Lepton Flavor Violation and Physics beyond the Standard Model

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BNL 5/14/04

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Introduction

Standard model + neutrino masses explains almost all the phenomena in particle physics.

Prediction to the LFV process

$\Rightarrow B(\mu \to e\gamma) \sim \underline{\underline{10^{-40}}}$

Why do we care LFV ?

Because we think there is something beyond the SM <u>@ TeV</u>

- Dark matter $\Omega_{DM} \sim 0.3$
  WIMP scenario supports the existence of new particles @ TeV
- Hierarchy problem
  $\Rightarrow$ SUSY ? Extra dim.? technicolor ?

⇒ It's reasonable to assume the SM is valid only up to TeV energy scale.

⊕

We know that Lepton Flavor isn't a fundamental symmetry at all.
It's just an <u>accidental</u> and <u>approximate</u> symmetry.

⇒ We naturally expect the effective operators from UV theory such as

$$\mathcal{L}_{eff} = \frac{v}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu} + h.c.$$

$$\Rightarrow B(\mu \to e\gamma) \simeq 10^{-11} \left(\frac{10^4 \text{ TeV}}{\Lambda} \right)^4 \quad !$$

If chiral symmetry is only broken by fermion masses,

$$\mathcal{L}_{eff} = \frac{m_\mu}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu} + h.c.$$

$$\Rightarrow B(\mu \to e\gamma) \simeq 10^{-11} \left(\frac{10^3 \text{ TeV}}{\Lambda} \right)^4 \quad !$$

LFV in physics beyond the SM

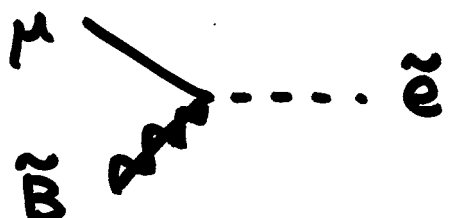
LFV in SUSY

SUSY :
- no quadratic divergence
- gauge coupling unification
- natural DM candidate
- only a little modification of the EW sector

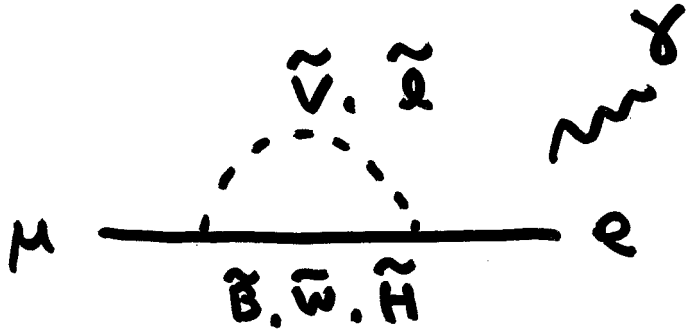
$$\ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \Leftrightarrow \tilde{\ell} = \begin{pmatrix} \tilde{\nu} \\ \tilde{e}_L \end{pmatrix}$$

$$e_R \Leftrightarrow \tilde{e}_R$$

⇒ This extension of the lepton sector generates LFV. In general, we cannot diagonalize the lepton and scalar lepton mass matrices simultaneously.



flavor changing !



$$\Rightarrow B(\mu \to e\gamma) \simeq 10^{-5} \left[\frac{M_W}{M_{SUSY}} \right]^4 \delta_{\tilde{\mu}\tilde{e}} \tan^2\beta$$

$$\left(\delta_{\tilde{\mu}\tilde{e}} \equiv \frac{\Delta m^2_{\tilde{\mu}\tilde{e}}}{\bar{m}^2_{\tilde{\ell}}} \right) \qquad 2 \lesssim \tan\beta \lesssim 60$$

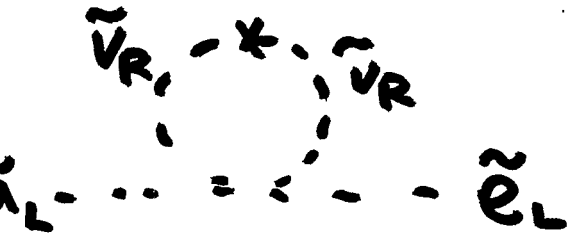
In order to satisfy $B(\mu \to e\gamma) < 10^{-11}$,

we need $\underline{M_{SUSY} \gtrsim 10\,\text{TeV}}$

for $\delta_{\tilde{\mu}\tilde{e}} \sim 1$, $\tan\beta \sim 10$

$\Rightarrow$ mixing has to be small.

