Muon EDM, g-2, and Flavor Violation From Physics Beyond the Standard Model

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Outline

Beyond the SM Scenarios:

- *Supersymmetry*
- *Neutrino Masses*
- *Grand Unification*
- *Flavor Symmery*
- *Other (TeV scale extra matter, ..)*

Effects on Muon Properties:

- *(g-2)*
- *Electric Dipole Moment (EDM)*
- *Lepton Flavor Violation*

  $\mu \to e\gamma$

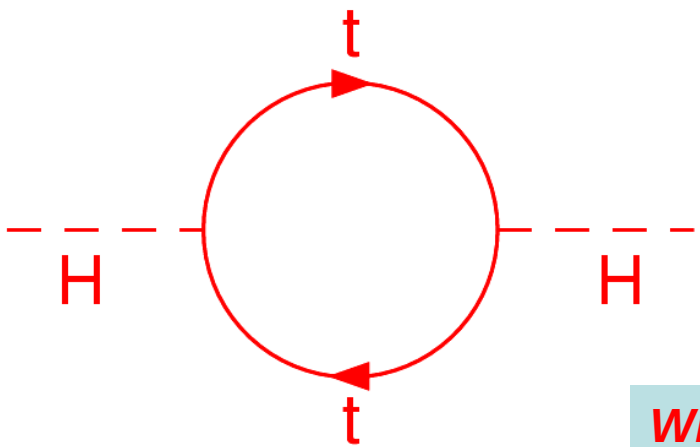
  $\mu - e$ *conversion*

Related Processes:

- *EDM of electron, neutron, deuteron*
- $\tau \to \mu\gamma$

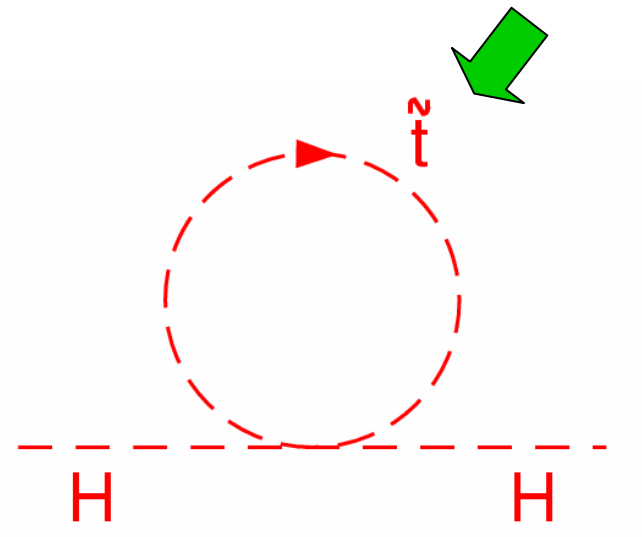
Conclusions

Stability of Higgs Mass



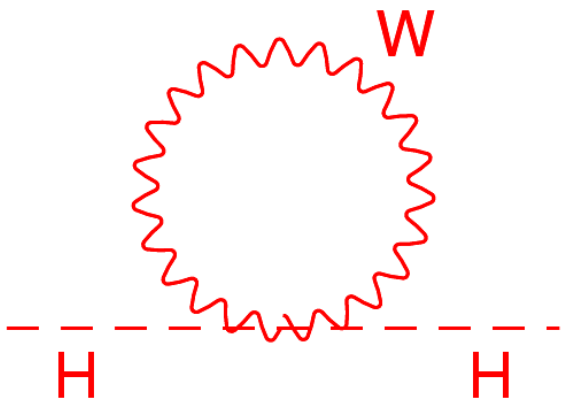
$$\Delta m_H^2 = -\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

With SUSY, Quadratic Divergence Cancels

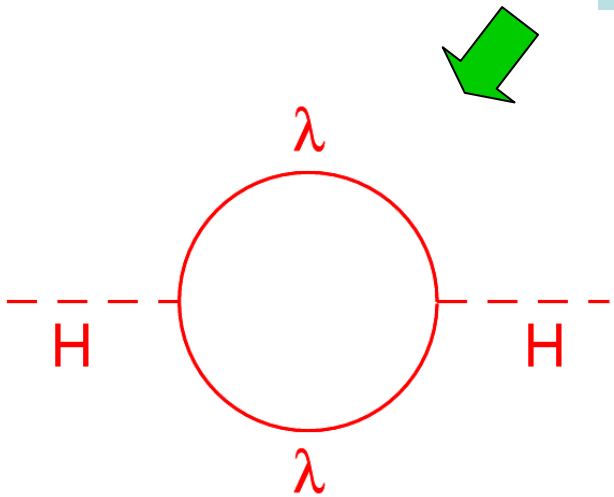


$$\Delta m_H^2 = +\frac{\lambda_t^2}{8\pi^2}\Lambda^2$$

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



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

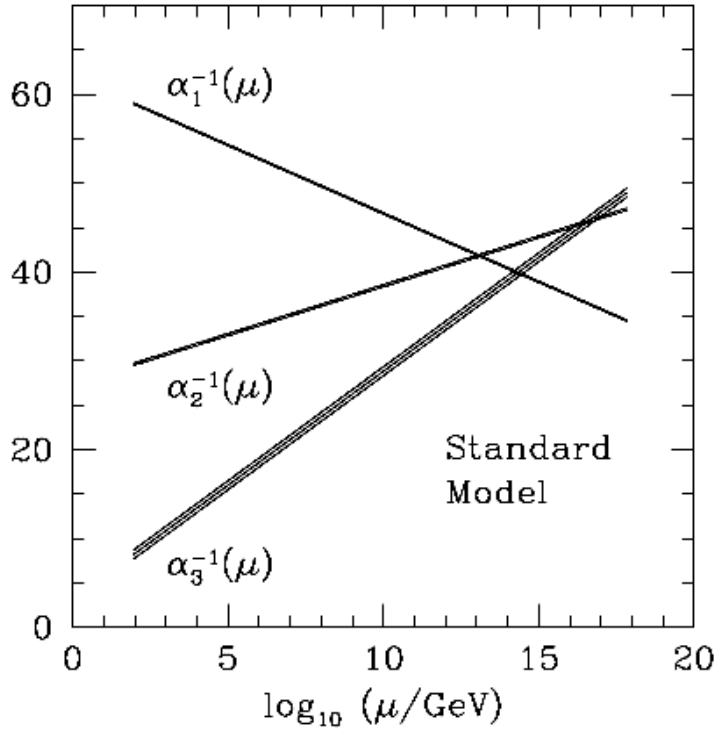


SUSY Spectrum

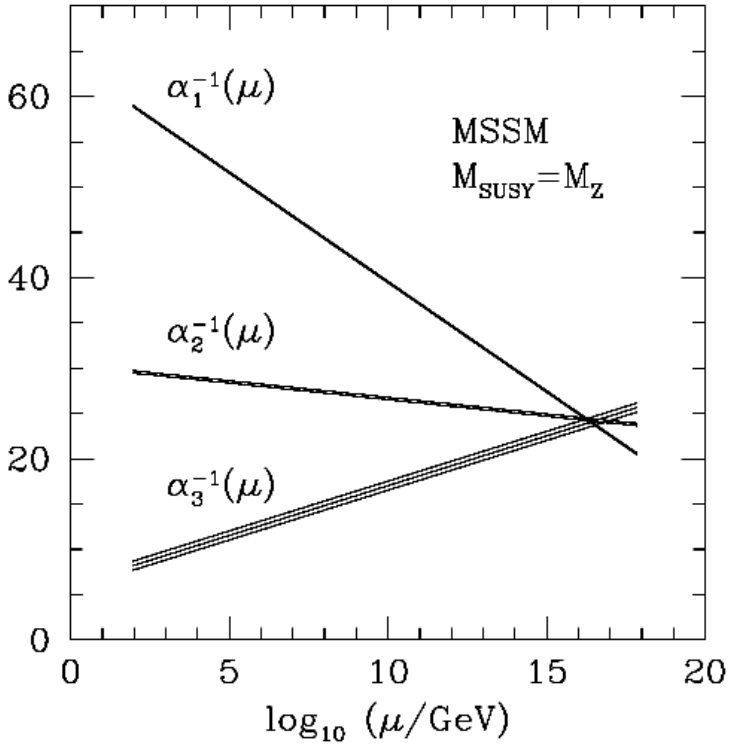
	SM Particles	SUSY Partners	
Spin = 1/2	Q	$\tilde{Q}$	Spin = 0
	u^c	$\tilde{u}^c$	
	d^c	$\tilde{d}^c$	
	L	$\tilde{L}$	
	e^c	$\tilde{e}^c$	
Spin = 0	H_u	$\tilde{H}_u$	Spin = 1/2
	H_d	$\tilde{H}_d$	
Spin = 1	g	$\tilde{g}$	Spin = 1/2
	W	$\tilde{W}$	
	B	$\tilde{B}$	

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

Evolution of Gauge Couplings



Standard Model



Supersymmetry

Structure of Matter Multiplets

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

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

$$d^c = \begin{pmatrix} d_1^c & d_2^c & d_3^c \end{pmatrix} \sim (\overline{3}, 1, \frac{1}{3})$$

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

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

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

Matter Unification in 16 of SO(10)

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	:	$\vert\uparrow\uparrow\uparrow\uparrow\uparrow>$

