(t) \to \phi K_S)} = -C_{\phi K} \cos(\Delta m_B t) + S_{\phi K} \sin(\Delta m_B t),$$

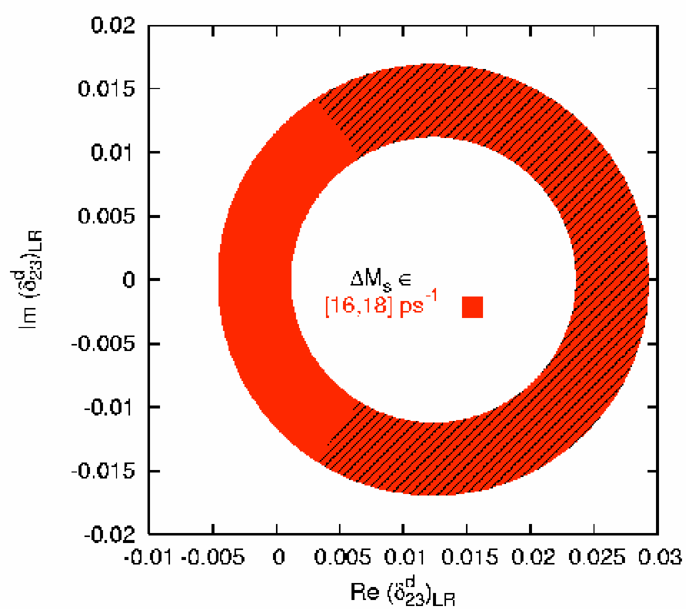
$$C_{\phi K} = \frac{1 - |\lambda_{\phi K}|^2}{1 + |\lambda_{\phi K}|^2}; \quad S_{\phi K} = \frac{2\ \text{Im}\lambda_{\phi K}}{1 + |\lambda_{\phi K}|^2};$$

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

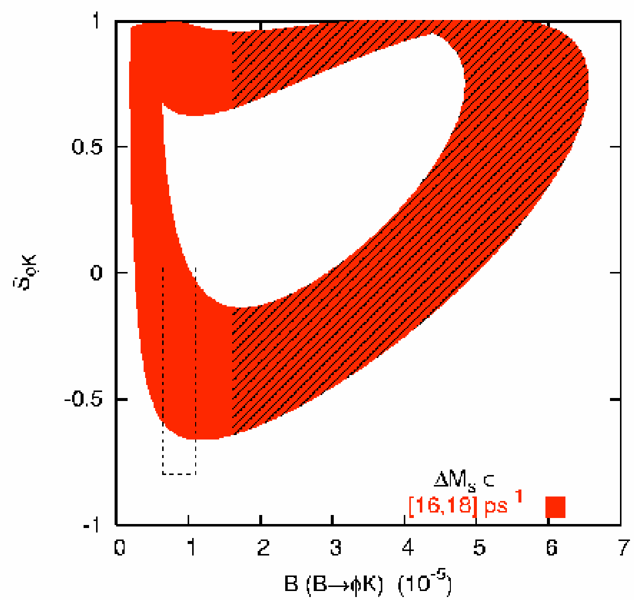


$$(\delta^d_{LR})_{23} \simeq 10^{-2}$$





(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

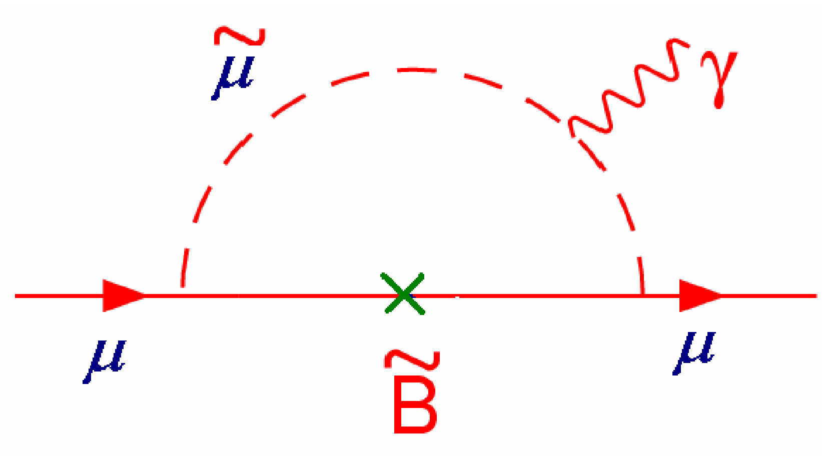
$$\mathcal{L}_{eff} = \frac{a_\mu}{2m_\mu}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$$