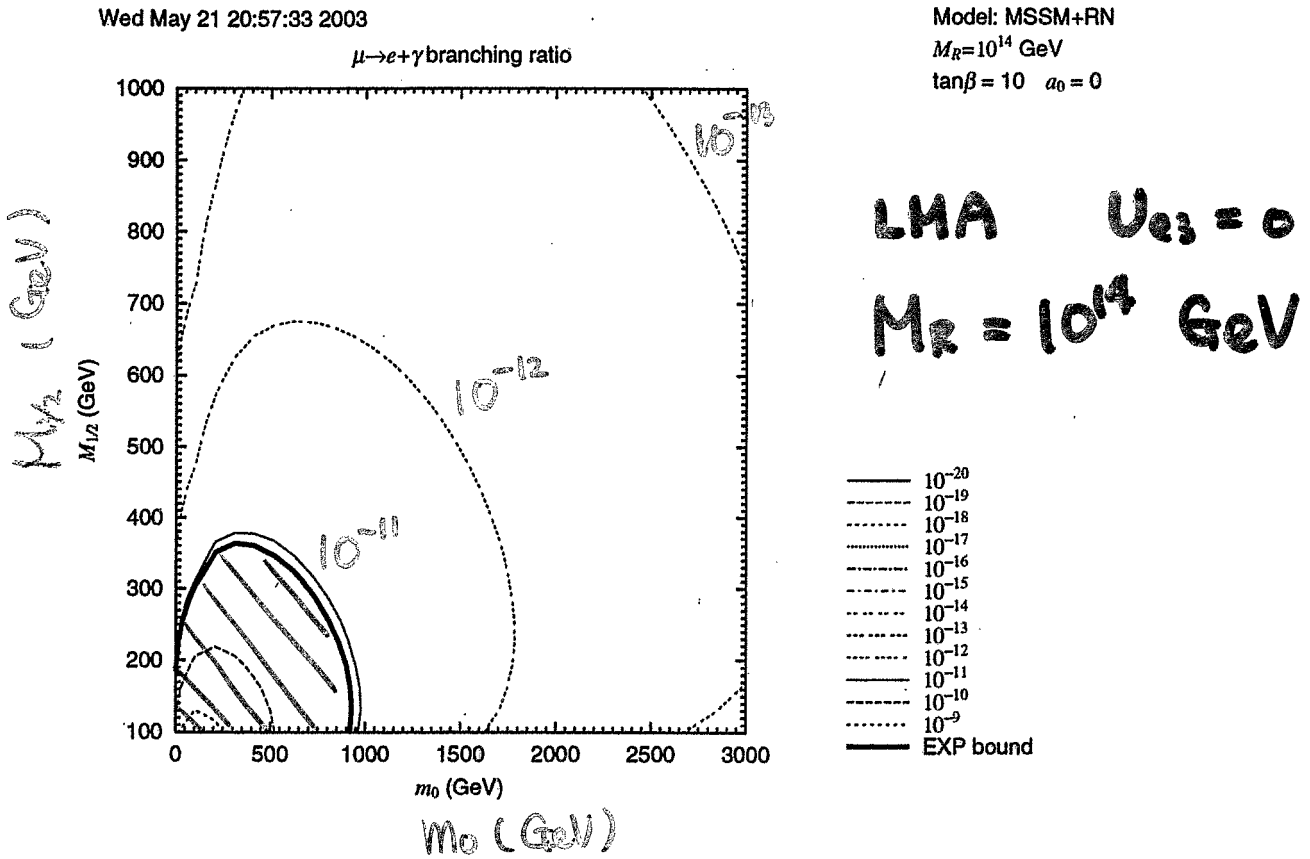
But mixing may be induced from neutrino interactions.