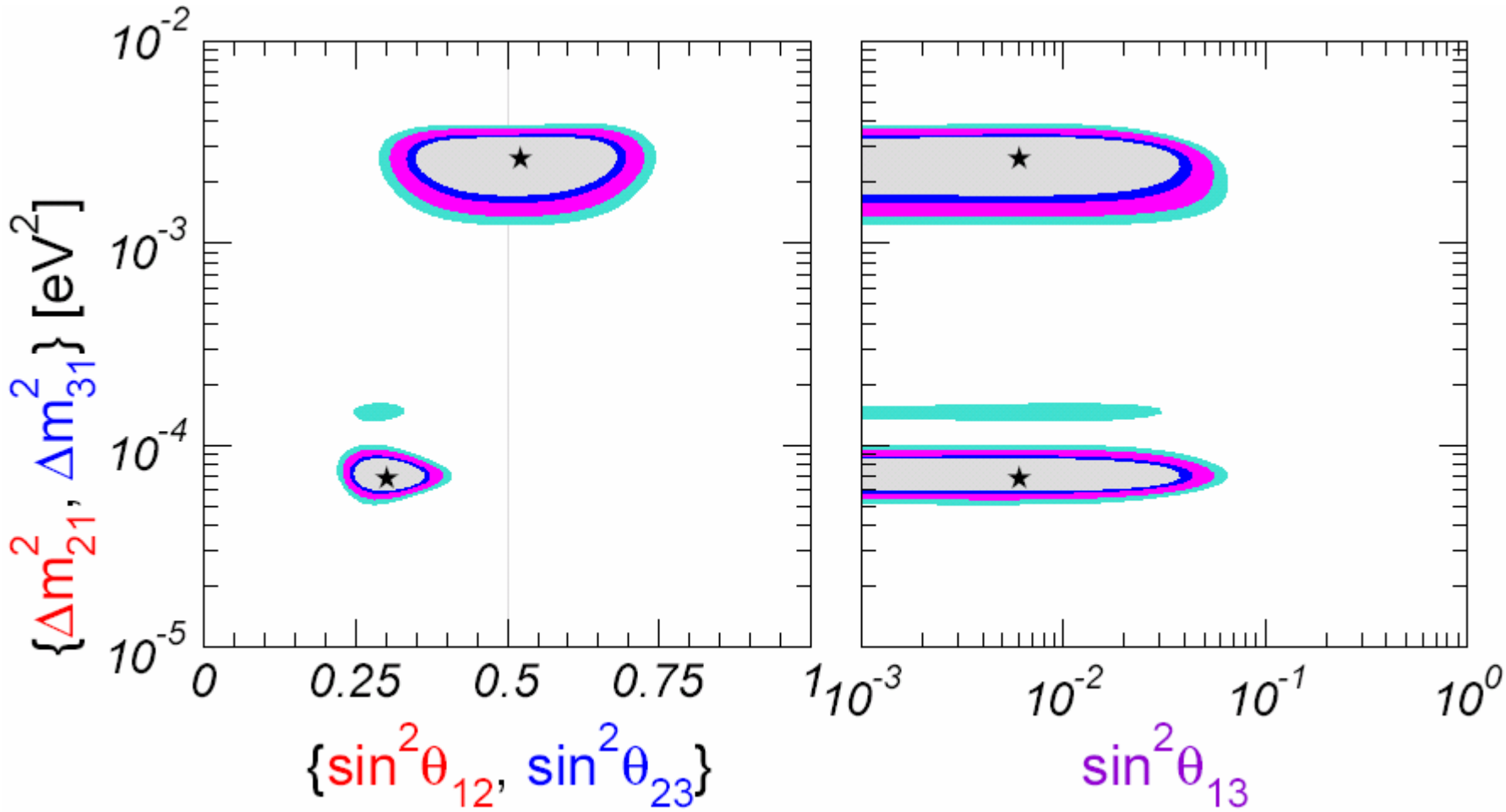
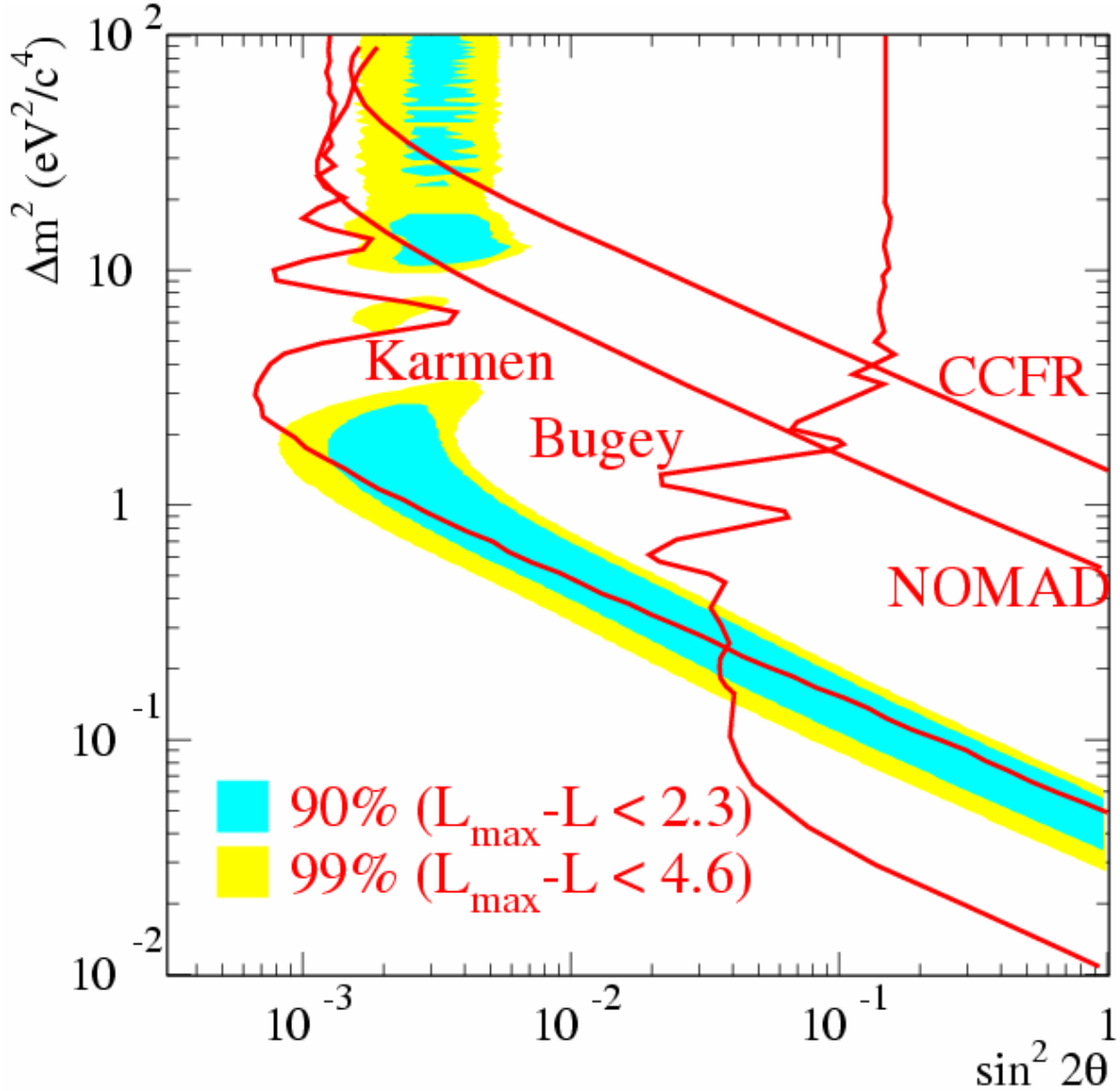


Figure 10: Projections of the allowed regions from the global oscillation data at 90%, 95%, 99%, and 3σ C.L. for 2 d.o.f. for various parameter combinations.

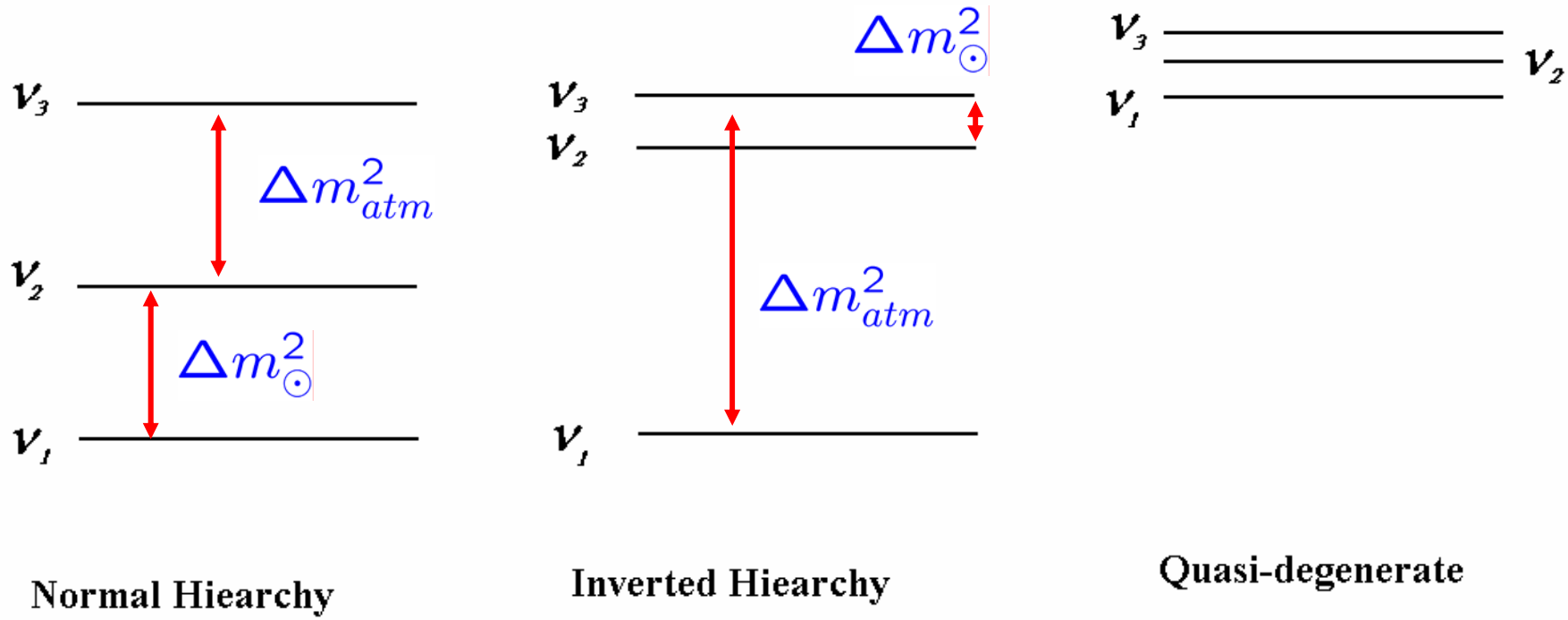
M. Maltoni et al., Phys. Rev. D68, 113010 (2003)

LSND



Aguilar, *et. al* hep-exp/0104049

Patterns of Neutrino Mass Spectrum



Neutrino Mixing versus Quark Mixing

Leptons

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

Quarks

$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.003 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix}$$

Disparity a challenge for Quark-Lepton unified theories.

Neutrino Masses and the Scale of New Physics

$$\mathcal{L} = \frac{LLHH}{M_R}$$

$$\langle H \rangle \sim 246 \text{ GeV and } m_{\nu_3} \sim 0.05 \text{ eV}$$

from atmospheric neutrino oscillation data

$$\Rightarrow \quad m_R \sim 10^{14} - 10^{15} \text{GeV}$$

Very close to the GUT scale.

Leptogenesis via ν_R decay explains cosmological baryon asymmetry

Muon $(g-2)$ in Supersymmetric Models

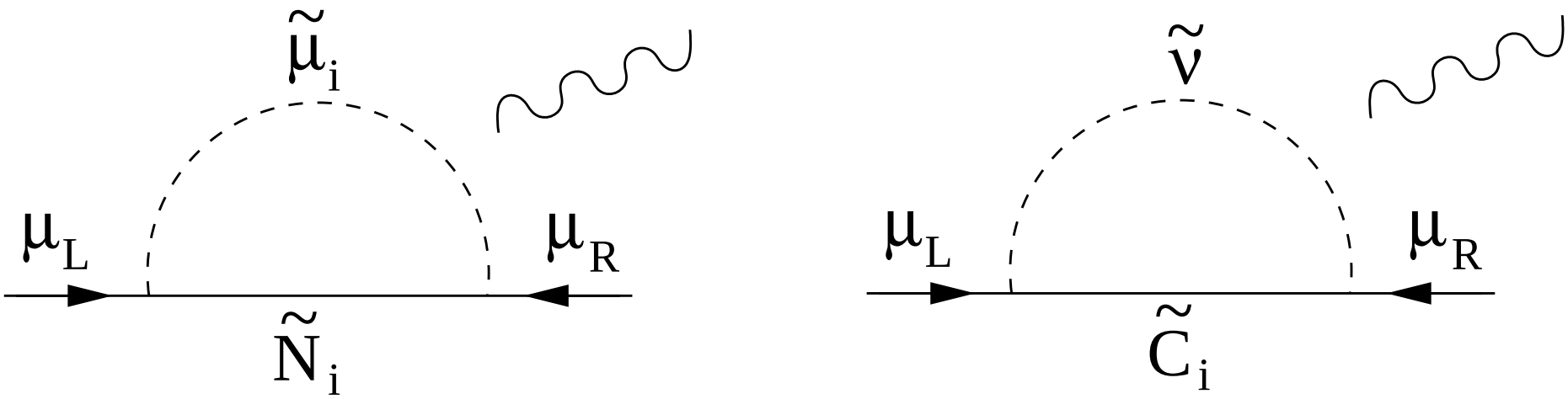


Figure 1: Neutralino and Chargino diagrams for muon $(g-2)$.