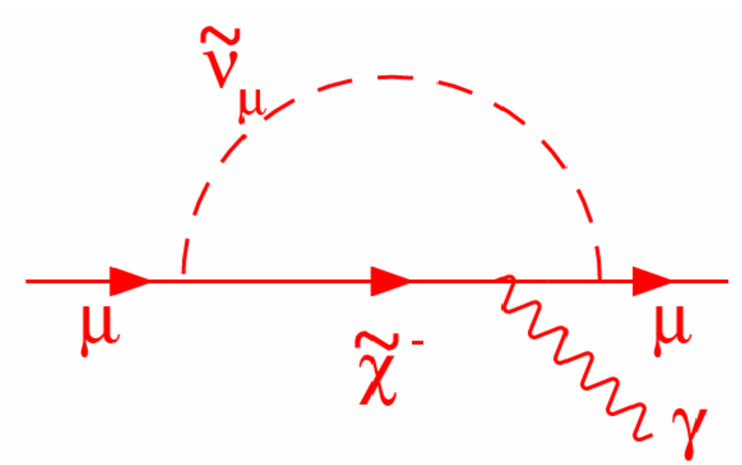
$$a_\mu(SM) = 11\ 659\ 182.1(7.2) \times 10^{-10}$$

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

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

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

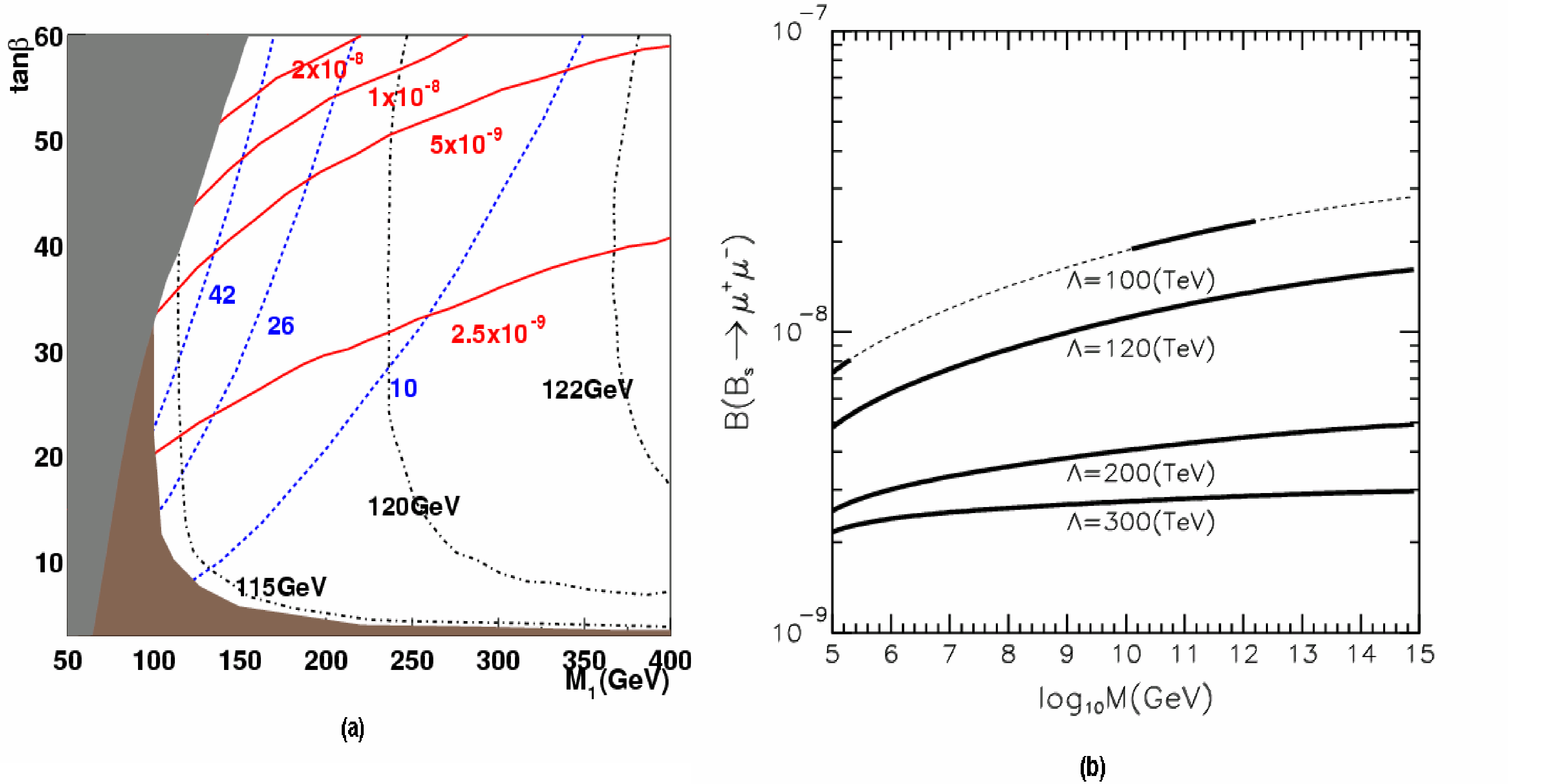


FIG. 2: (a) The contour plots for the a_μ^{SUSY}, m_{h^0}, and $B(B_s \to \mu^+\mu^-)$ with $N = 1$ and $M = 10^6$ GeV. (b) The branching ratio for $B_s \to \mu^+\mu^-$ as a function of the messenger scale M in the GMSB with $N = 1$ for various Λ's with a fixed $\tan\beta = 50$. The dashed parts are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