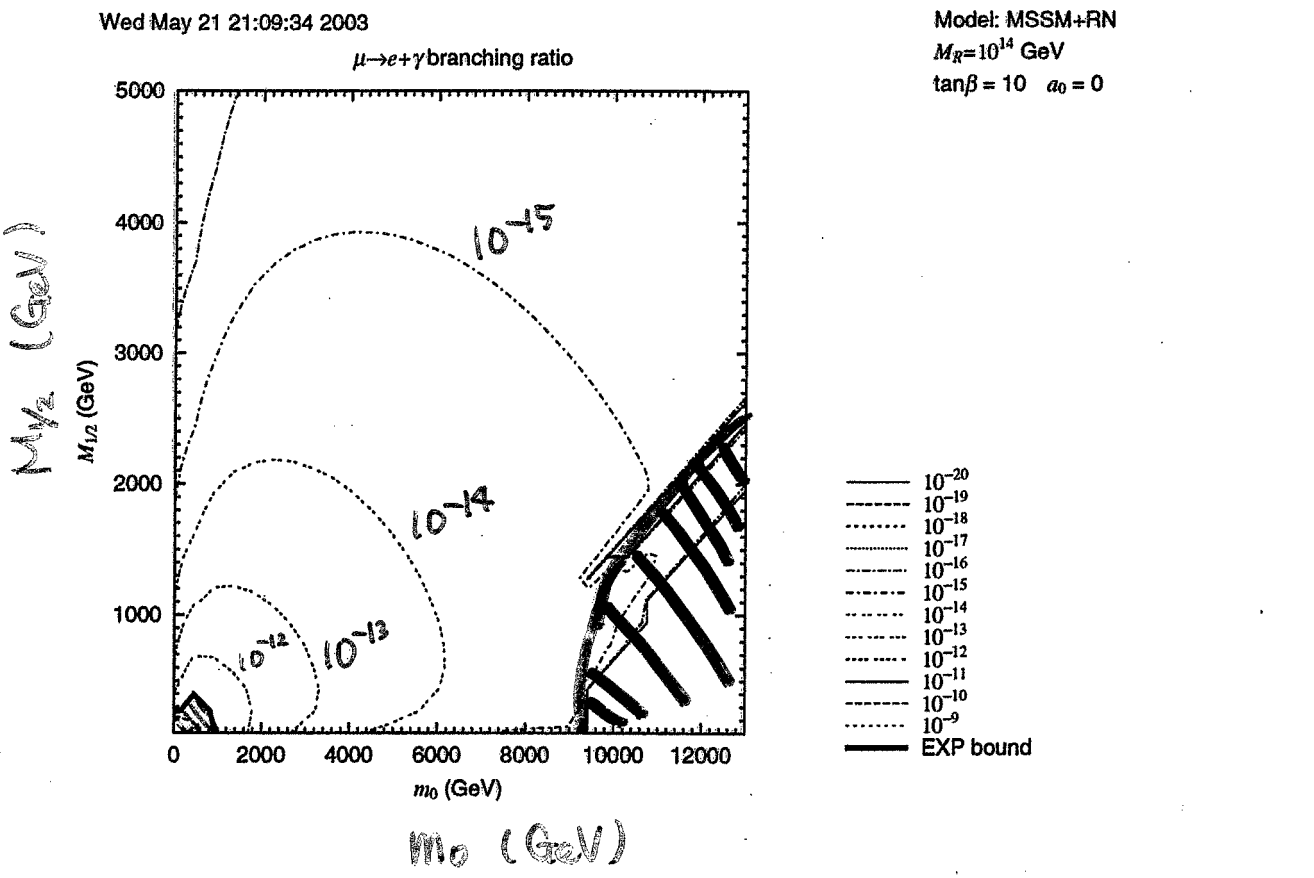


$$\Rightarrow \delta_{\tilde{\mu}\tilde{e}} \simeq \frac{1}{8\pi^2} (f_\nu^\dagger f_\nu)_{e\mu} \times \log \frac{M_{\nu_R}}{M_{pl}}$$

$$\sim 0.1 \quad \text{for } f_\nu \sim O(1)$$

$$\Rightarrow M_{SUSY} \gtrsim 1\,\text{TeV}$$


Wed May 21 20:57:33 2003
μ→e+γ branching ratio
Model: MSSM+RN
M_R=10^14 GeV
tanβ = 10 a_0 = 0
LHA U_{e3} = 0
M_R = 10^14 GeV
$M_{1/2}$ (GeV)
m_0 (GeV)
10^-13
10^-12
10^-11
10^-20
10^-19
10^-18
10^-17
10^-16
10^-15
10^-14
10^-13
10^-12
10^-11
10^-10
10^-9
EXP bound