$$L = \frac{ie}{2m_\mu} F(q^2)\bar{u}(p_f)\sigma_{\mu\nu}q^\mu\epsilon^\nu u(p_i)$$

$$
\begin{aligned}
g_\mu^{(C)} &= \frac{1}{48\pi^2}\frac{m_\mu^2}{m_{\tilde{\nu}_X}^2}|C_{2AX}^{L(l)}|^2\frac{2+3x_{AX}-6x_{AX}^2+x_{AX}^3+6x_{AX}\ln x_{AX}}{(1-x_{AX})^4} \\
&+\frac{1}{16\pi^2}\frac{m_\mu M_{\tilde{\chi}_A^-}}{m_{\tilde{\nu}_X}^2}C_{2AX}^{L(l)}C_{2AX}^{R(l)*}\frac{-3+4x_{AX}-x_{AX}^2-2\ln x_{AX}}{(1-x_{AX})^3} \\
&+(L\leftrightarrow R)
\end{aligned}
$$

$$
\begin{aligned}
g_\mu^{(N)} &= -\frac{1}{48\pi^2}\frac{m_\mu^2}{m_{\tilde{l}_X}^2}|N_{2AX}^{L(l)}|^2\frac{1-6x_{AX}+3x_{AX}^2+2x_{AX}^3-6x_{AX}^2\ln x_{AX}}{(1-x_{AX})^4} \\
&-\frac{1}{16\pi^2}\frac{m_\mu M_{\tilde{\chi}_A^0}}{m_{\tilde{l}_X}^2}N_{2AX}^{L(l)}N_{2AX}^{R(l)*}\frac{1-x_{AX}^2+2x_{AX}\ln x_{AX}}{(1-x_{AX})^3} \\
&+(L\leftrightarrow R),
\end{aligned}
$$

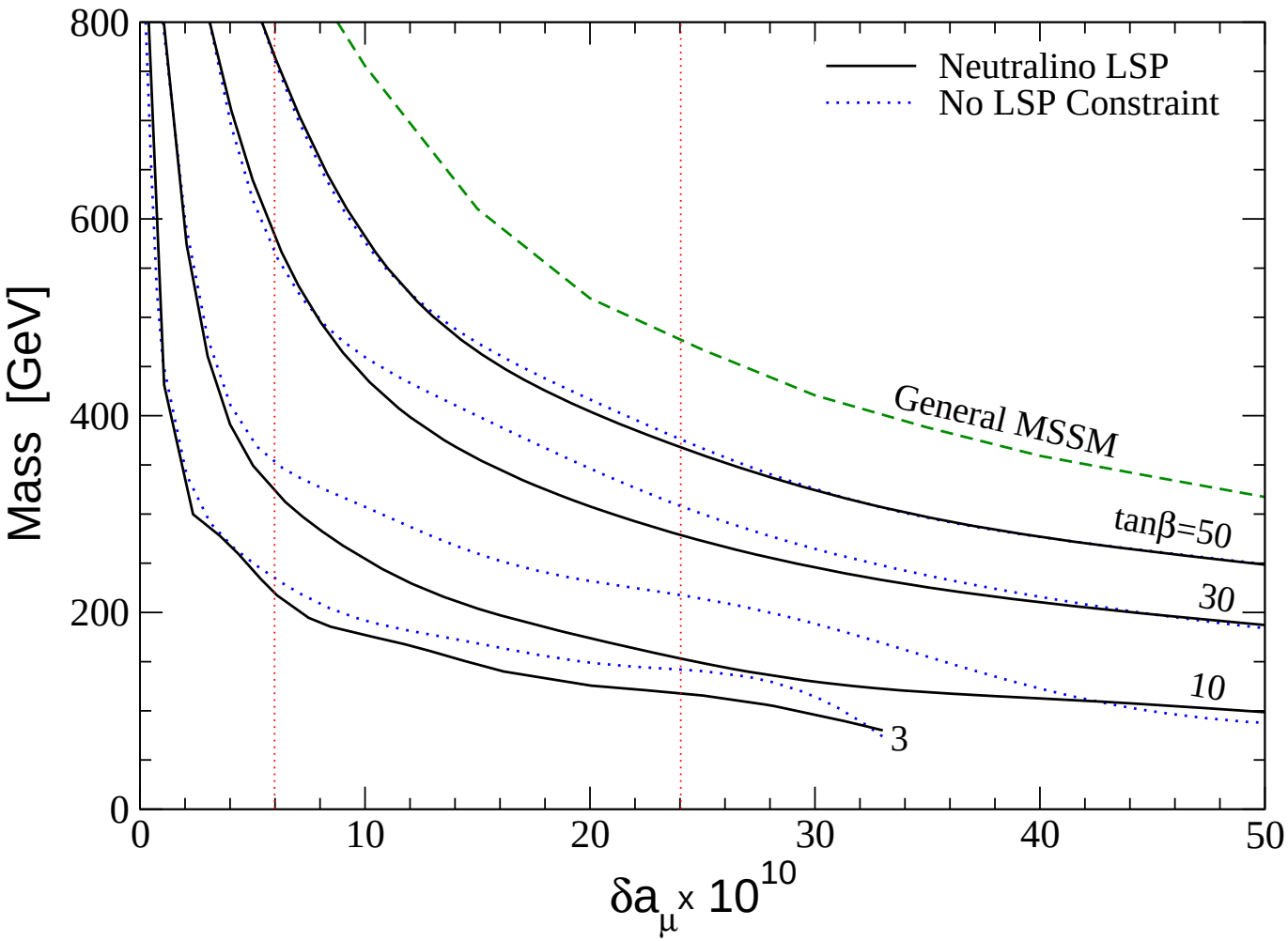


Figure 2: LSP mass vs. δa_μ.

M. Byrne, C. Kolda and J.E. Lennon, hep-ph//0208067.

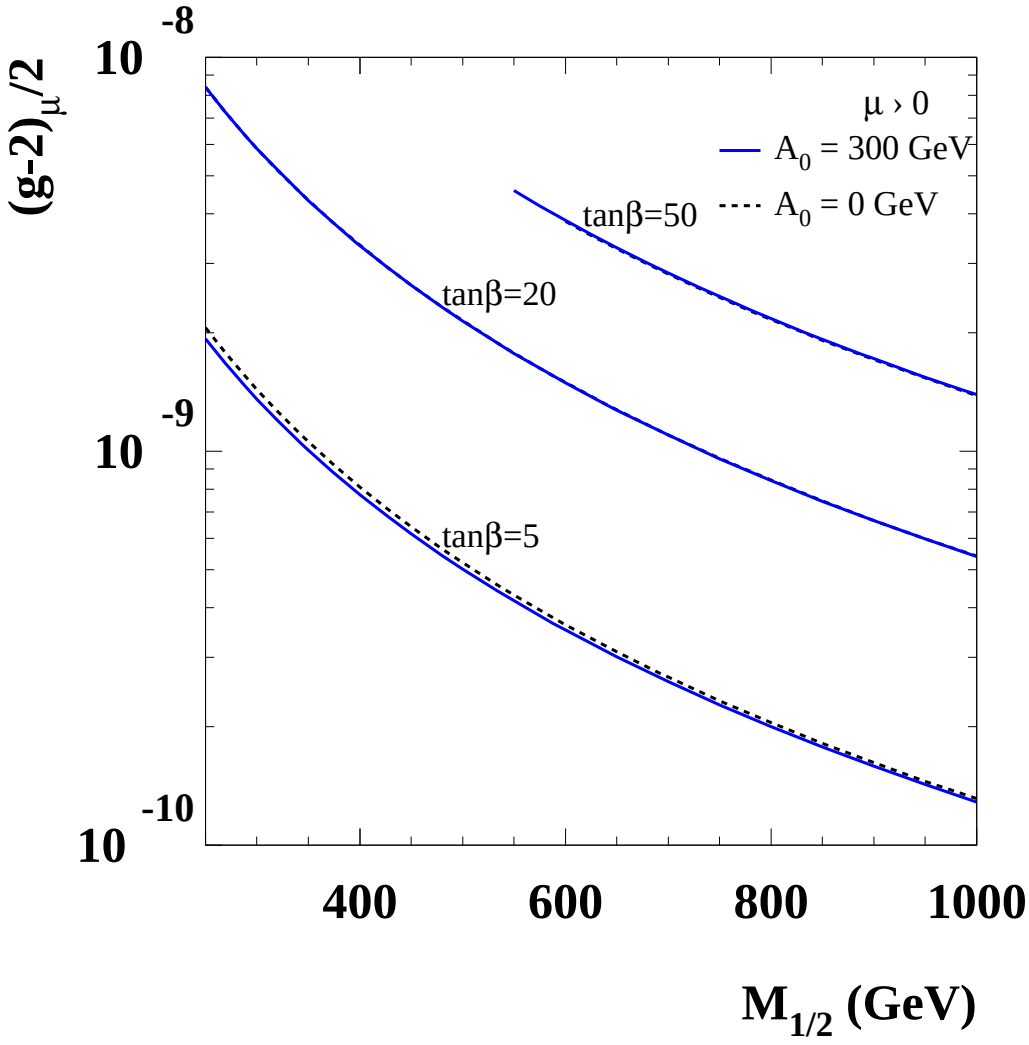


Figure 3: Muon Anomalous Magnetic Moment.

Ts. Enkhbat, KSB

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)

Hisano, Okada (1998)

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)

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

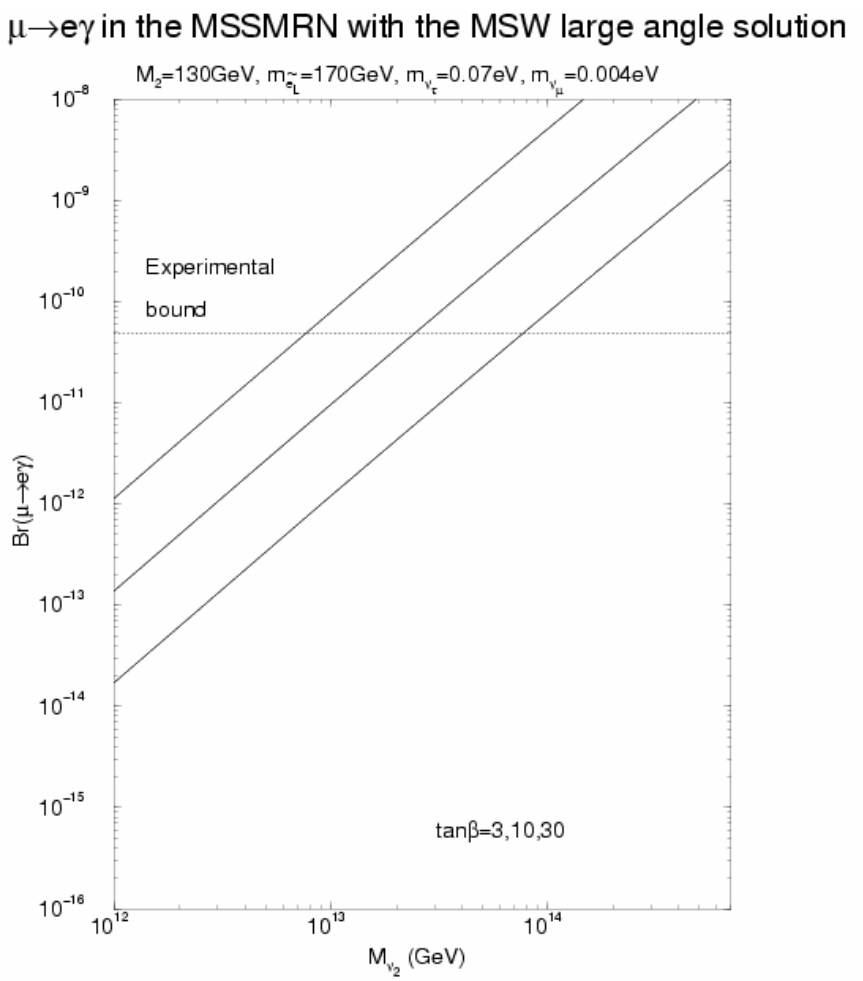
If flavor violation occurs only in *f* (Majorana LFV)