Electric Dipole Moments

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

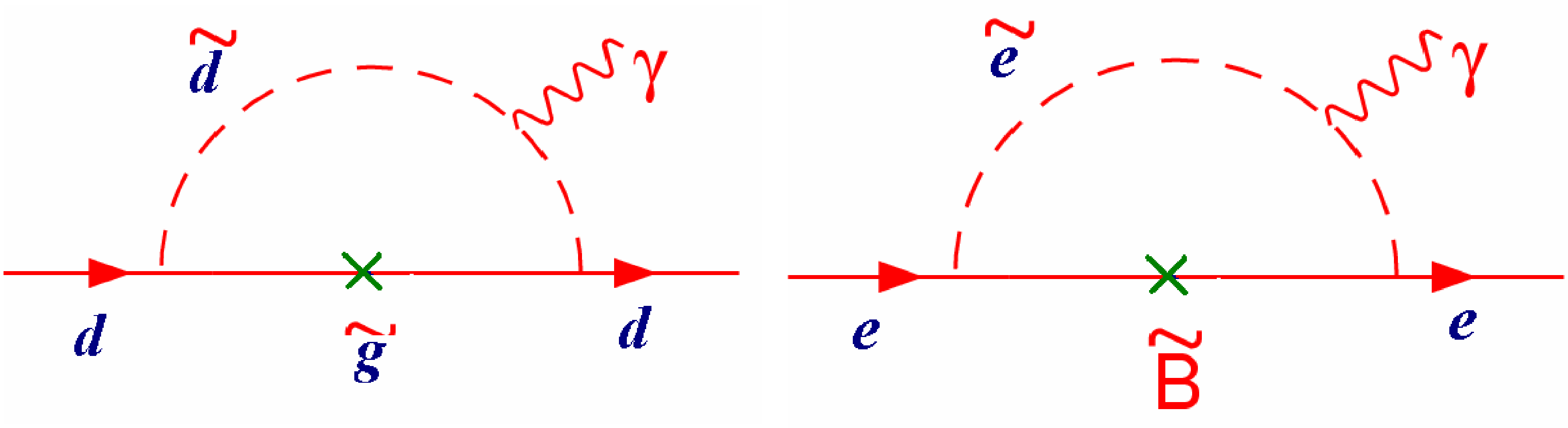
Violates CP

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,

$$Y_U, \;\; Y_D, \;\; Y_E \qquad \text{HERMITIAN}$$

$$A_U, \;\; A_D, \;\; A_E \qquad \text{HERMITIAN}$$

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

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

Flavor change in neutrino-sector

→ **Flavor change in charged leptons**

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

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

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**

