

Supersymmetry and Its Experimental Tests

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DPF 2003

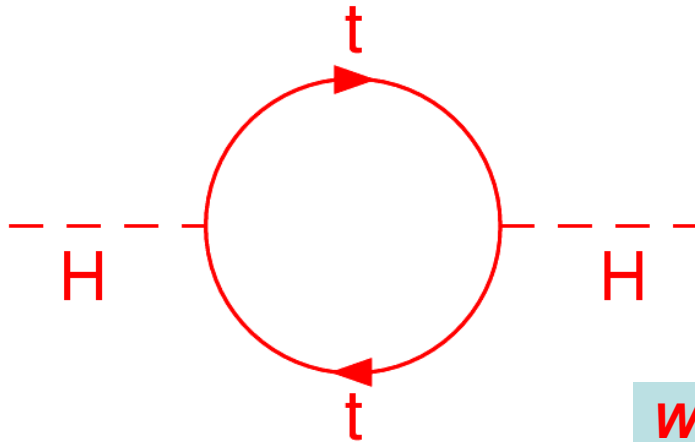
**Annual Meeting Of The Division Of Particles And Fields (DPF)
Of The American Physical Society (APS)**

Philadelphia, April 6, 2003

Outline

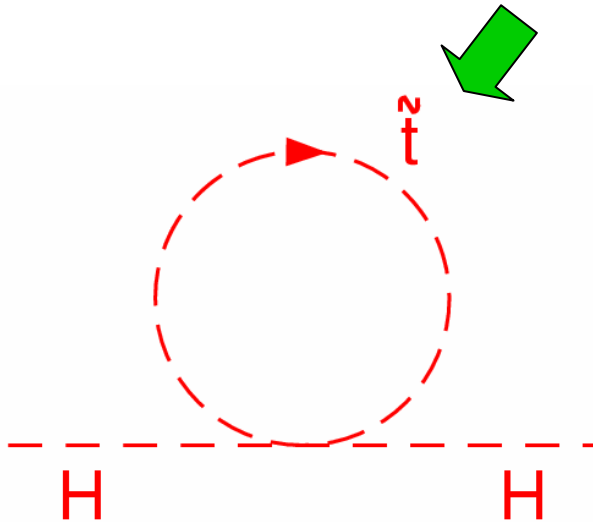
- ☆ Motivations
- ☆ Supersymmetry Breaking
- ☆ Direct Tests at Colliders
- ☆ Indirect Tests
 - *Rare B Decays*
 - *Dipole Moments*
 - *Lepton Flavor Violation*
- ☆ SUSY GUTs and Proton Decay
- ☆ Conclusions

Stability of Higgs Mass



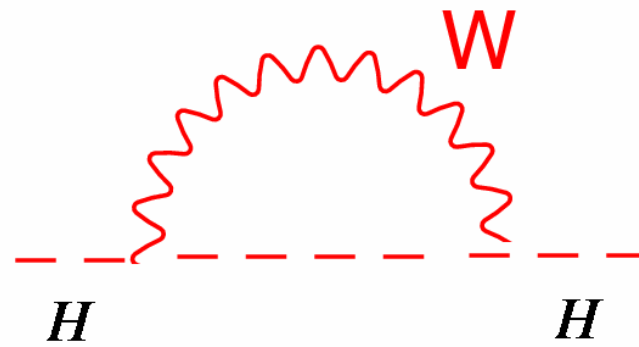
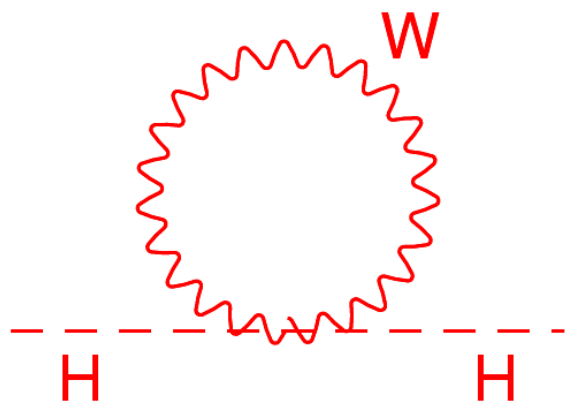
$$\Delta m_H^2 = -\frac{\lambda_t^2}{8\pi^2} \Lambda^2$$

With SUSY, Quadratic Divergence Cancels

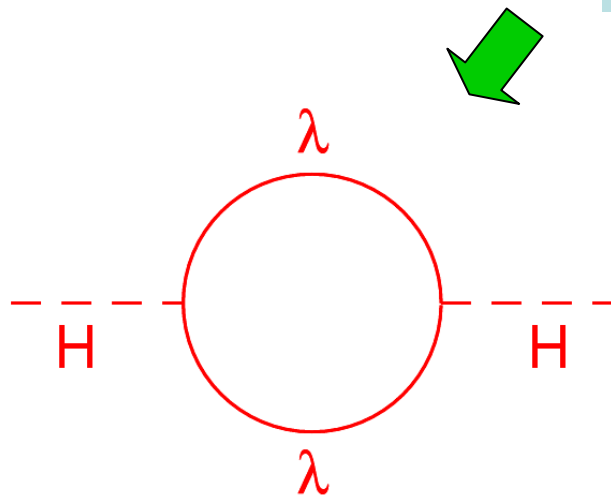


$$\Delta m_H^2 = +\frac{\lambda_t^2}{8\pi^2} \Lambda^2$$

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



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

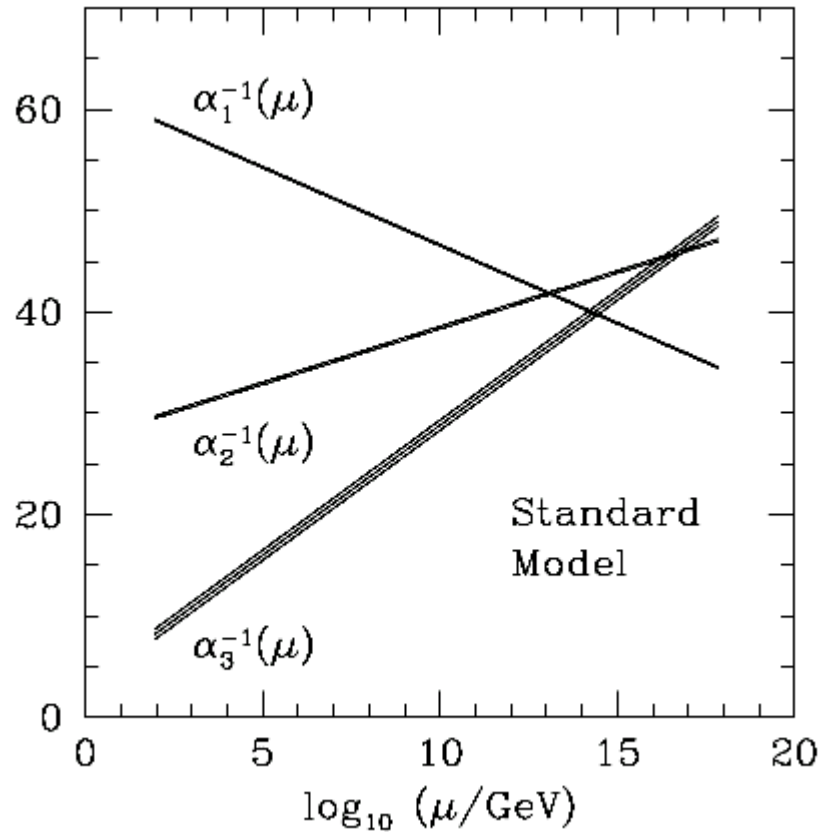


SUSY Spectrum

SM Particles		SUSY Partners	
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