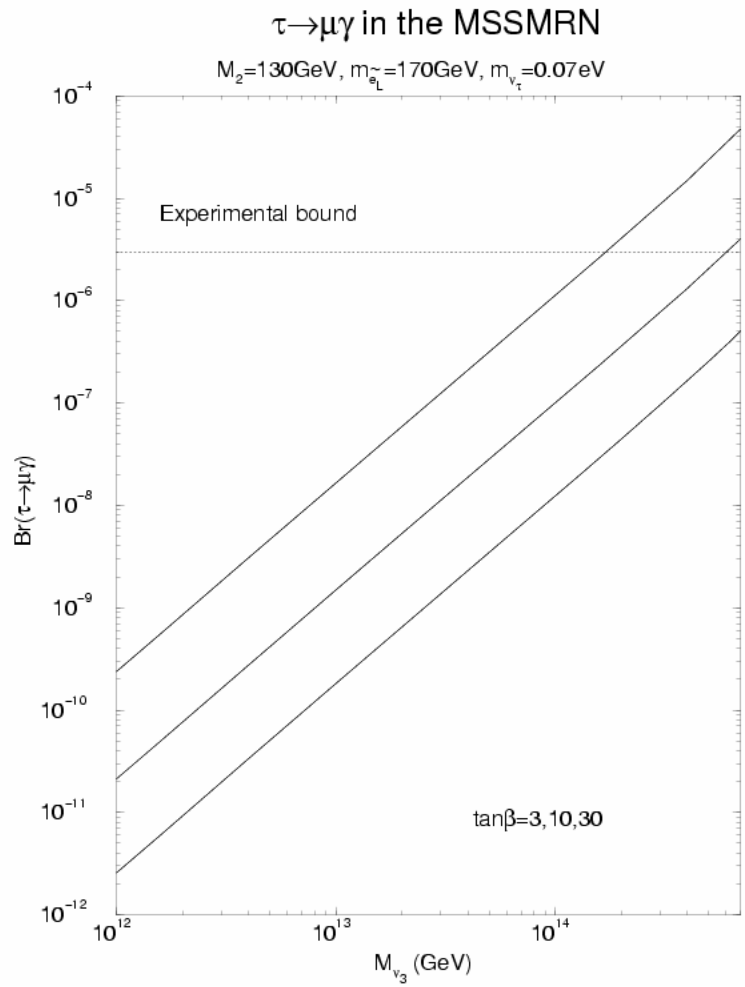
$$A_{\ell ij}(i \neq j) \simeq \frac{-3}{64\pi^4}[A_\ell(Y_\nu^\dagger Y_\nu f^\dagger f + f^\dagger f Y_\nu^\dagger Y_\nu)]_{ij}\left(\ell n \frac{M_{P\ell}}{M_{B-L}}\right)^2$$

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

LFV in the two scenarios are comparable.

More detailed study is needed.





LFV from Dirac neutrino Yukawa couplings

Hisano, Okada, (1998)

LFV from Majorana Yukawa Couplings

Minimal SUSY Left-Right Symmetric Model **Dutta, Mohapatra, KSB (2002)**

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

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

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

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

Relevant for Leptogenesis: Baryon asymmetry can be related to neutrino oscillation parameters

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

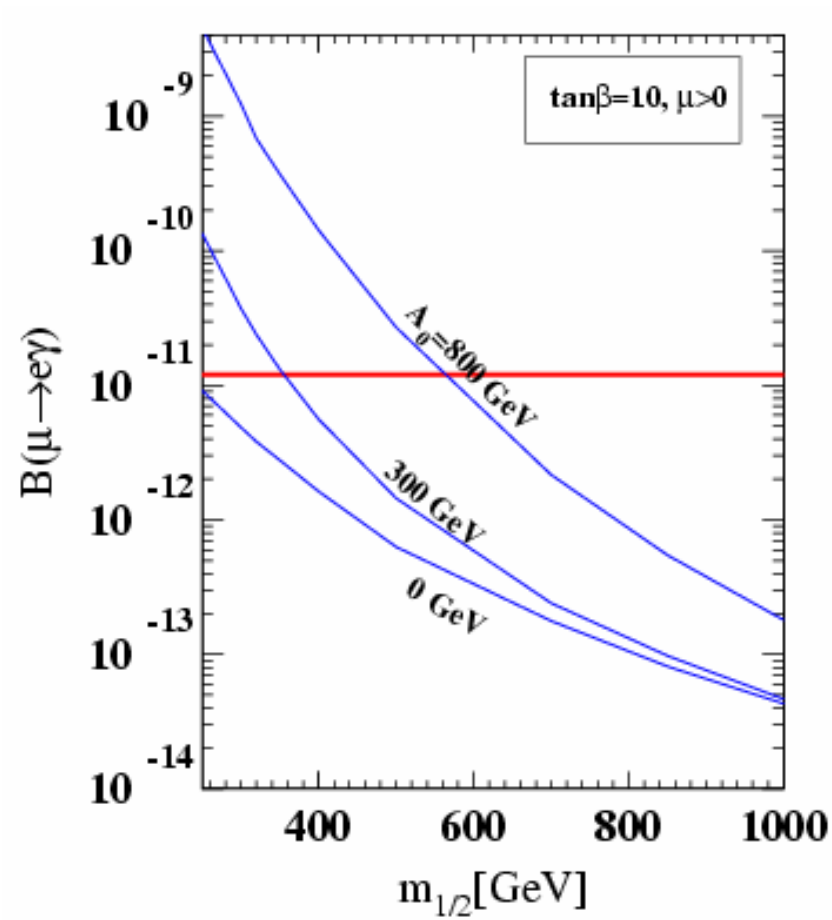
The two scenarios differ in predictions for