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

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

$$\Downarrow$$

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

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

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

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

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

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

$$\mu \rightarrow e\gamma$$

$$\tau \rightarrow \mu\gamma$$

$$\tau \rightarrow e\gamma$$

Dirac LFV

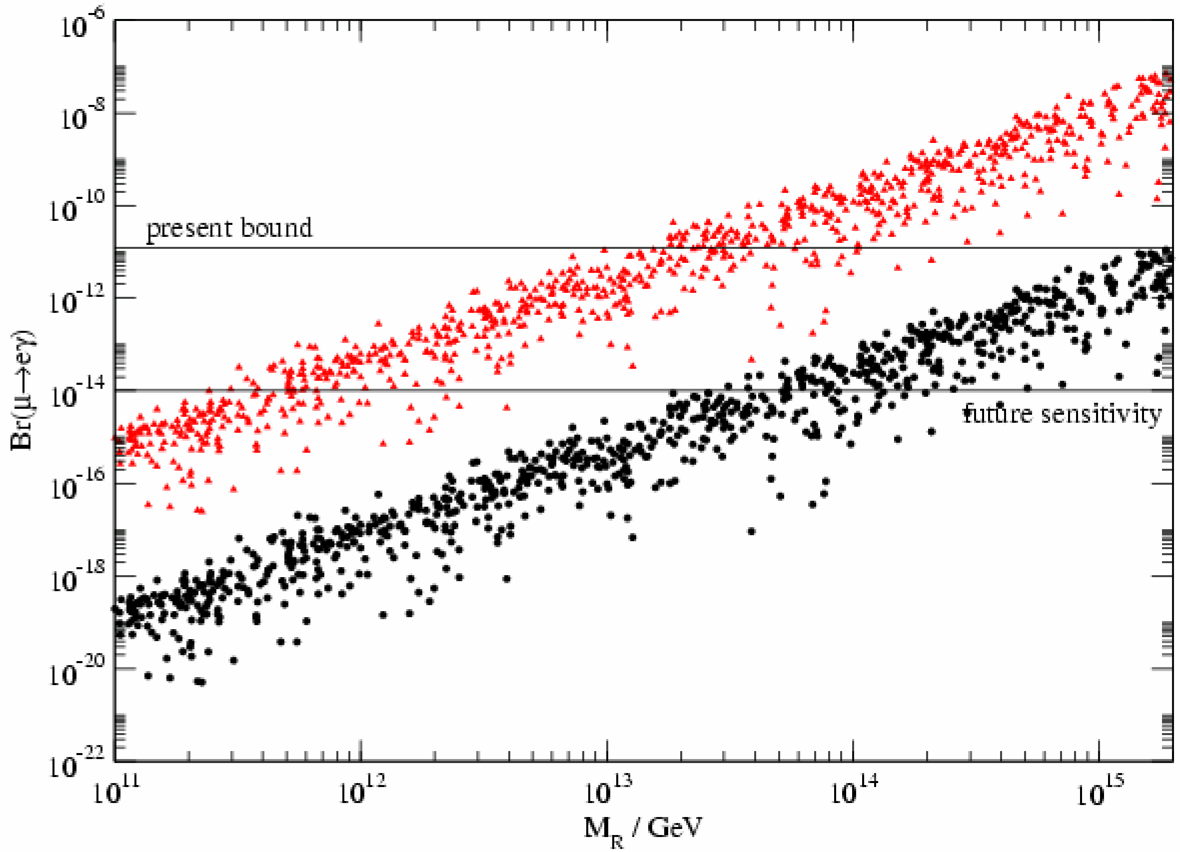
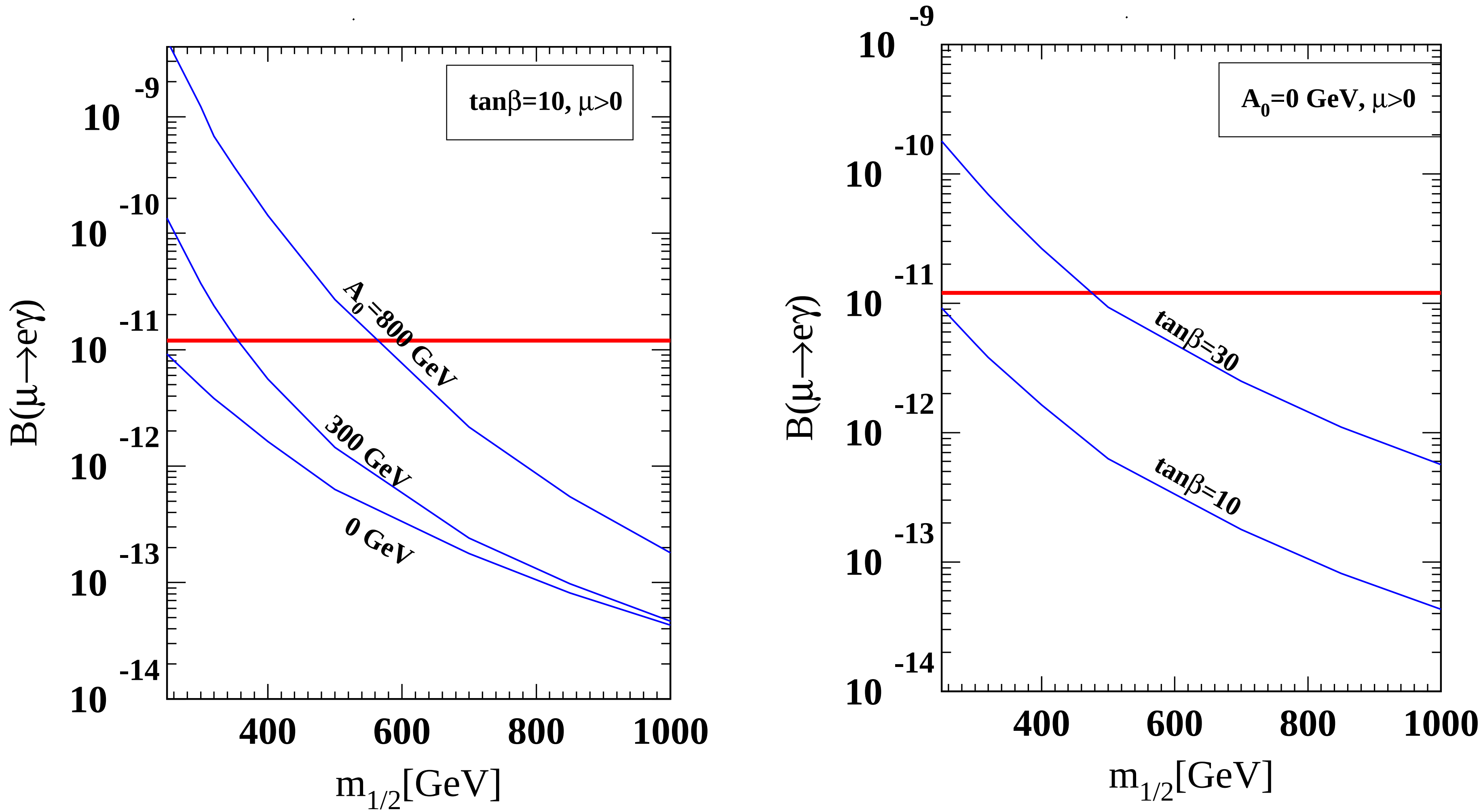