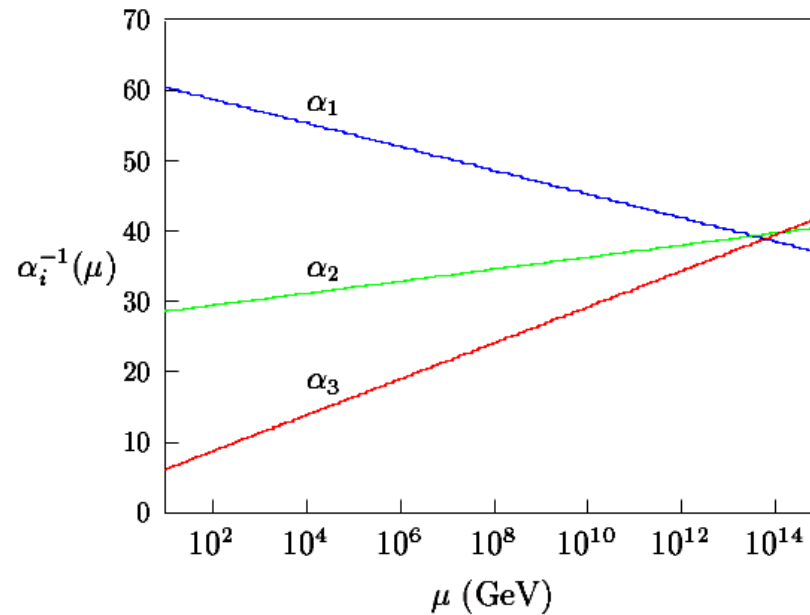
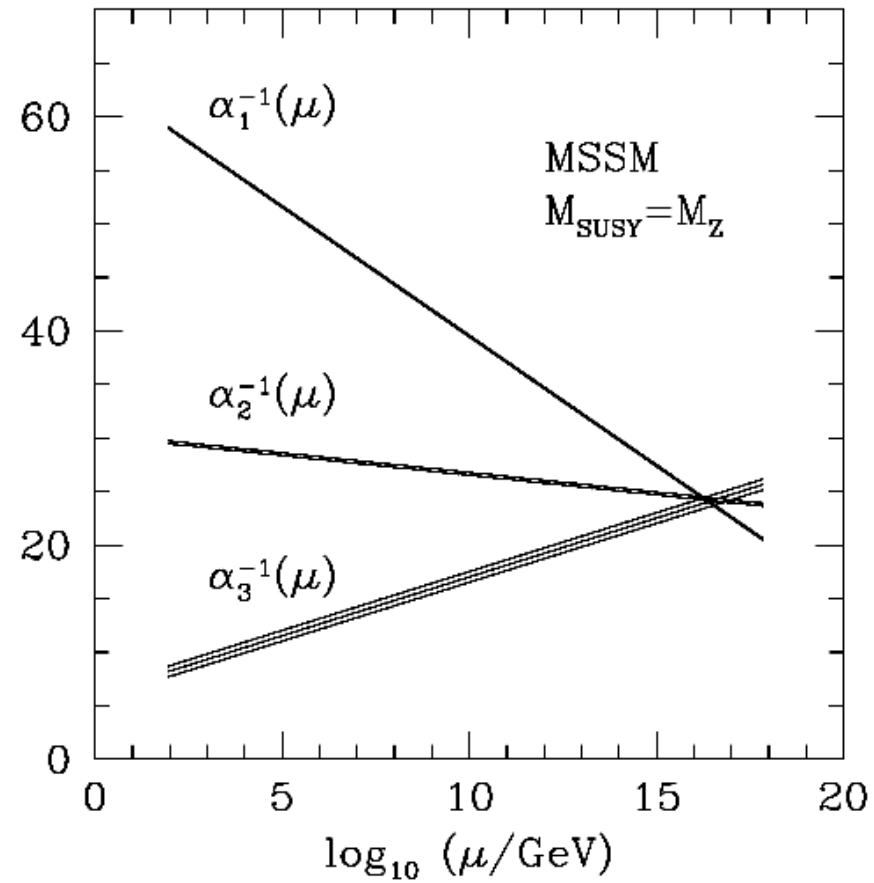


Figure 1: Leading-order evolution of the gauge couplings from their low-energy values to the unification scale in the six-Higgs-doublet standard model. The couplings meet around 10^{14} GeV, within the accuracy of a leading-order calculation.

Gauge Coupling Unification in MSSM



Structure of Matter Multiplets

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

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

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

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

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

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

$$\begin{aligned}
u_1 & : & | \uparrow \downarrow \uparrow \uparrow \downarrow \rangle \\
u_2 & : & | \uparrow \downarrow \uparrow \downarrow \uparrow \rangle \\
u_3 & : & | \uparrow \downarrow \downarrow \uparrow \uparrow \rangle \\
d_1 & : & | \downarrow \uparrow \uparrow \uparrow \downarrow \rangle \\
d_2 & : & | \downarrow \uparrow \uparrow \downarrow \uparrow \rangle \\
d_3 & : & | \downarrow \uparrow \downarrow \uparrow \uparrow \rangle \\
u_1^c & : & | \downarrow \downarrow \uparrow \downarrow \downarrow \rangle \\
u_2^c & : & | \downarrow \downarrow \downarrow \uparrow \downarrow \rangle \\
u_3^c & : & | \downarrow \downarrow \downarrow \downarrow \uparrow \rangle \\
d_1^c & : & | \uparrow \uparrow \uparrow \downarrow \downarrow \rangle \\
d_2^c & : & | \uparrow \uparrow \downarrow \uparrow \downarrow \rangle \\
d_3^c & : & | \uparrow \uparrow \downarrow \downarrow \uparrow \rangle \\
\nu & : & | \uparrow \downarrow \downarrow \downarrow \downarrow \rangle \\
e & : & | \downarrow \uparrow \downarrow \downarrow \downarrow \rangle \\
e^c & : & | \downarrow \downarrow \uparrow \uparrow \uparrow \rangle \\
\nu^c & : & | \uparrow \uparrow \uparrow \uparrow \uparrow \rangle
\end{aligned}$$

MSSM Lagrangian

$$W = Qu^c H_u + Qd^c H_d + Le^c H_d \\ + L\nu^c H_u + M_R \nu^c \nu^c + \mu H_u H_d$$

 $\mu \sim 10^2 \text{ GeV}$

R-parity Violation: Potentially Dangerous Proton Decay

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

Soft SUSY Breaking:

$$\mathcal{L}_{SUSY} = \sum m_\phi^2 \phi^\dagger \phi + A_u \tilde{Q} \tilde{u}^c H_u + A_d \tilde{Q} \tilde{d}^c H_d \\ + A_l \tilde{L} \tilde{e}^c H_d + A_\nu \tilde{L} \tilde{\nu}^c H_u \\ + B\mu H_u H_d + \sum M_\lambda \lambda \lambda$$

Generic soft breaking leads to large flavor violation

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

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

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

L. Krauss, F. Wilczek, (1989)

L. Ibanez, G. Ross, (1991)

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

T. Banks, M. Dine, (1992)

Green-Schwarz Anomaly Cancellation Mechanism For Z_N

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

Guidice-Masiero Mechanism

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

SUSY Breaking Scenarios

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

mSUGRA

Neutralino LSP Stable



(Dark Matter)