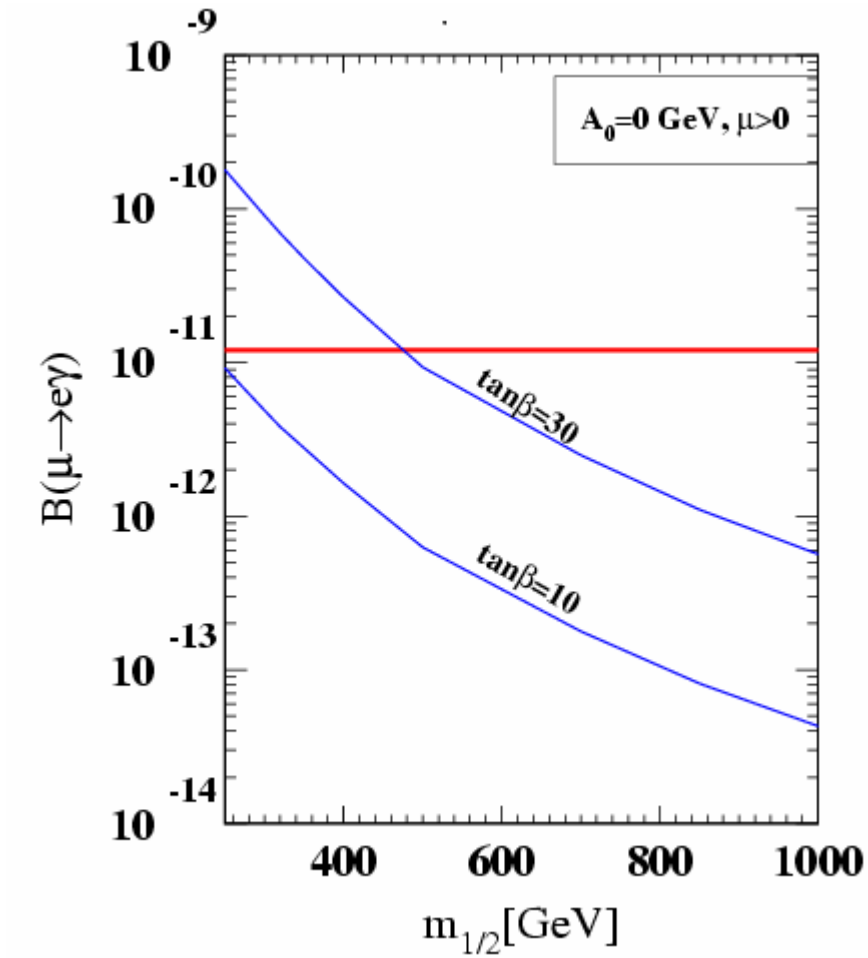
$$\mu \rightarrow e\gamma$$

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

$$\tau \rightarrow e\gamma$$

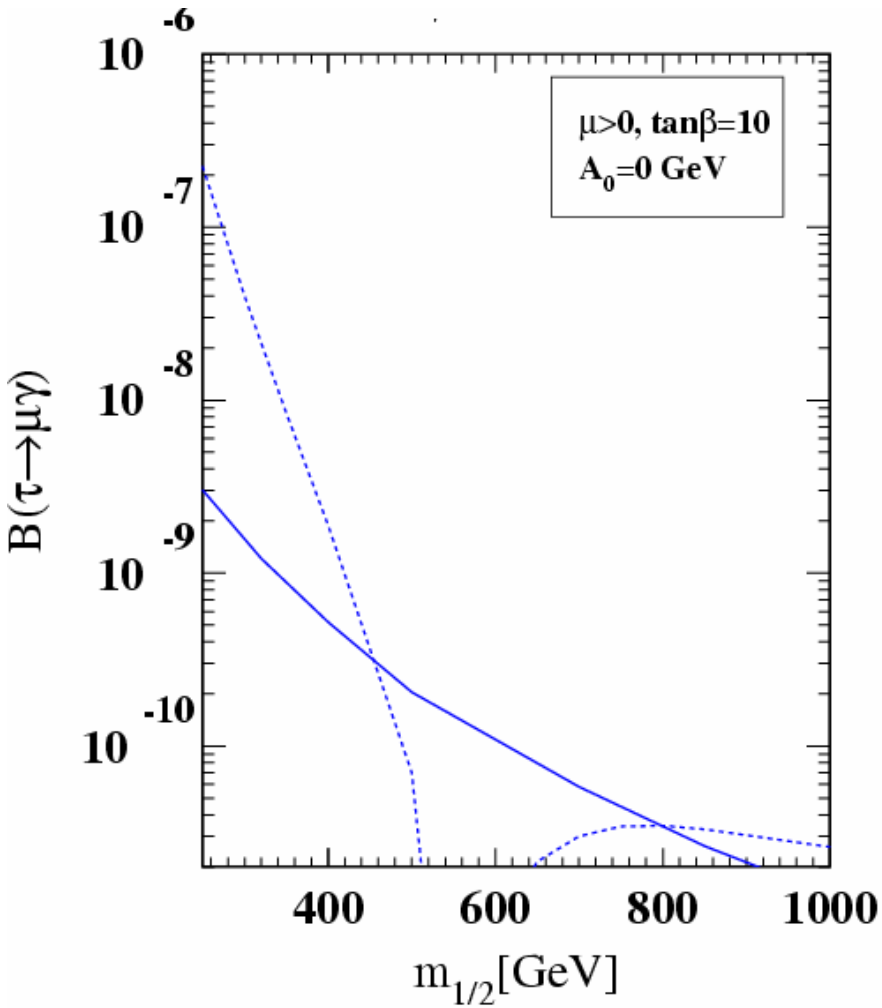
$\mu \to e\gamma$ Majorana LFV

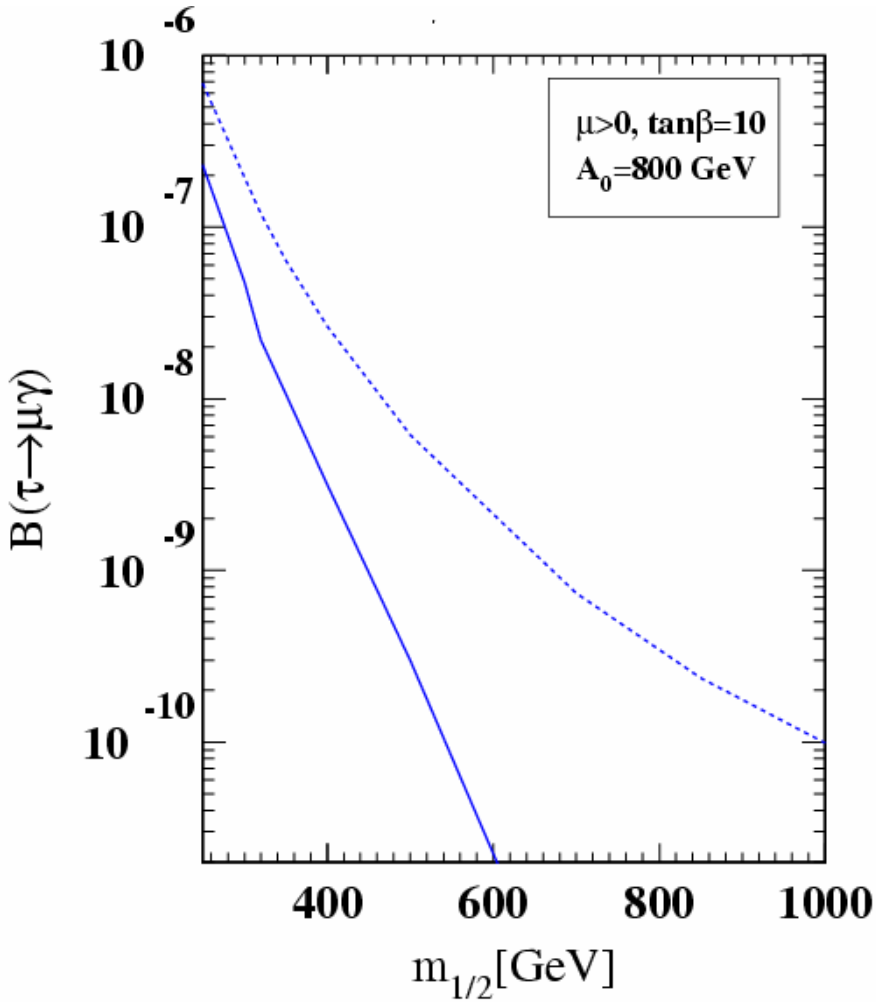




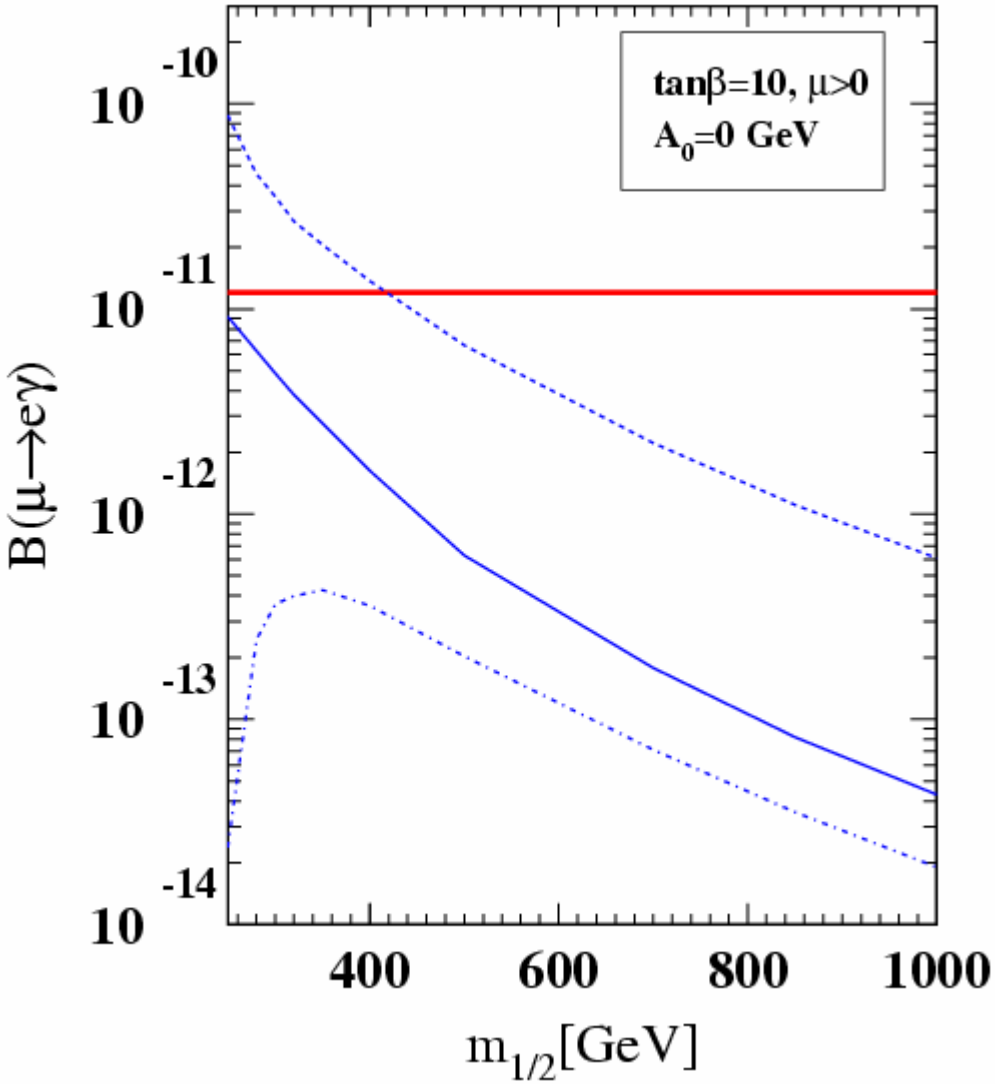
Dutta, Mohapatra, KSB (2002)

$\tau \to \mu\gamma$ Majorana LFV





Dirac versus Majorana LFV



Solid line: Majorana LFV

Dotted line: Dirac LFV

Dutta, Mohapatra, KSB (2002)

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 ($\tan\beta = 5$)

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

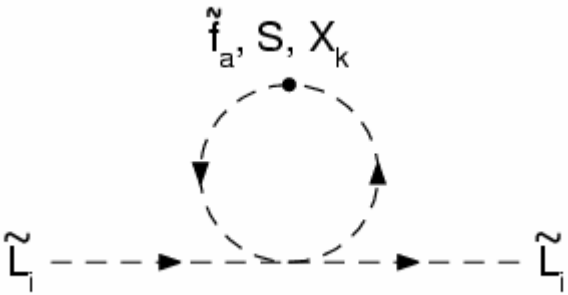
$$Y^d = \epsilon^2 \begin{pmatrix} (1.87 - 1.69\,i)\,\epsilon^5 & (1.93 + 0.849\,i)\,\epsilon^4 & (1.29 + 0.957\,i)\,\epsilon^4 \\ (-0.404 - 0.248\,i)\,\epsilon^3 & (0.5542 + 1.54 \times 10^{-2}\,i)\,\epsilon^2 & (0.702 - 0.546\,i)\,\epsilon^2 \\ (-0.152 - 0.435\,i)\,\epsilon & 0.312 - 0.314\,i & 0.543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

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

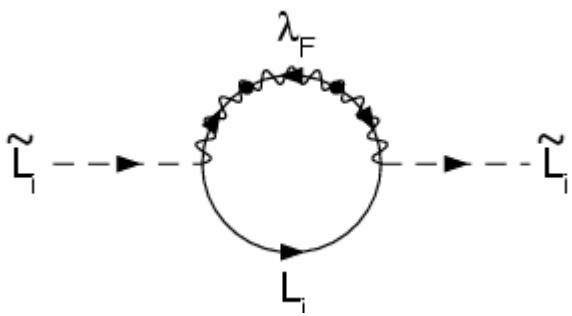
$$Y^\nu = \epsilon^2 \begin{pmatrix} (0.232 - 0.190\,i)\,\epsilon^2 & (0.217 - 6.09 \times 10^{-2}\,i)\,\epsilon & (-0.206 - 0.637\,i)\,\epsilon \\ (0.638 - 0.652\,i)\,\epsilon & -7.82 \times 10^{-2} + 0.537\,i & 0.804 + 0.296\,i \\ (0.305 - 0.392\,i)\,\epsilon & -4.41 \times 10^{-3} + 0.277\,i & 0.404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

Anomalous U(1) Symmetry and Lepton Flavor Violation

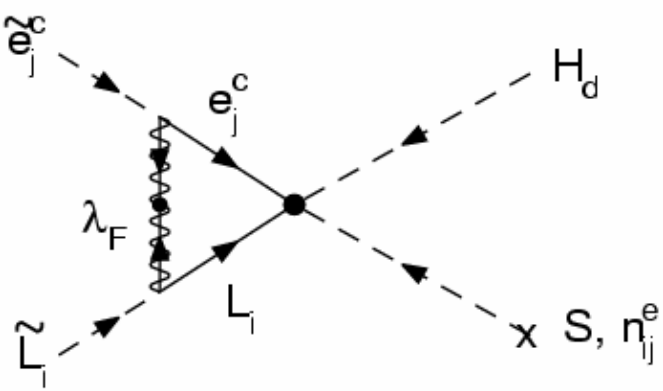
Enkhbat, Gogoladze, KSB (2003)



$$\delta\left(\tilde{m}_L^2\right)_{ij}^{A} \simeq -q_i^L |q_s| g_F^2 \delta_{ij} m_0^2 \mathrm{Tr}(Q) \frac{\ln\left(M_{st}/M_F\right)}{8\pi^2}$$