Figure 3: Branching ratio of $\mu \to e\gamma$ for hierarchical neutrinos and uncertainties of future neutrino experiments in the mSUGRA scenarios leading to the largest (L, upper) and the smallest (H, lower) LFV rates.

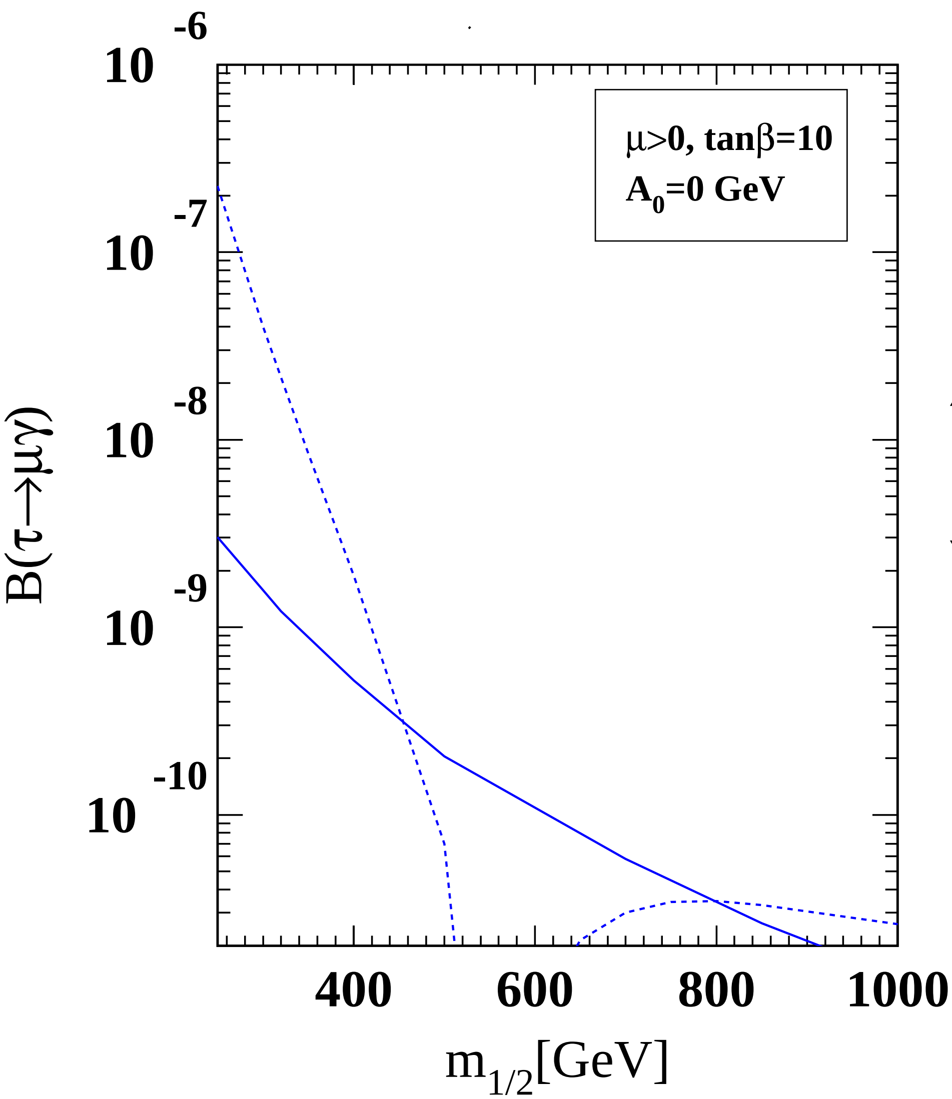
F. Deppisch, et al, hep-ph/0206122

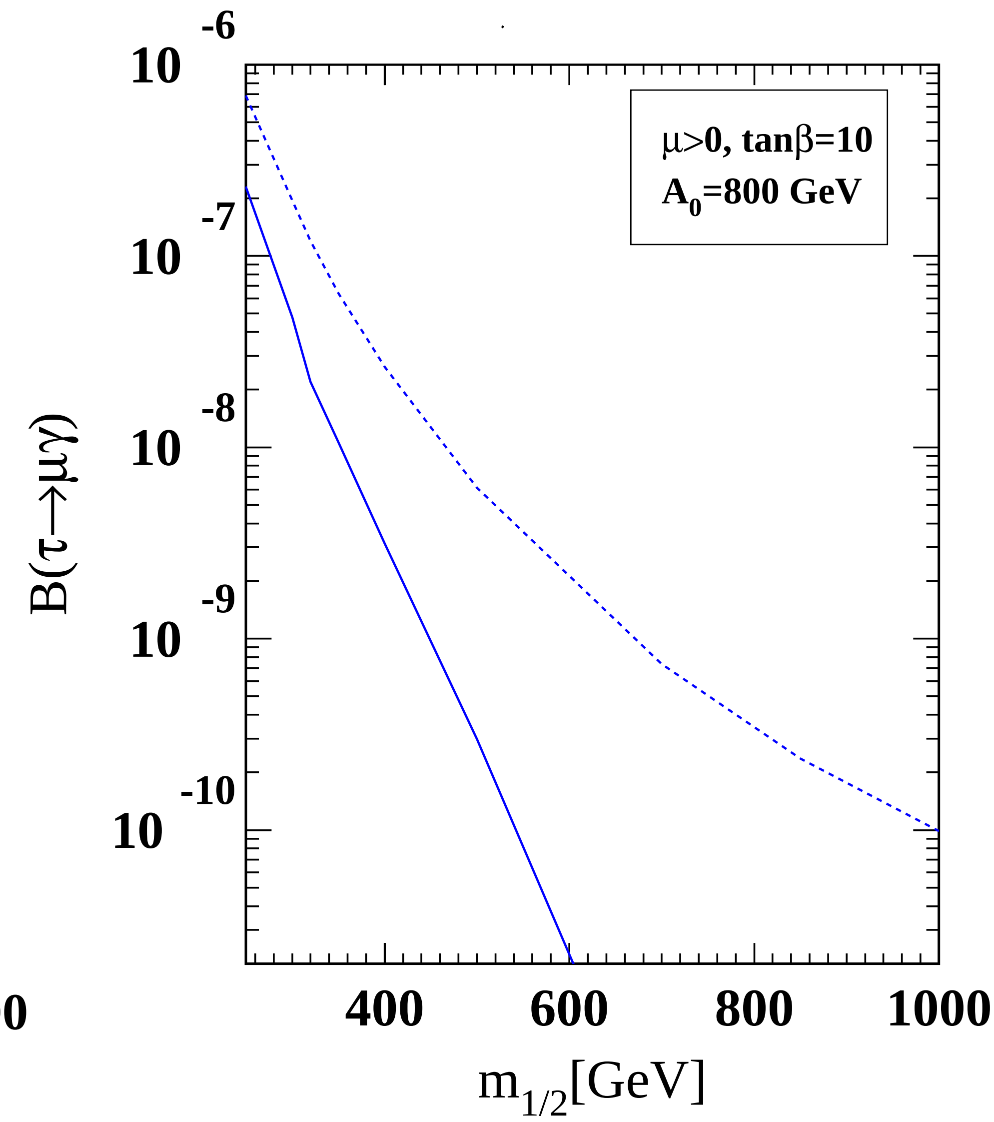
$\mu \to e\gamma$ Majorana LFV



Dutta, Mohapatra, KB (2002)