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

GMSB

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



LSP : Gravitino

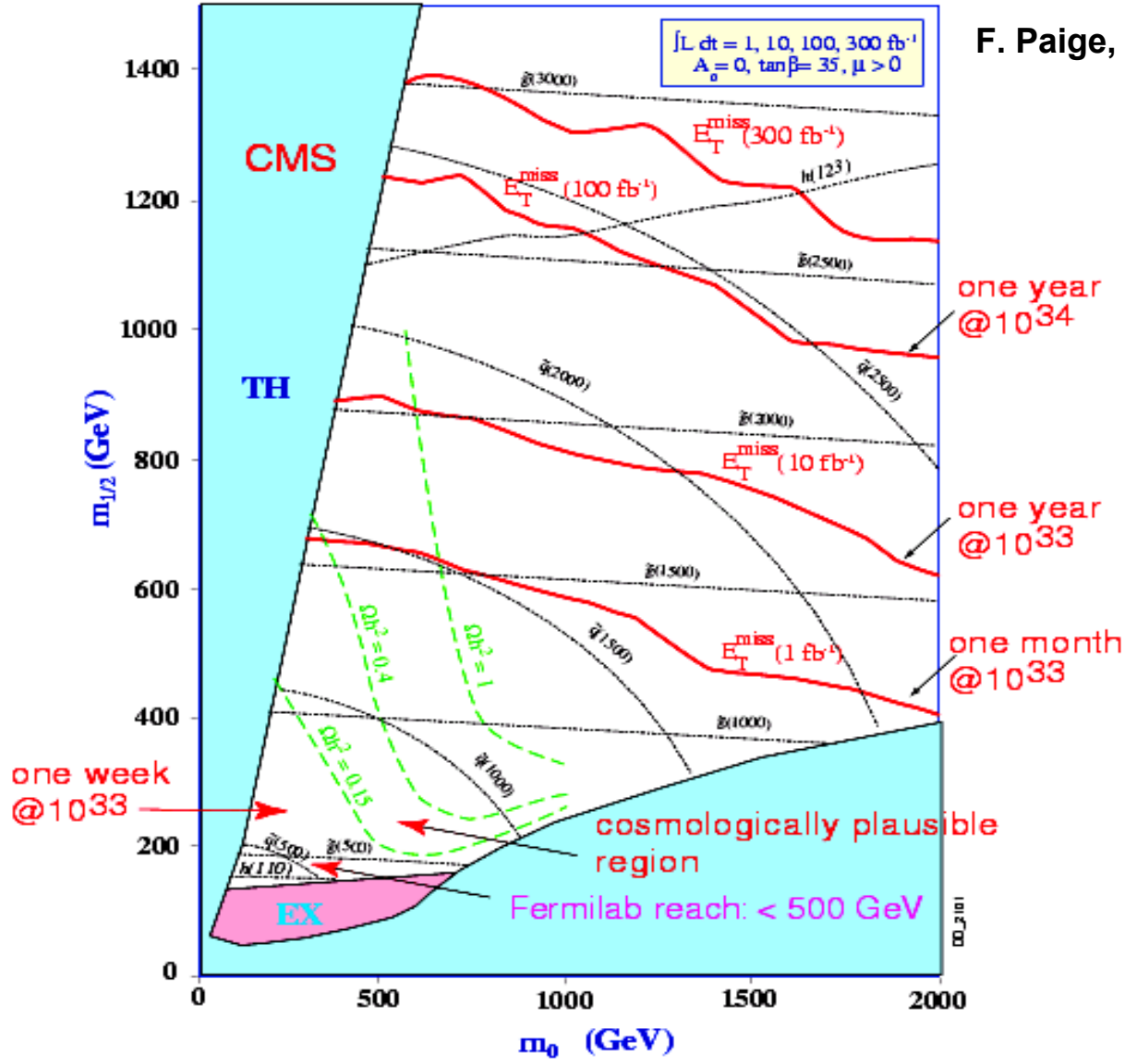


Figure 1: Plot of 5σ reach in jets + E_T^{miss} channel for mSUGRA model .

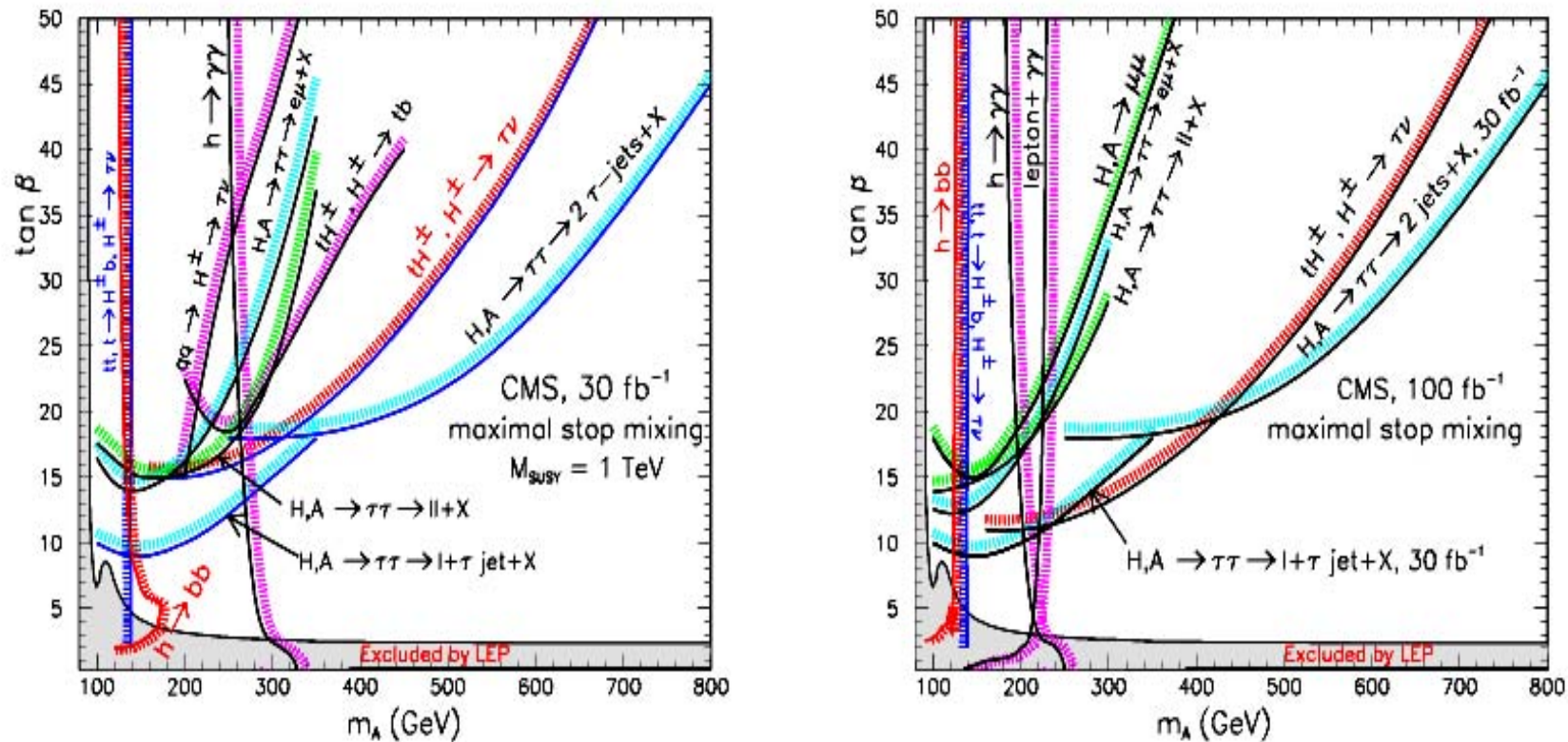


Fig. 6. Expected 5σ discovery limits of various MSSM Higgs signals at LHC for luminosities of 30 fb^{-1} and 100 fb^{-1} .

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

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

Kolda, KB (1999)

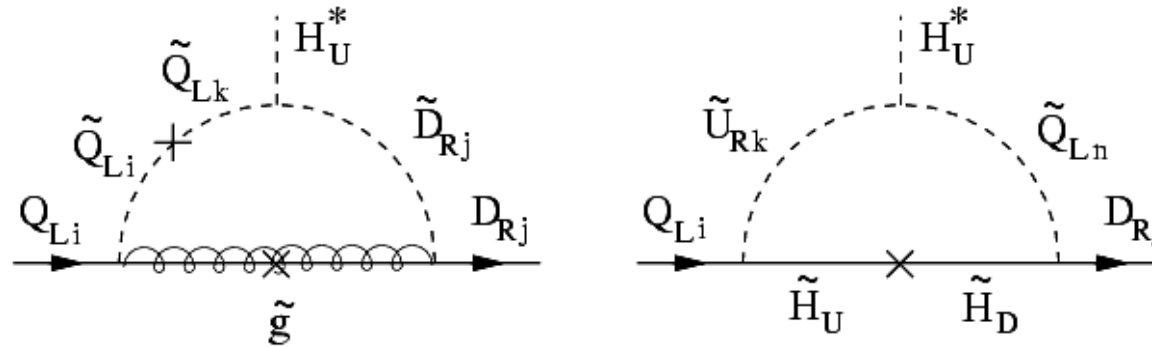
$$-\mathcal{L}_{eff} = \bar{D}_R Y_D Q_L H_d + \bar{D}_R Y_D \left[\epsilon_g + \epsilon_u Y_U^\dagger Y_U \right] Q_L H_u^* + h.c. + \dots$$

MSSM is a general two-Higgs-doublet model.