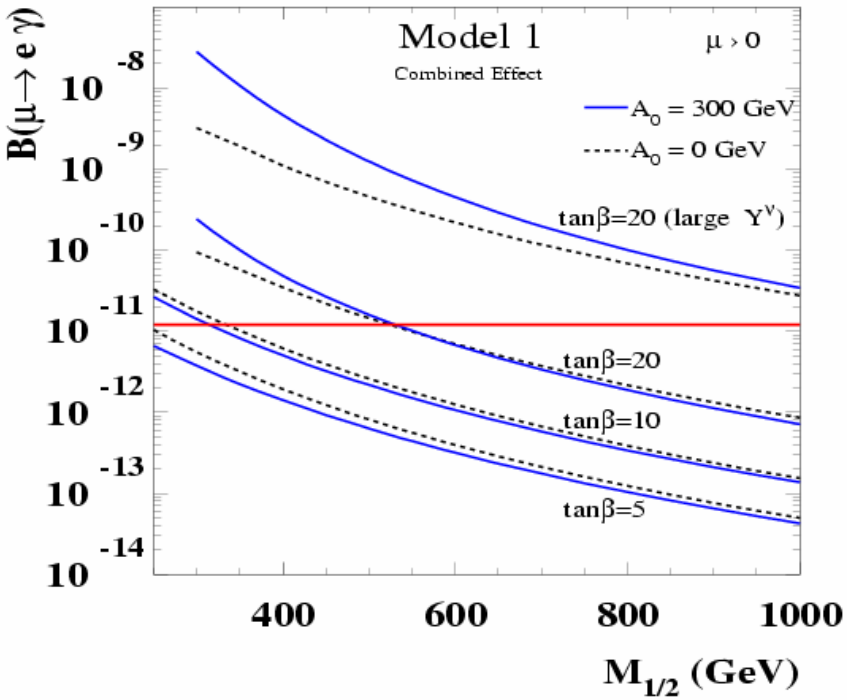


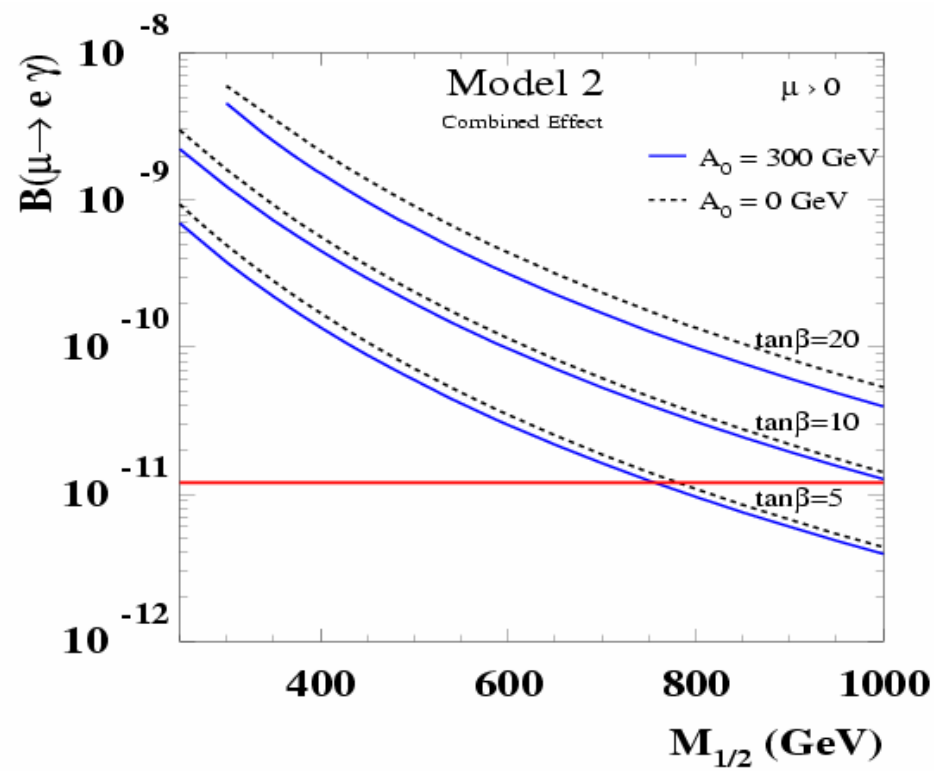
$$\delta\left(\tilde{m}_L^2\right)_{ij}^{G} \simeq \left(q_i^L\, g_F\right)^2 \delta_{ij} \left(M_{\lambda_F}\right)^2 \frac{\ln\left(M_{st}/M_F\right)}{2\pi^2}$$



$$\delta A_{ij}^e \simeq -M_{\lambda_F} {g_F}^2 Y_{ij}^e Z_{ij}^e \frac{\ln\left(M_{st}/M_F\right)}{4\pi^2}$$

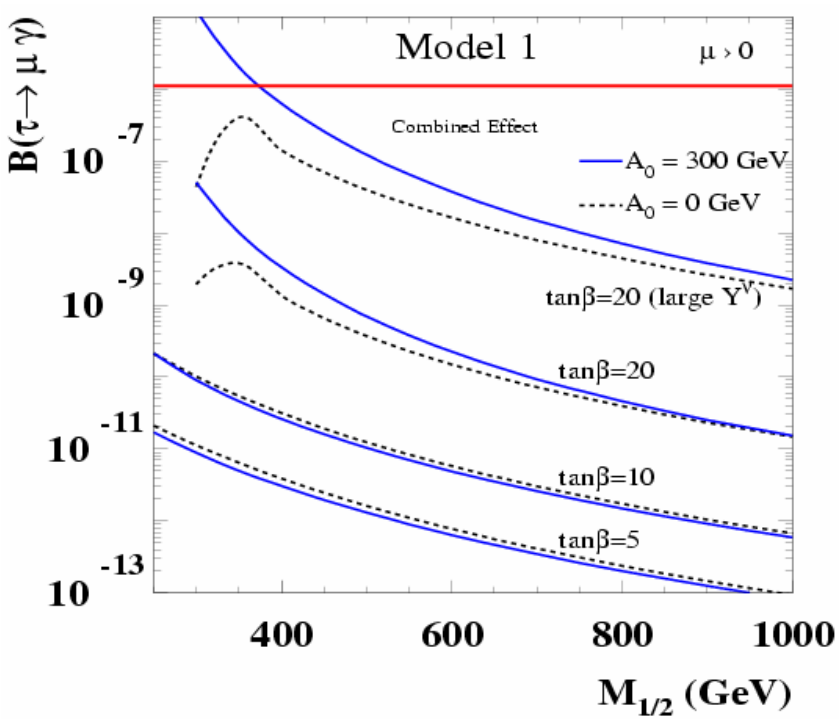
$\mu \to e\gamma$ in Anomalous $U(1)$ Models

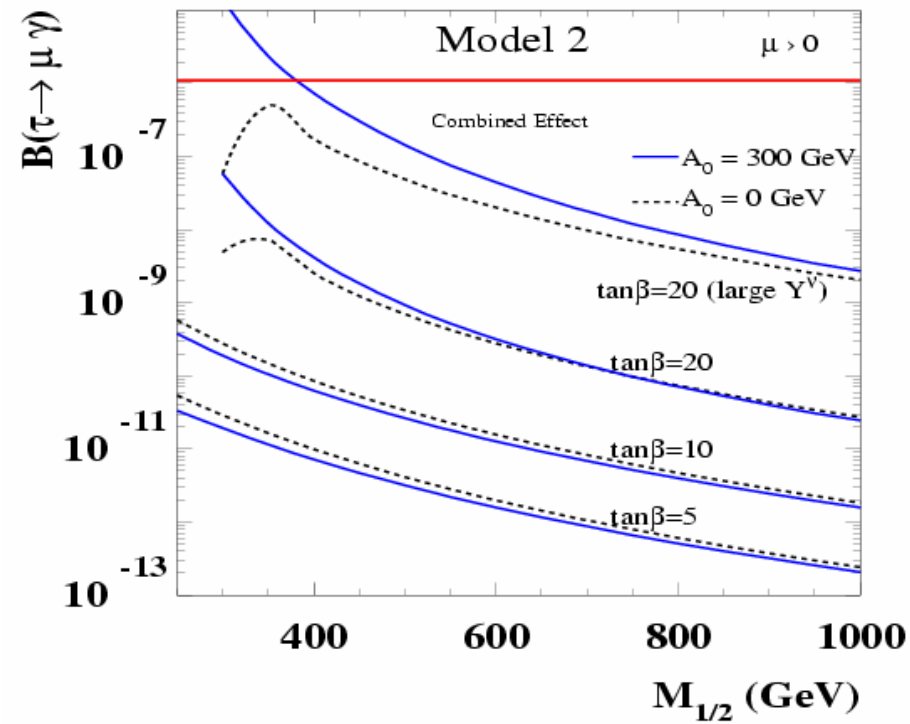




Enkhbat, Gogoladze, KSB (2003)

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





Enkhbat, Gogoladze, KSB (2003)

Electric Dipole Moments of the leptons and the neutron

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

Violates CP

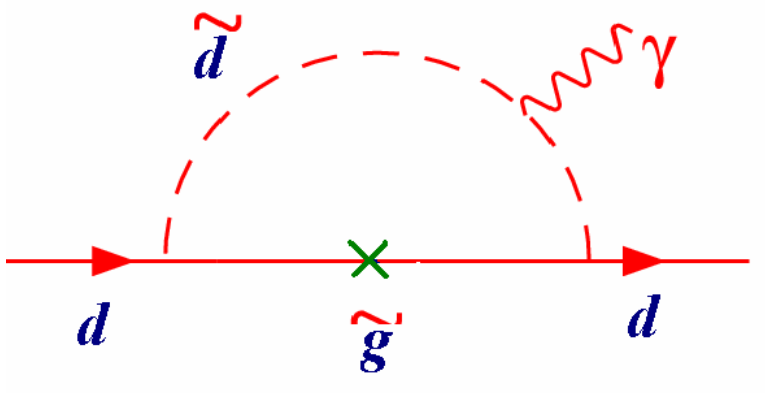
Electron: $d_e(\text{Exp}) \leq 1.6 \times 10^{-27}$ e-cm

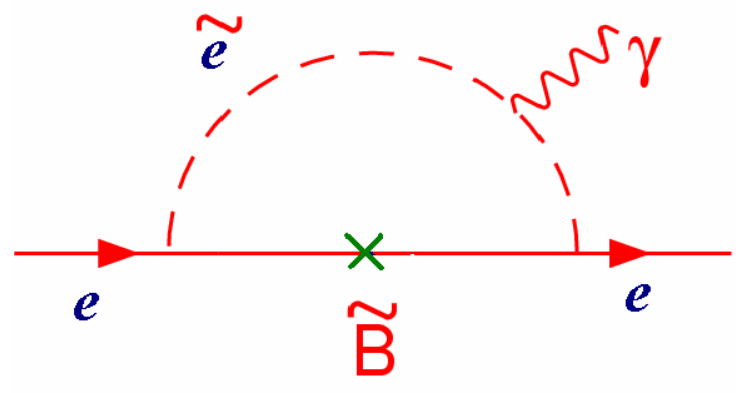
Muon: $d_\mu(\text{Exp}) \leq 1.2 \times 10^{-18}$ e-cm

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

Phases in SUSY breaking sector contribute to EDM.

SUSY Contributions:





A, B are complex in MSSM

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

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

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

If SUSY-breaking parameters are all real, EDMs can still arise from neutrino Yukawa couplings

$d_e \sim 10^{-31}$ e-cm

Ellis et al (2002)