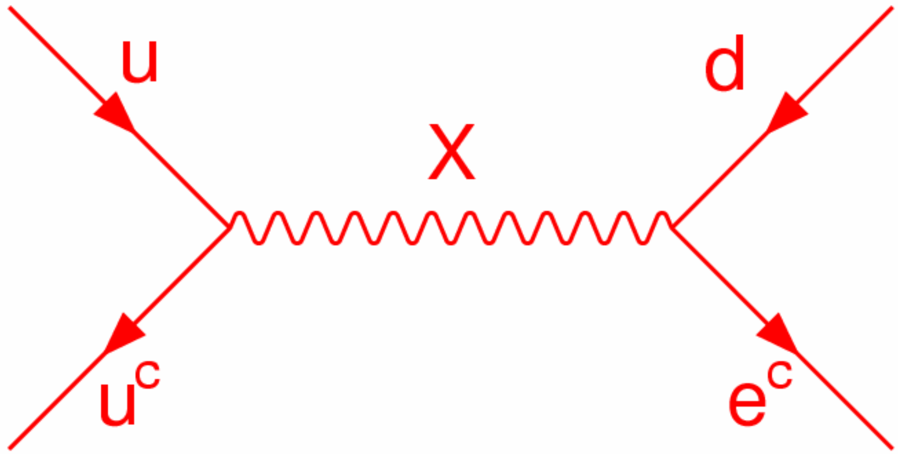
$\tau \to \mu\gamma$





Nucleon Decay in SUSY GUTs

Gauge boson Exchange

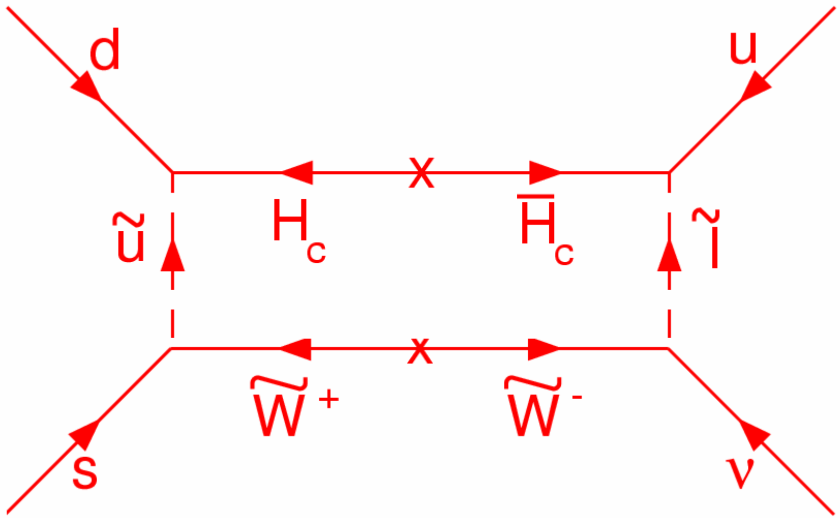


$$p \to e^+ \pi^0, \ \tau_p^{-1} \approx \left[\frac{g^2}{M_X^2}\right]^2 m_p^5 \approx [10^{36 \pm 1} yr]^{-1}$$

Higgsino Exchange

Sakai, Yanagida(1982)

Weinberg (1982)



$$p \to \bar{\nu} K^{+},$$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{34} yr]^{-1}$$

MSSM Higgs doublets have color triplet partners in GUTs.

$$H(1,2,1/2) \oplus H_c(3,1,-1/3) = \mathbf{5} \text{ of } SU(5)$$
$$\bar{H}(1,2,-1/2) \oplus \bar{H}_c(\bar{3},1,1/3) = \bar{\mathbf{5}}$$

$H, \ \bar{H}$ **must remain light**

$H_C, \bar{H}_C$ **must have GUT scale mass to prevent rapid proton decay**

⇩

Doublet-triplet splitting

Even if color triplets have GUT scale mass, d=5 proton decay is problematic.