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

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

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



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

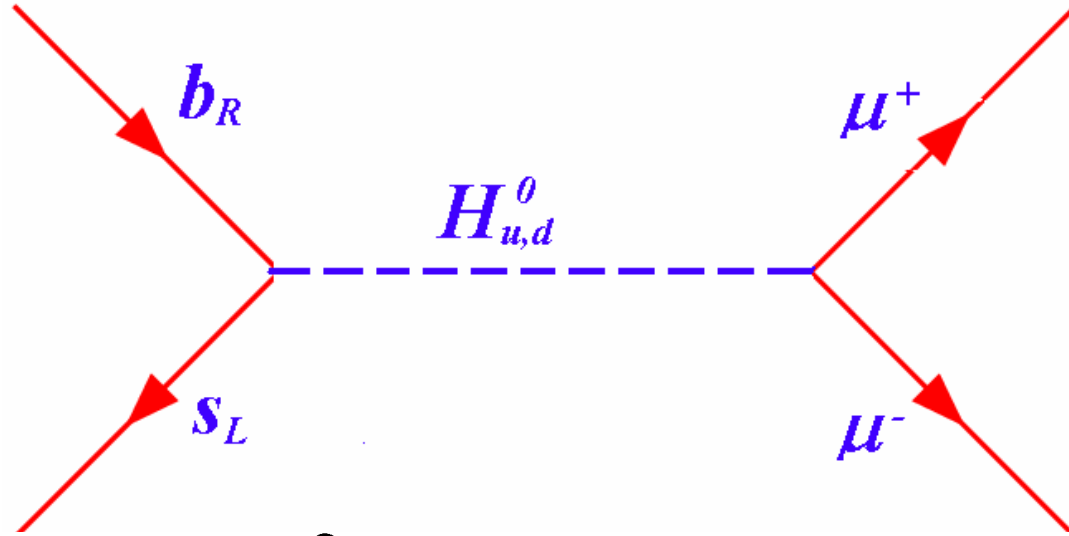
$$\epsilon_g \simeq \frac{2\alpha_3}{3\pi} (\mu^* M_3 f(M_3^2, M_{\tilde{Q}_L}^2, M_{\tilde{d}_R}^2))$$

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

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

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

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



$$\Gamma(B_{(d,s)}^0 \rightarrow \mu^+ \mu^-) = \frac{\eta_{QCD}^2}{128\pi} m_B^3 f_B^2 \bar{y}_b^2 y_\mu^2 |V_{t(d,s)}^* V_{tb}|^2 \chi_{FC}^2 (a_1^2 + a_2^2)$$

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

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

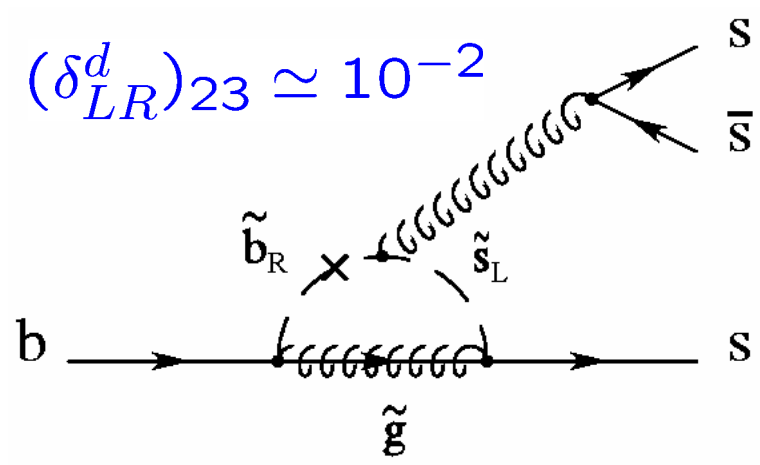
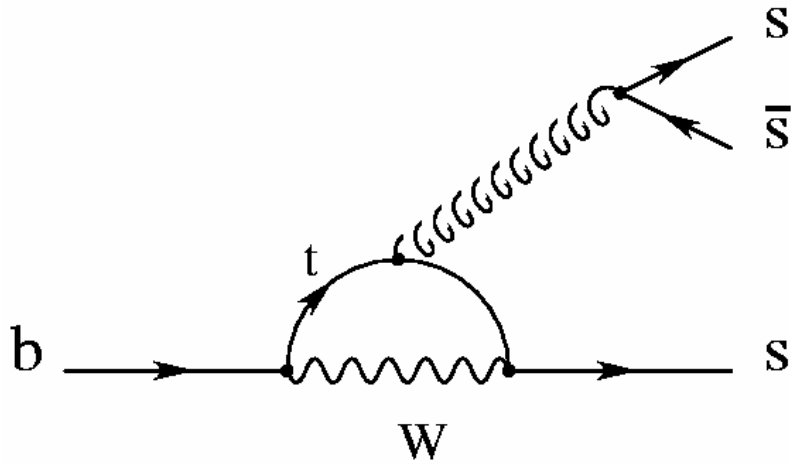
SUSY CP Violation in $B_d \rightarrow \phi K_S$ Decay

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

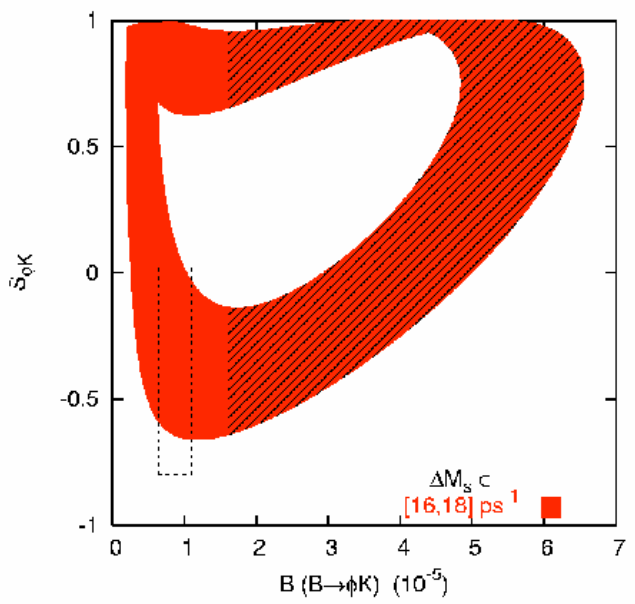
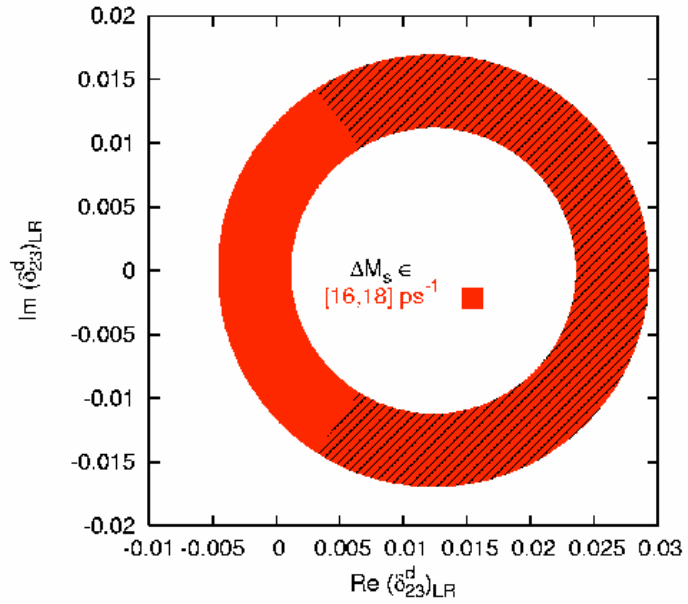
$$\begin{aligned} \mathcal{A}_{\phi K}(t) &\equiv \frac{\Gamma(\bar{B}_{\text{phys}}^0(t) \rightarrow \phi K_S) - \Gamma(B_{\text{phys}}^0(t) \rightarrow \phi K_S)}{\Gamma(\bar{B}_{\text{phys}}^0(t) \rightarrow \phi K_S) + \Gamma(B_{\text{phys}}^0(t) \rightarrow \phi K_S)} \\ &= -C_{\phi K} \cos(\Delta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