EDM from Flavor Symmetry

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

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

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

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

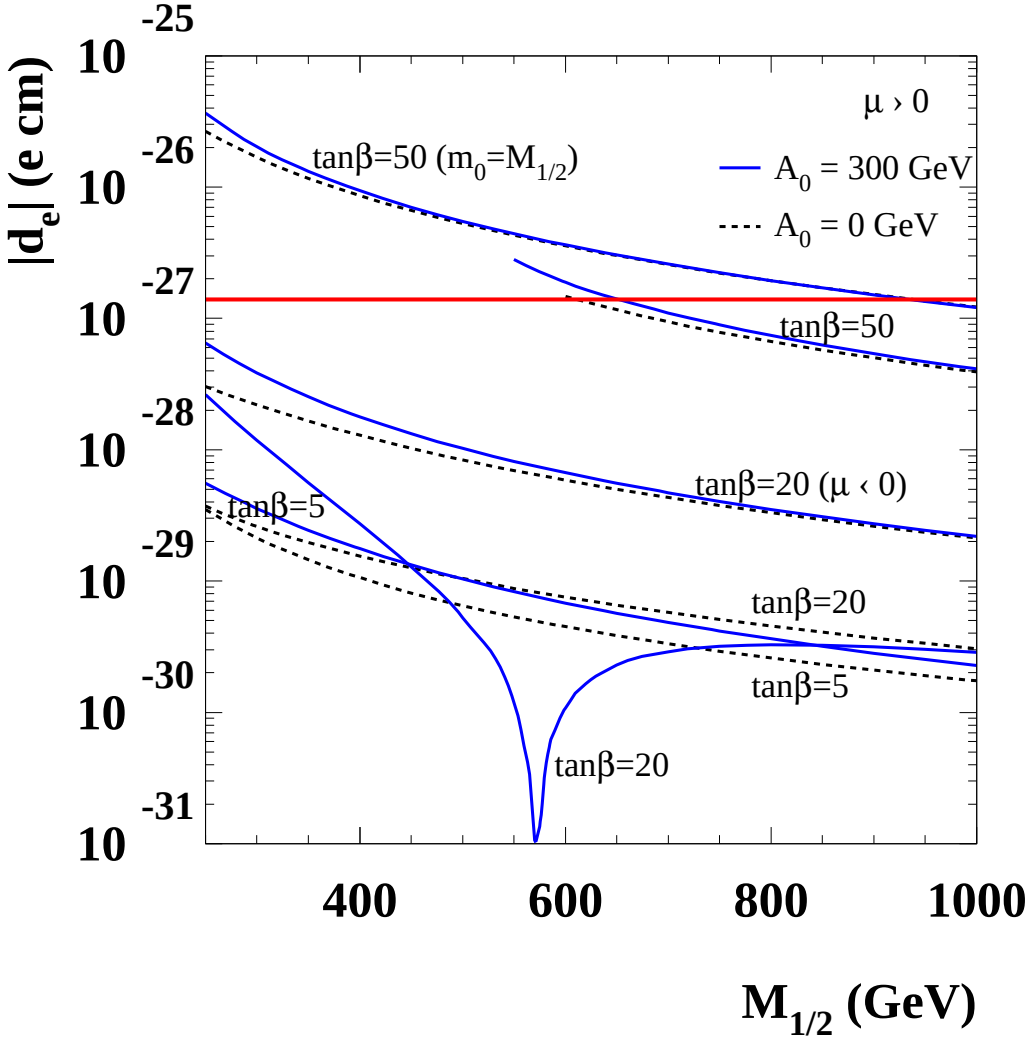


Figure 4: The Electron Electric Dipole Moment. The red line: experimental bound

Ts. Enkhbat, KSB, hep-ph/0406003

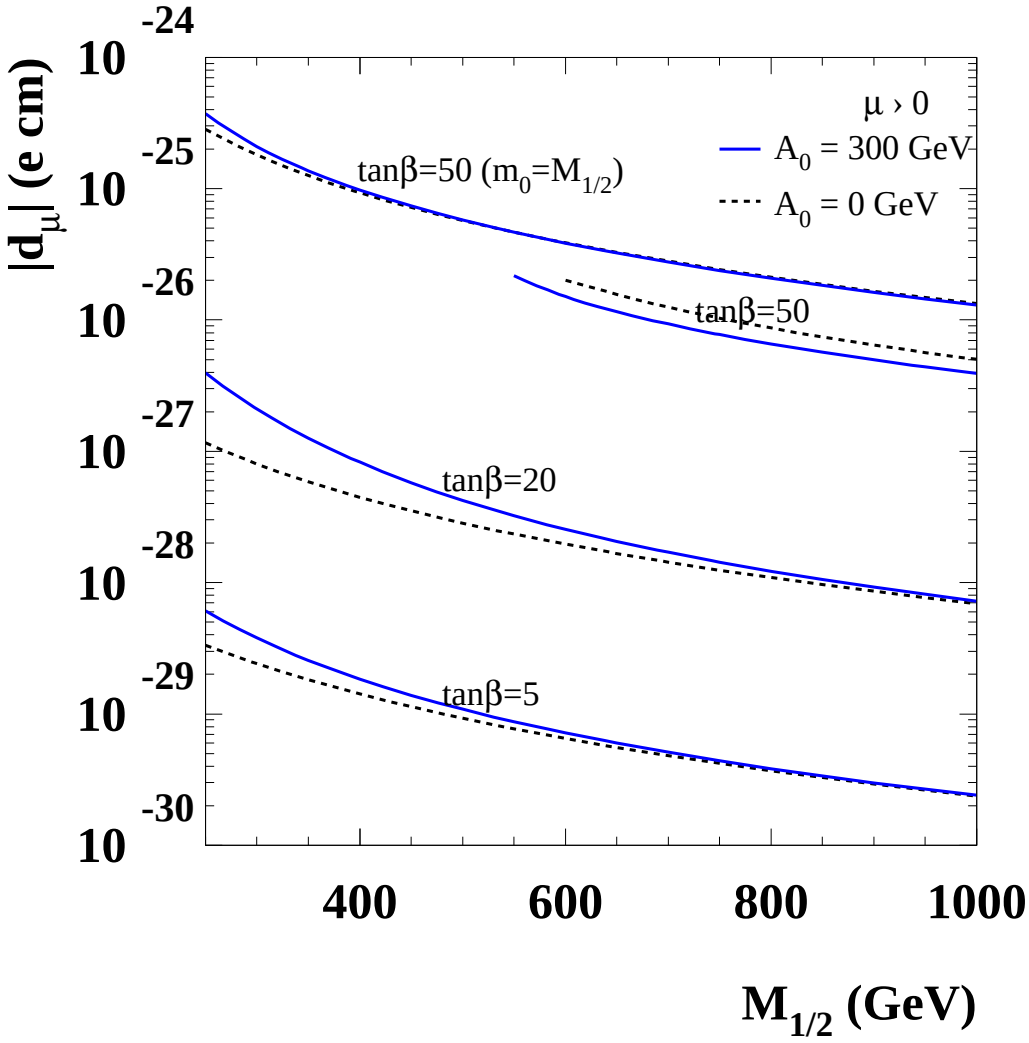


Figure 5: Muon Electric Dipole Moment.

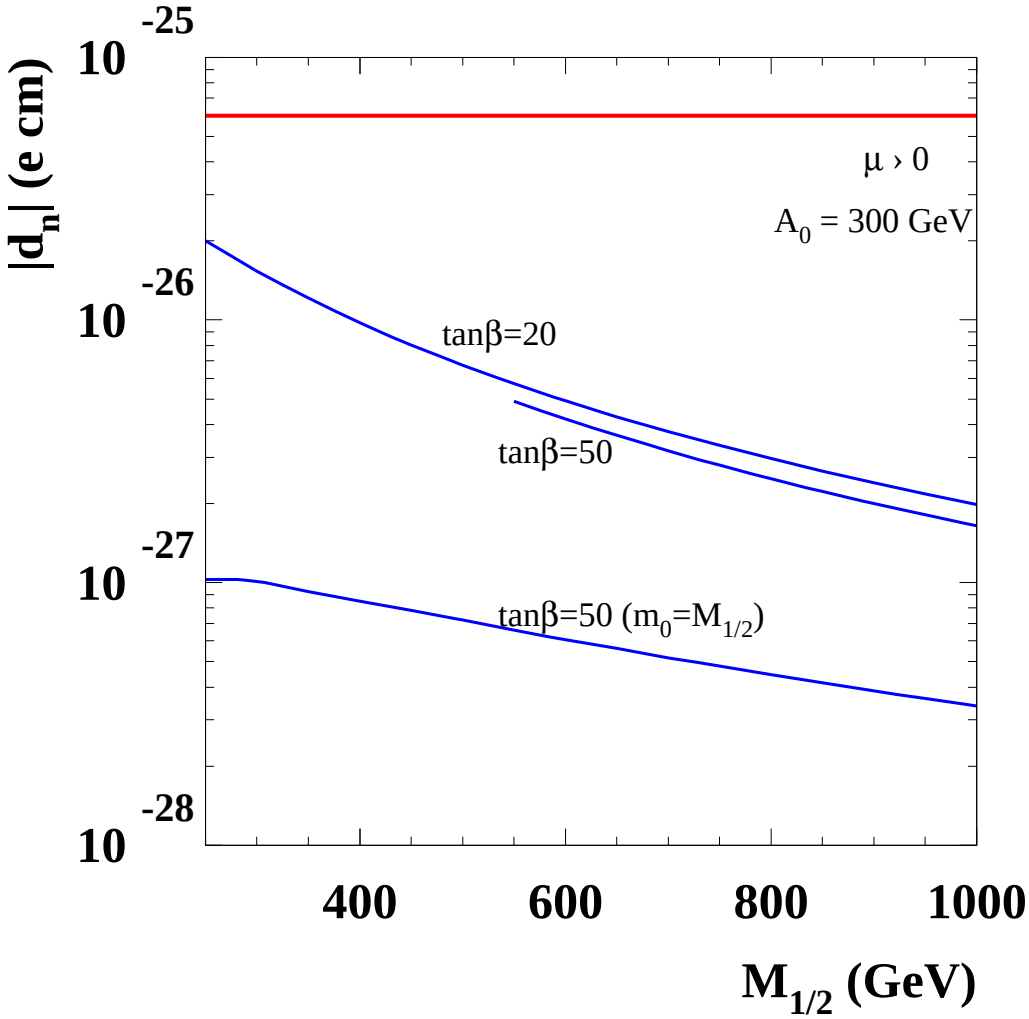


Figure 6: Neutron Electric Dipole Moment.

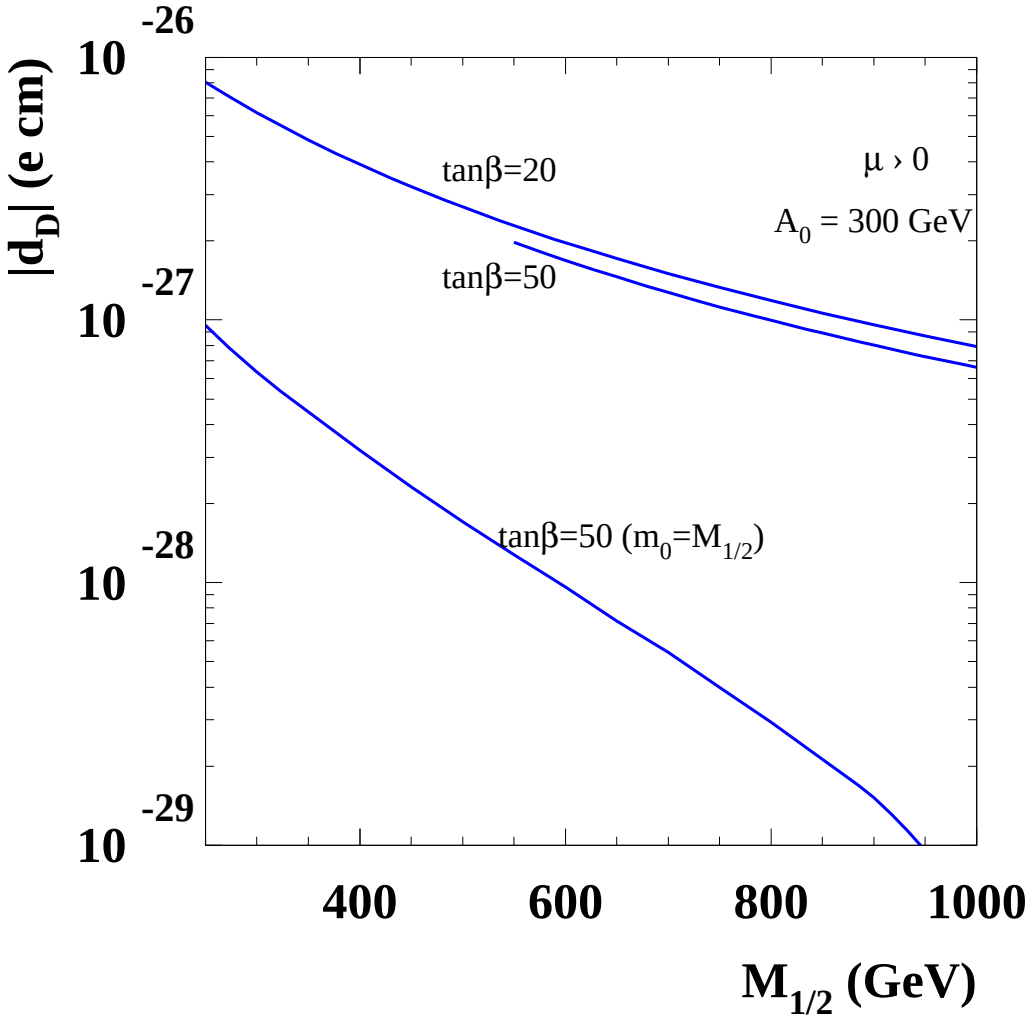


Figure 7: Deuteron Electric Dipole Moment.