Symmetry Breaking

SUSY SU(5)

$$W_{D-T} = \bar{\mathbf{5}}_H(\lambda \mathbf{24}_H + M)\mathbf{5}_H$$

$$< 24_H >= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -3/2 & 0 \\ 0 & 0 & 0 & 0 & -3/2 \end{pmatrix} V$$

FINE-TUNED TO $O(M_W)$

$$M_{H_c} = \lambda V + M \sim O(M_{GUT}) \quad M_H = -\frac{3}{2}\lambda V + M$$

The GOOD

(1) Predicts unification of couplings

(2) Uses economic Higgs sector

The BAD

(1) Unnatural fine tuning

(2) Large proton decay rate

SUSY SO(10)

$$W_{D-T} = \lambda(\bar{10}_H 45_H 10'_H) + \ldots$$

$$< 45_H >= \begin{pmatrix} a & 0 & 0 & 0 & 0 \\ 0 & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \otimes i\tau_2 \quad \propto B - L$$

⇨ B-L VEV gives mass to triplets only (DIMOPOULOS-WILCZEK)

⇨ If 10_H only couples to fermions, no d=5 proton decay

⇨ Doublets from 10_H and $10'_H$ light

4 doublets, unification upset

⇩

Add mass term for $10'_H$

$$W_{D-T} = \lambda(\bar{10}_H 45_H 10'_H) + M 10'_H 10'_H$$

SO(10)

- ☆ **Quarks and leptons ~{*16$_i$*}**
- ☆ **Contains ν_R and Seesaw mechanism**
- ☆ **Higgs** ~ $\{45_H + 16_H + \bar{16}_H + 10_H\}$

$$\mathcal{L}_{Yukawa} = f_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H$$

$$\Longrightarrow \quad M_{up} = M_\nu^D;\ M_d = M_l \text{ also } M_{Up} \propto M_{down}$$

$$\mathcal{L}_{Majorana} = h_{ij}16_i16_j\bar{16}_H\bar{16}_H/M_{Pl}$$

$$\Longrightarrow \quad m^D_{\nu_\tau} \simeq m_t;\ m^M_{\nu_{\tau R}} \simeq h_{33}\frac{M^2_{GUT}}{M_{Pl}}$$

$$m_{\nu_\tau} = \frac{m_t^2}{m_{\nu_{\tau R}}} \simeq 0.05 \text{ eV},\ h_{33} \sim 1$$

⇧ *Fits the atmospheric neutrino data well*

Realistic SO(10) Model

Pati, Wilczek, KB (1998)

$$U = \begin{pmatrix} 0 & \epsilon' & 0 \\ -\epsilon' & 0 & \epsilon + \sigma \\ 0 & -\epsilon + \sigma & 1 \end{pmatrix} m_U, \quad D = \begin{pmatrix} 0 & \epsilon' + \eta' & 0 \\ -\epsilon' + \eta' & 0 & \epsilon + \eta \\ 0 & -\epsilon + \eta & 1 \end{pmatrix} m_D,$$

$$N = \begin{pmatrix} 0 & -3\epsilon' & 0 \\ 3\epsilon' & 0 & -3\epsilon + \sigma \\ 0 & 3\epsilon + \sigma & 1 \end{pmatrix} m_U, \quad L = \begin{pmatrix} 0 & -3\epsilon' + \eta' & 0 \\ 3\epsilon' + \eta' & 0 & -3\epsilon + \eta \\ 0 & 3\epsilon + \eta & 1 \end{pmatrix} m_D$$

$$M_\nu^R = \begin{pmatrix} x & 0 & z \\ 0 & 0 & y \\ z & y & 1 \end{pmatrix} M_R$$

$$\begin{aligned} "1" &: \ 16_3 16_3 10_H \\ "\epsilon" &: \ 16_2 16_3 (10_H \times 45_H)/M \\ "\sigma" &: \ 16_2 16_3 (10_H \times 1_H)/M \\ "\eta" &: \ 16_2 16_3 16_H 16_H / M \end{aligned}$$

$$< 45_H > \propto (B - L)$$

Predictions

$$m_b^0 \approx m_\tau^0$$

$$m_s(1GeV) \approx 116MeV$$

$$V_{cb} \approx 0.043$$

$$\sin^2 2\theta_{\mu\tau} = (0.96,\ 0.91,\ 0.86,\ 0.83\ ,0.81)$$

$$\frac{m_{\nu_\mu}}{m_{\nu_\tau}} = (1/10,\ 1/15,\ 1/20,\ 1/25,\ 1/30)$$

$$m_d(1GeV) \approx 8MeV$$

$$\theta_c \approx |\sqrt{m_d/m_s} - e^{i\phi}\sqrt{m_u/m_c}|$$

$$|\frac{V_{us}}{V_{cs}}| \approx \sqrt{\frac{m_u}{m_c}} \approx 0.07$$

$$\tau(p \to \bar{\nu} K^+) \lesssim 10^{34}\ \text{yr}$$

$$Br(p \to \mu^+ K^0) \sim 10\%$$

Conclusions

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