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

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



$$(\delta_{LR}^d)_{23} \simeq 10^{-2}$$



(a) Allowed region for the LR insertion

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

Lepton Dipole Moments

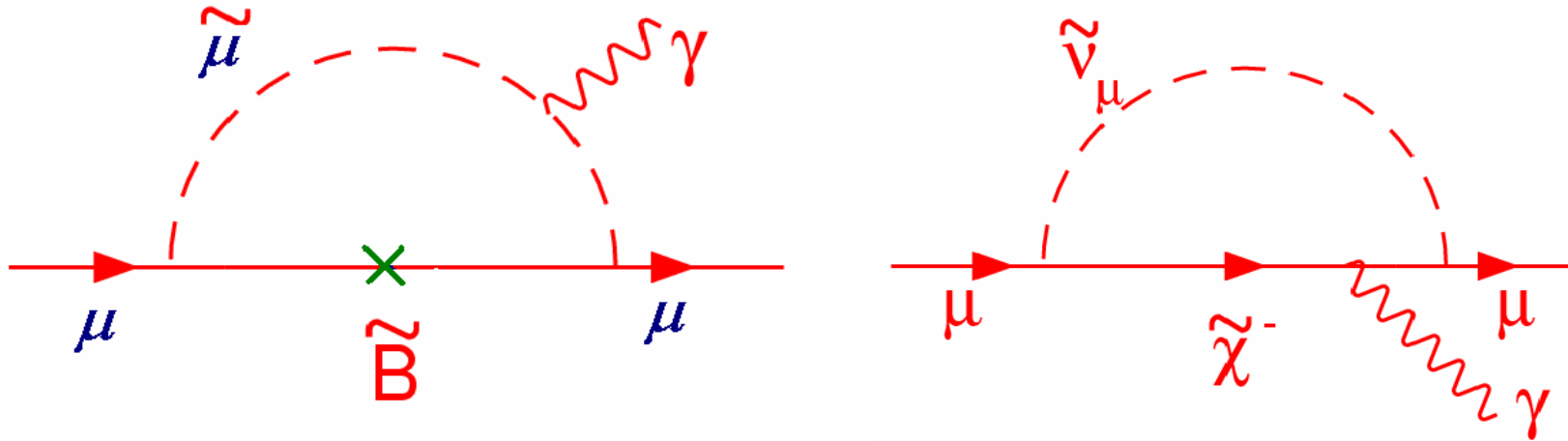
$$\mathcal{L}_{eff} = \frac{a_\mu}{2m_\mu} \bar{\psi} \sigma^{\mu\nu} \psi F_{\mu\nu}$$

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

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

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

SUSY Contributions:



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

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

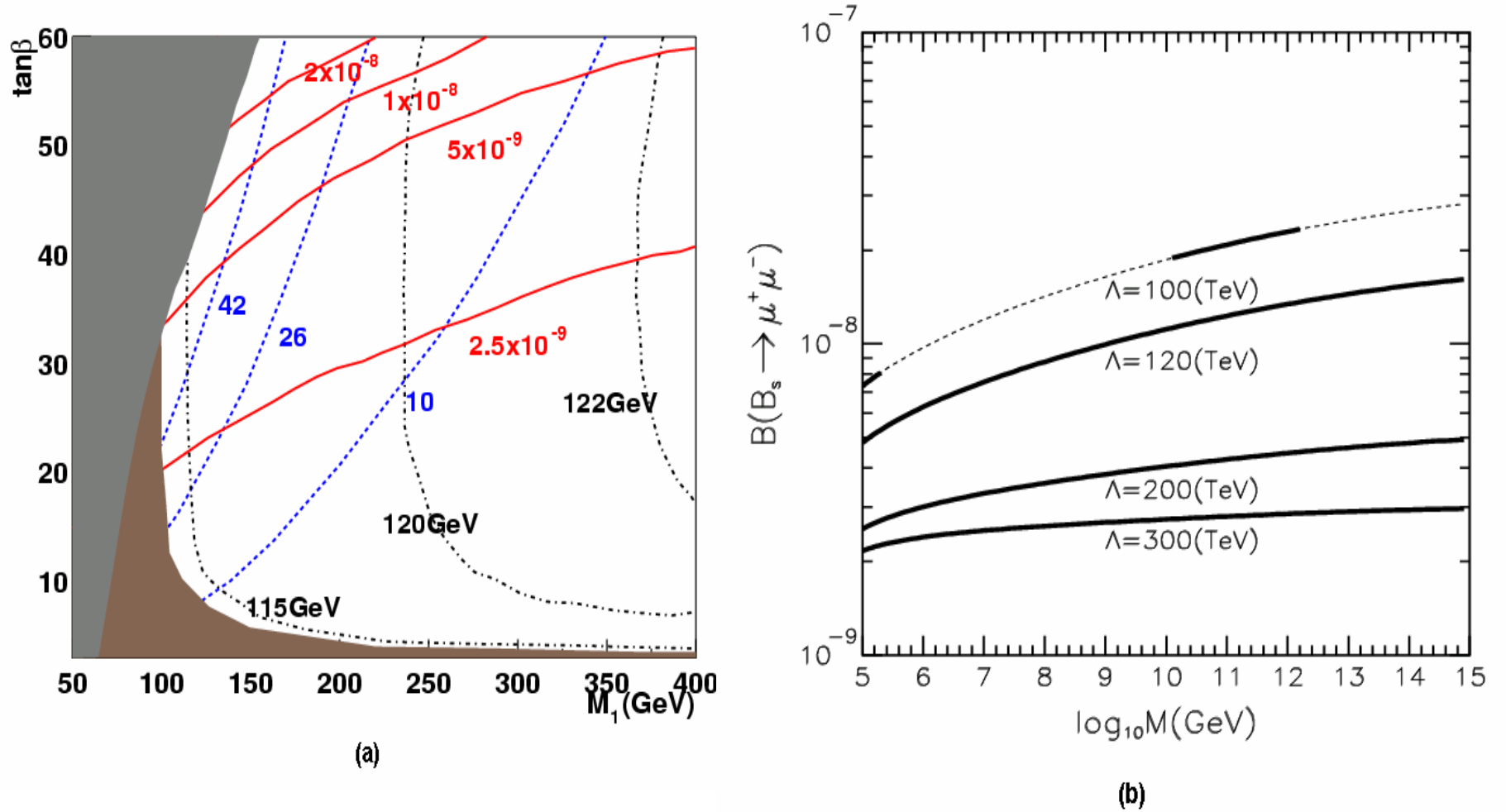


FIG. 2: (a) The contour plots for the a_μ^{SUSY} , m_{h^0} , and $B(B_s \rightarrow \mu^+ \mu^-)$ with $N = 1$ and $M = 10^6$ GeV. (b) The branching ratio for $B_s \rightarrow \mu^+ \mu^-$ as a function of the messenger scale M in the GMSB with $N = 1$ for various Λ 's with a fixed $\tan\beta = 50$.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