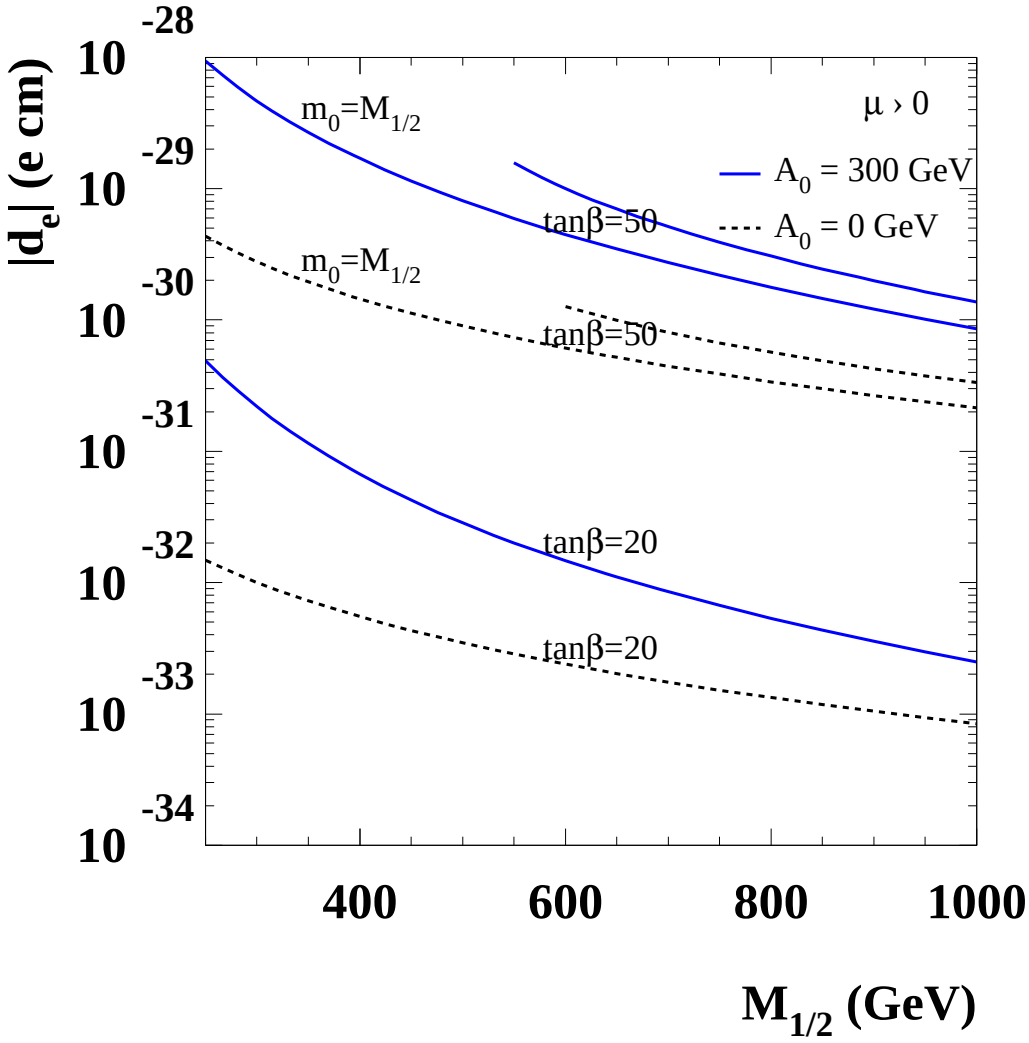


Figure 8: Electron Electric Dipole Moment by purely the neutrino effects.

Parity Symmetry and EDM: If parity is realized asymptotically,

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

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

$$f \qquad \text{Complex Symmetric}$$

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, KSB (2001)

Scaling of Lepton EDM with Lepton Mass

Lepton Dipole Moment Matrix D:

$$D_{ij} \sim d_\tau \begin{pmatrix} (m_e/m_\tau)^3 + c\frac{\alpha}{4\pi}(m_e/m_\tau) & - & - \\ (m_e m_\mu^2/m_\tau^3) & (m_\mu/m_\tau)^3 & - \\ (m_e/m_\tau)^2 & (m_\mu m_\tau) & 1 \end{pmatrix} .$$

Here $e,\ \mu,\ \tau$ obtain masses by mixing with exotic leptons X.

$$(\ell_{iL}^-, X_{iL}^-) \begin{pmatrix} \hat{m}_i & 0 \\ M_i & \langle F_i \rangle \end{pmatrix} \begin{pmatrix} \ell_{iL}^+ \\ X_{iL}^+ \end{pmatrix} .$$

Lepton EDM given by

$$d_i \cong \frac{3e}{32\pi^2}\lambda_i \frac{\hat{m}_i \langle F_i \rangle}{M_i^3} = \frac{3e}{32\pi^2}\lambda_i \frac{m_i}{M_i^2} .$$

For $M \sim$ 1 TeV, $d_\mu \sim 3 \times 10^{-23} e$ cm. S. Barr, KSB (2001)

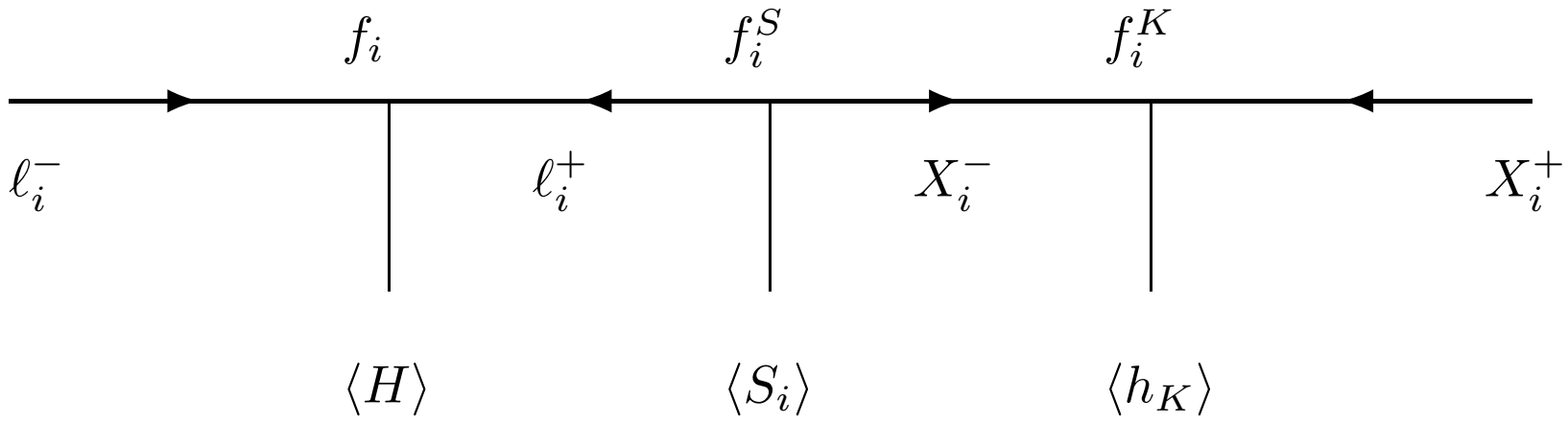

f_i
f_i^S
f_i^K
ℓ_i^-
ℓ_i^+
X_i^-
X_i^+
$\langle H \rangle$
$\langle S_i \rangle$
$\langle h_K \rangle$

Fig. 2(a)

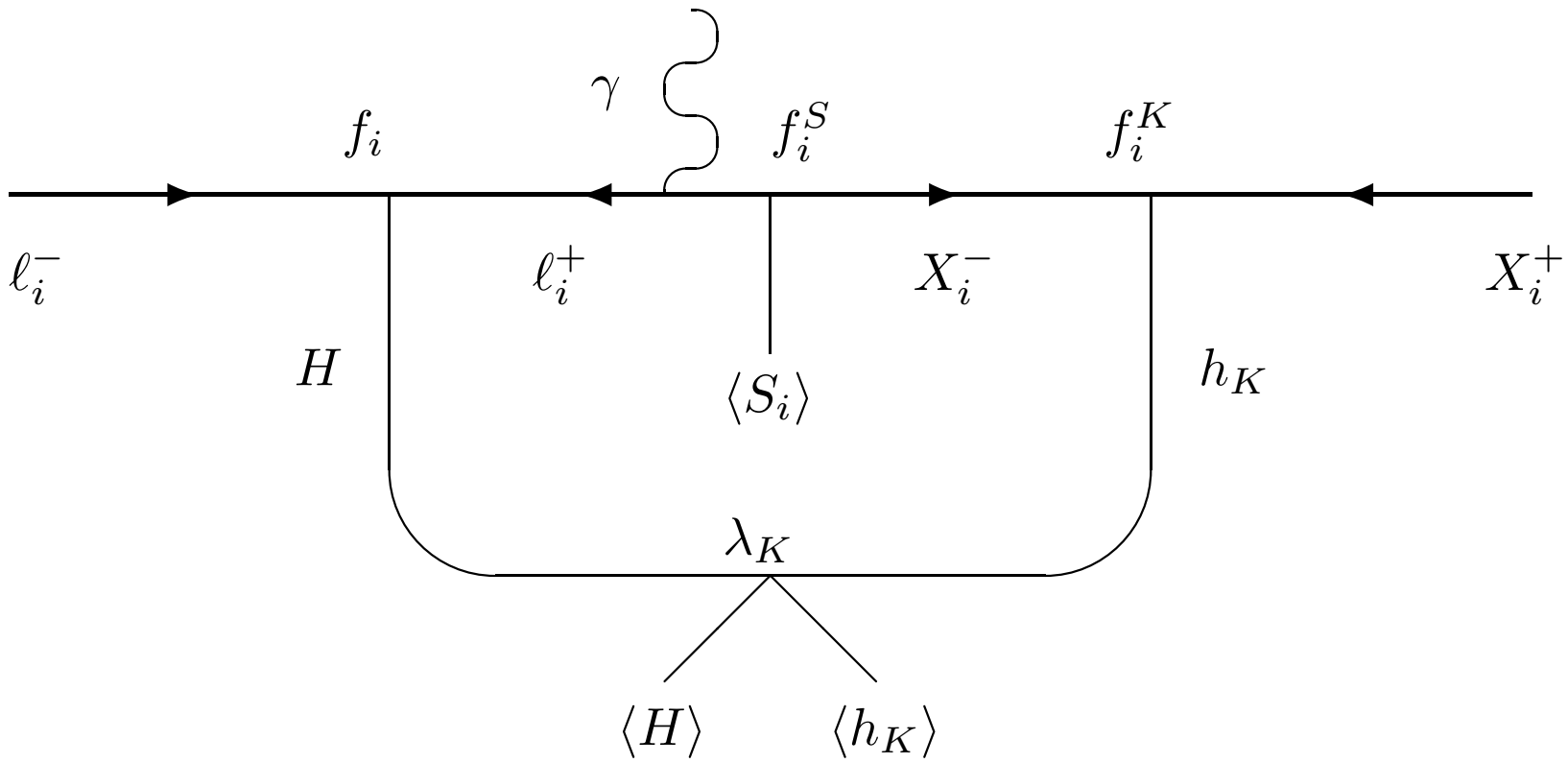

γ
f_i
f_i^S
f_i^K
ℓ_i^-
ℓ_i^+
X_i^-
X_i^+
H
$\langle S_i \rangle$
h_K
λ_K
$\langle H \rangle$
$\langle h_K \rangle$

Fig. 2(b)

Conclusions

- **Muons can serve as powerful probes of physics beyond the Standard Model**
- **Supersymmetry naturally leads to large corrections to muon g-2**
- **Supersymmetric seesaw mechanism suggests observable *$\mu \to e\gamma$ rate***
- **Flavor symmetry for fermion masses and mixings leads to sizable *$\mu \to e\gamma$ rate and EDM***
- **Leptonic EDM need not scale linearly with lepton mass**
- **Large neutrino mixing may indicate muon EDM as large as 10^(-22) e cm**