Electric Dipole Moments

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

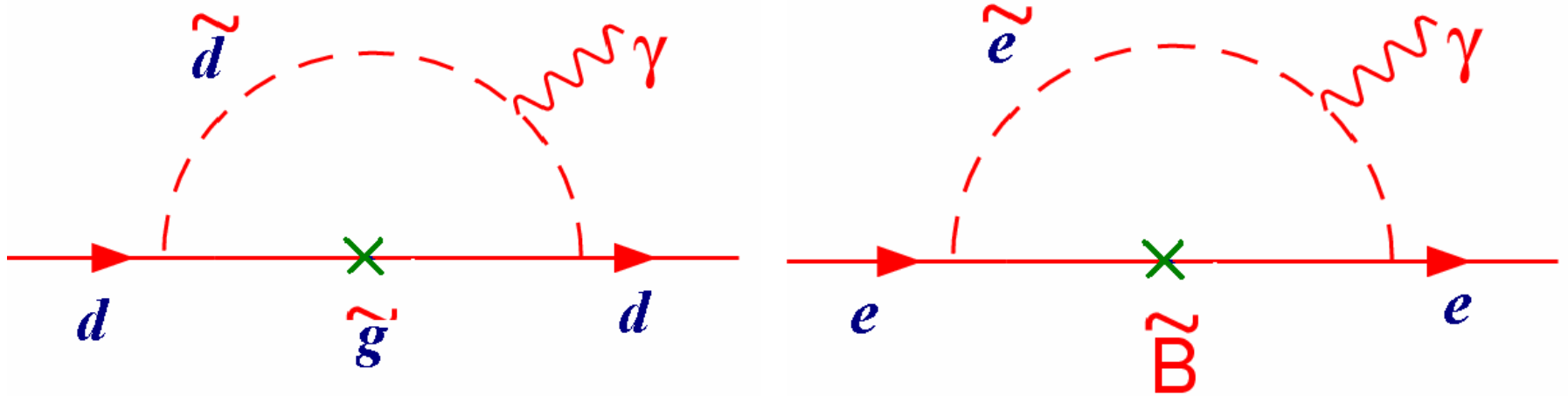
Violates CP

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

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

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

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



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

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

Flavor change in neutrino-sector



Flavor change in charged leptons

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

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

In Supersymmetric Standard model

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

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

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

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

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)

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

If flavor violation occurs only in f (Majorana LFV)

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

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

LFV in the two scenarios are comparable.

More detailed study is needed.

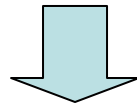
Neutrino Fit

For Majorana LFV scenario, take

Dutta, Mohapatra, KB 2002

$$m_d \propto \text{diag}[c\epsilon^3, \epsilon, 1] \quad \epsilon \sim 1/10$$

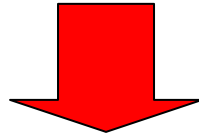
$$\mathcal{M}_\nu = m_0 \begin{pmatrix} e\epsilon^n & h\epsilon^m & d\epsilon \\ h\epsilon^m & 1 + a\epsilon & 1 \\ d\epsilon & 1 & 1 + b\epsilon \end{pmatrix}$$



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

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

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



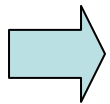
$$(m_1, m_2, m_3) = (-2.7 \times 10^{-3}, 6.4 \times 10^{-3}, 8.6 \times 10^{-2}) \text{ eV}$$

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

For Dirac LFV scenario

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

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



Same neutrino oscillation parameters as in Majorana LFV

The two scenarios differ in predictions for

$$\mu \rightarrow e\gamma$$

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

$$\tau \rightarrow e\gamma$$

Dirac LFV

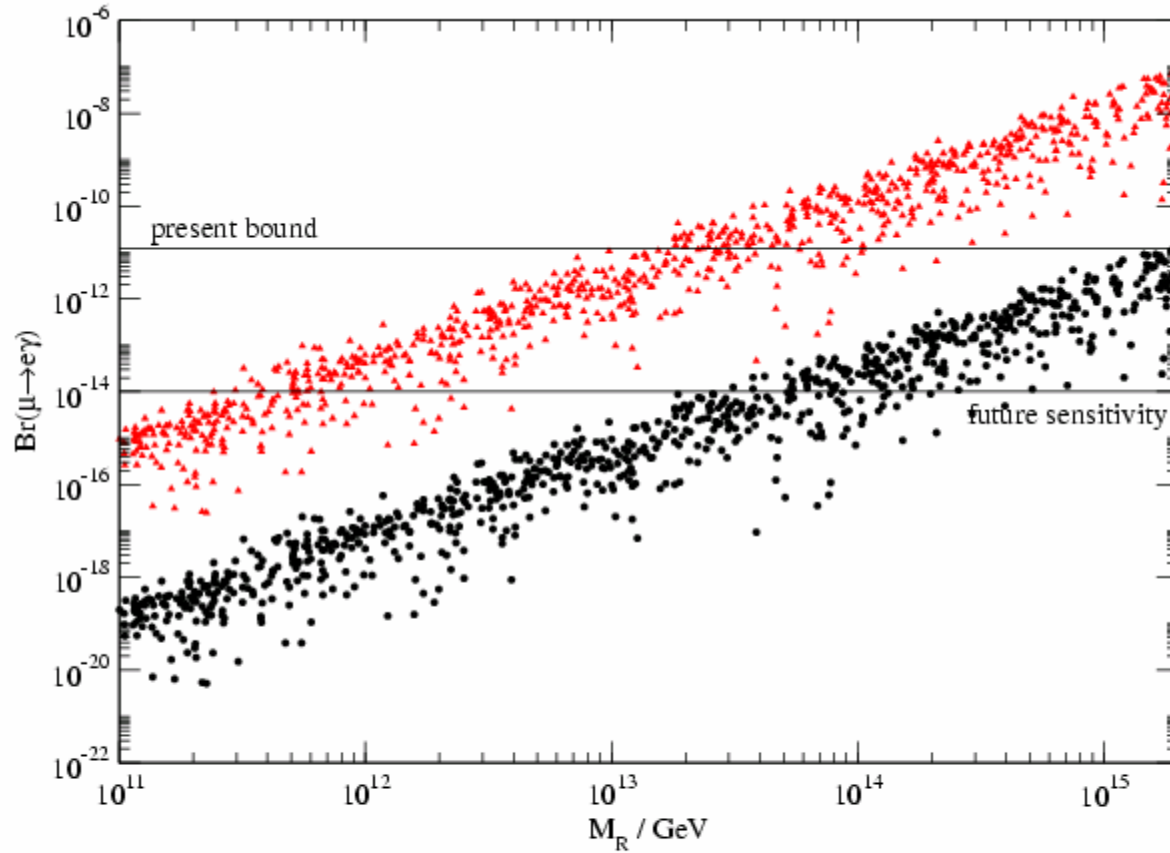
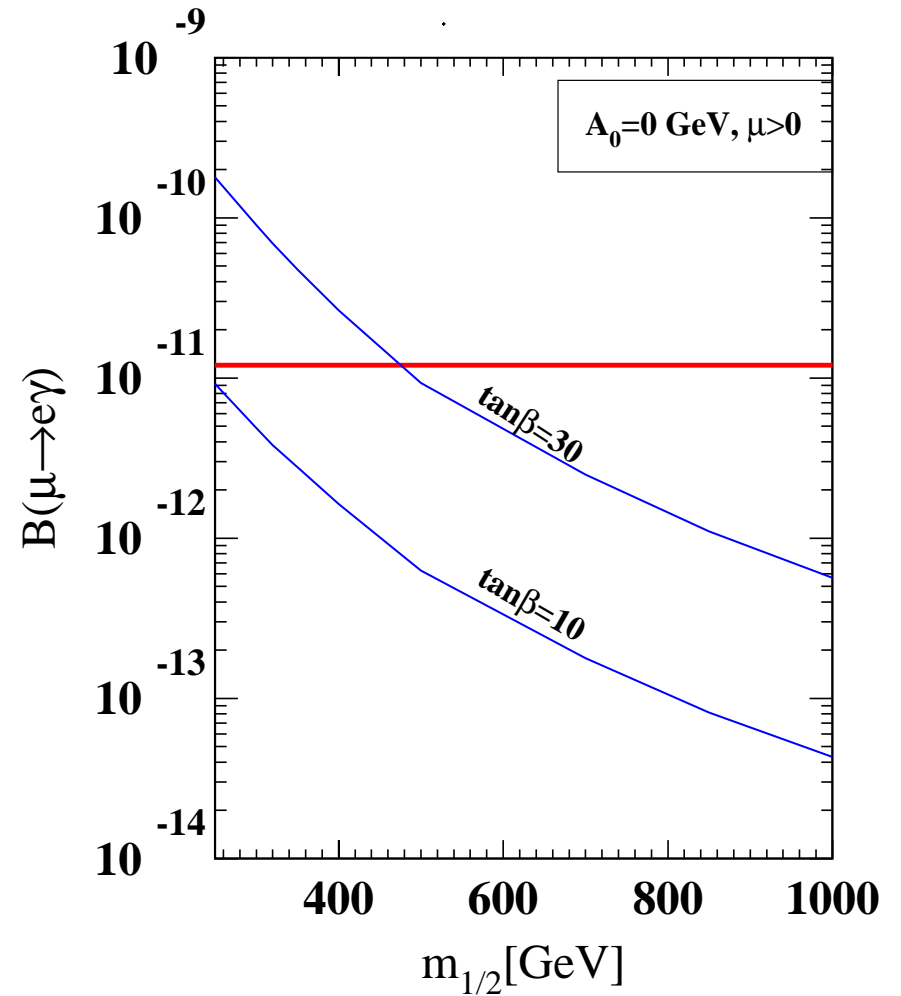
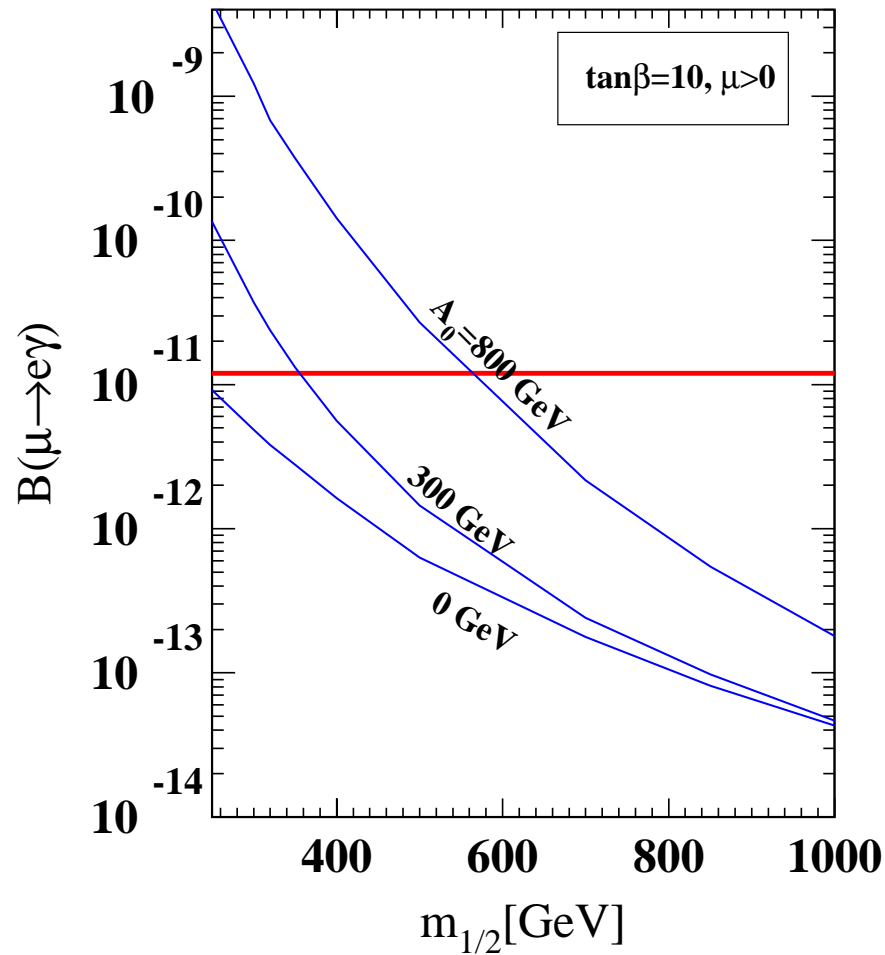
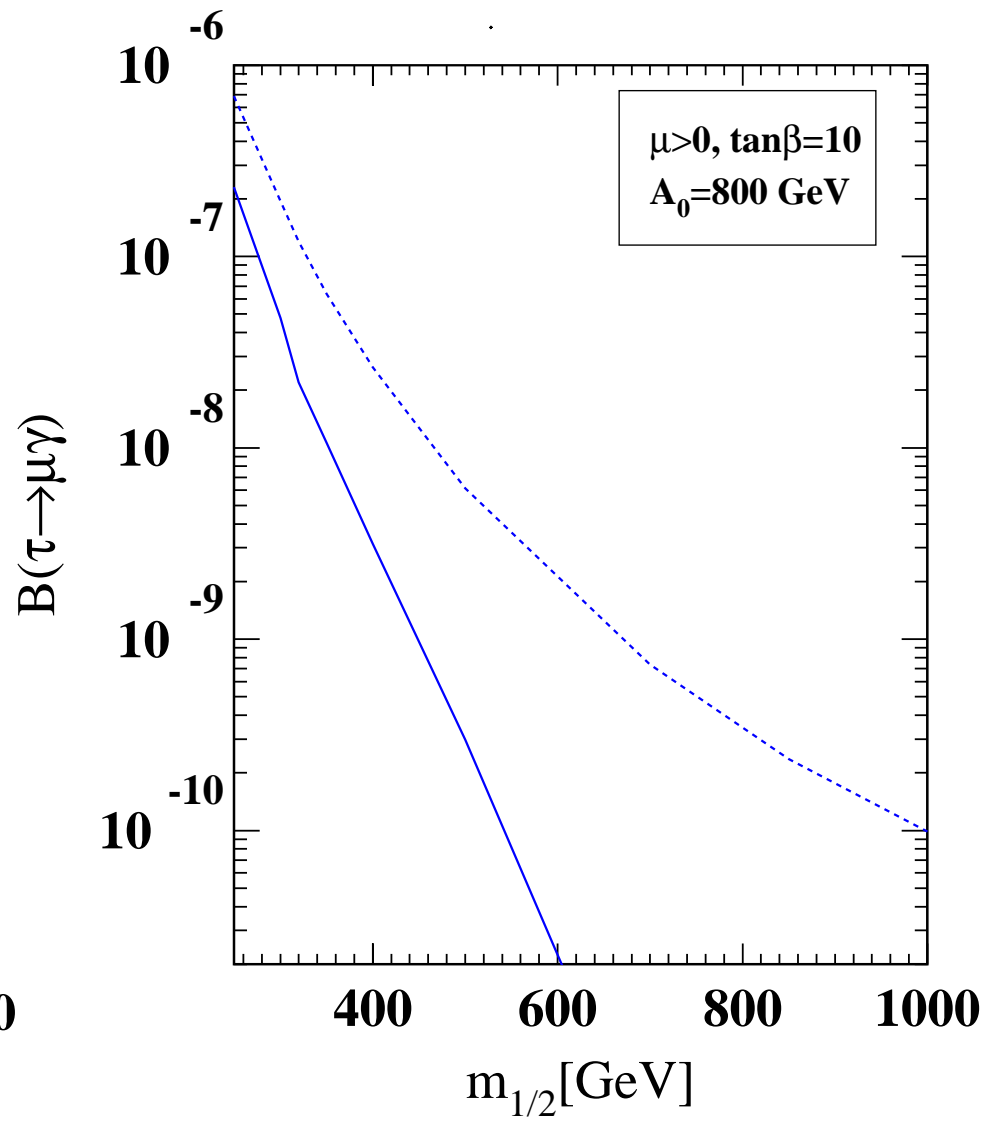
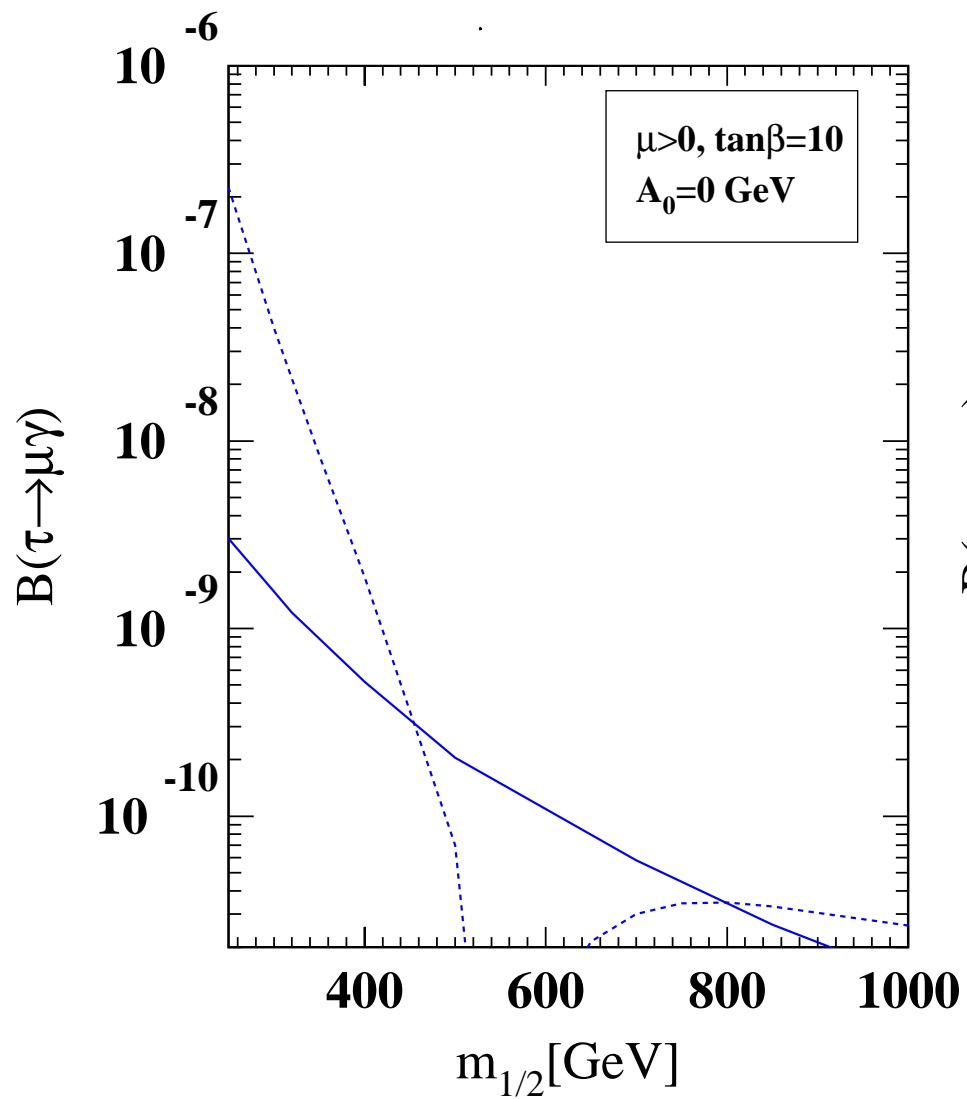


Figure 3: Branching ratio of $\mu \rightarrow e\gamma$ for hierarchical neutrinos and uncertainties of future neutrino experiments in the mSUGRA scenarios leading to the largest (L, upper) and the smallest (H, lower) LFV rates.

$\mu \rightarrow e\gamma$ Majorana LFV

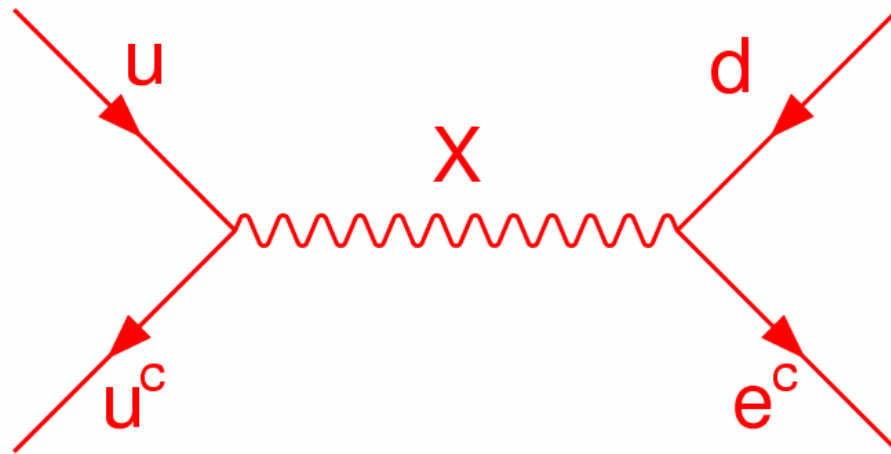


$\tau \rightarrow \mu \gamma$



Nucleon Decay in SUSY GUTs

Gauge boson Exchange

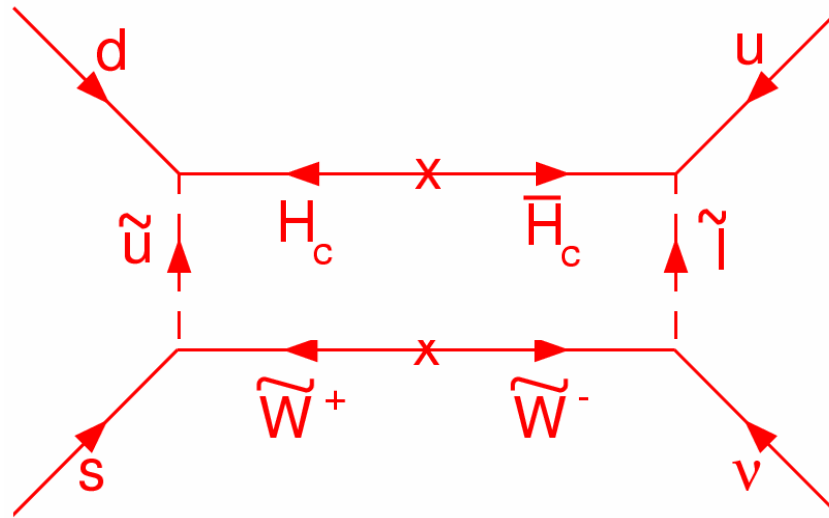


$$p \rightarrow e^+ \pi^0, \quad \tau_p^{-1} \approx \left[\frac{g^2}{M_X^2} \right]^2 m_p^5 \approx [10^{36 \pm 1} \text{yr}]^{-1}$$

Higgsino Exchange

Sakai, Yanagida (1982)

Weinberg (1982)



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

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

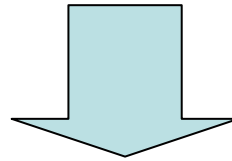
MSSM Higgs doublets have color triplet partners in GUTs.

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

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

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)

$$W_{D-T} = \bar{5}_H (\lambda 24_H + M) 5_H$$
$$\langle 24_H \rangle = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -3/2 & 0 \\ 0 & 0 & 0 & 0 & -3/2 \end{pmatrix} V$$

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

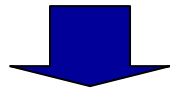
SUSY SO(10)

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

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

- 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 $\sim \{16_i\}$
- ★ Contains ν_R and Seesaw mechanism
- ★ Higgs $\sim \{45_H + 16_H + \bar{16}_H + 10_H\}$

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

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

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

$$\Rightarrow m_{\nu_\tau}^D \simeq m_t; m_{\nu_{\tau R}}^M \simeq h_{33} \frac{M_{GUT}^2}{M_{Pl}}$$

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



Fits the atmospheric neutrino data well

Realistic SO(10) Model

Pati, Wilczek, KB (1998)

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

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

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

"1" : $16_3 16_3 10_H$

" ϵ " : $16_2 16_3 (10_H \times 45_H) / M$

" σ " : $16_2 16_3 (10_H \times 1_H) / M$

" η " : $16_2 16_3 16_H 16_H / M$

$\langle 45_H \rangle \propto (B - L)$

Predictions

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

$$m_s(1\text{GeV}) \approx 116\text{MeV}$$

$$V_{cb} \approx 0.043$$

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

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

$$m_d(1\text{GeV}) \approx 8\text{MeV}$$

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

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

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

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

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**