Wed May 21 21:09:34 2003
μ→e+γ branching ratio
Model: MSSM+RN
M_R=10^14 GeV
tanβ = 10 a_0 = 0
$M_{1/2}$ (GeV)
m_0 (GeV)
10^-15
10^-14
10^-13
10^-12
10^-20
10^-19
10^-18
10^-17
10^-16
10^-15
10^-14
10^-13
10^-12
10^-11
10^-10
10^-9
EXP bound

Leptogenesis and LFV

Ibe, RK, Murayama
Tanagida (2009)

$\bar{\ell}$ $\quad H^\dagger$ $\quad \Delta L \to \Delta B$

$\Rightarrow$ $M_{\nu_{R1}} \gtrsim 10^9$ GeV for enough $\cancel{CP}$

$\Rightarrow$ $T_{RH} \gtrsim 10^9$ GeV

$\Rightarrow$ too much gravitinos which spoil the success of BBN

$\Rightarrow$ anomaly mediation
gravitinos are heavy. They decay before BBN

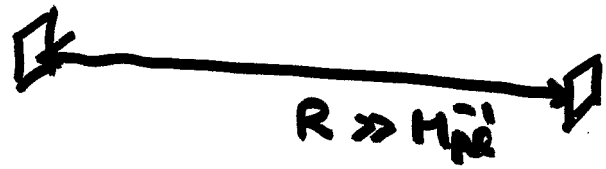
$\Rightarrow$ Prediction on LFV

$B(\mu \to e\gamma) \sim 10^{-11}$!

LFV in extra dim.

extra dim. : Solution to the Hierarchy problem by lowering the cut-off scale.

- large extra dim.



$$M_{pl}^2 = M_F^{2+D} R^D$$

$\Rightarrow M_F \ll M_{pl}$

- Randall - Sundrum model

$$M_{pl} = e^{kr_c} \Lambda_{IR}$$

$\Rightarrow$ cut-off scale is TeV

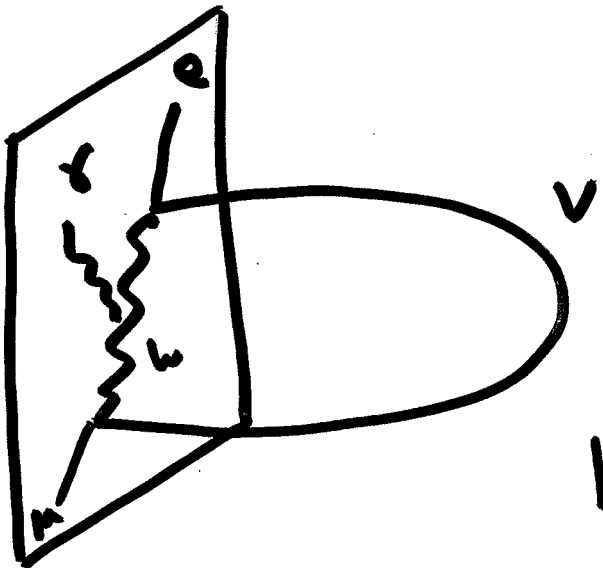
$\Rightarrow$ We expect

$$\mathcal{L}_{eff} = \frac{v}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu} + \dots$$

$\Rightarrow$ too large $B(\mu \to e\gamma)$!

Even if we could avoid $1/\Lambda^2$ operators.

we have ...



bulk neutrino loop

(neutrinos are in the bulk to explain the tiny neutrino masses)

⇒ large extra dim. $M_F \gtrsim 35$ TeV

Faraggi, Pospelov (1999)

RS model $m_{KK} \gtrsim 25$ TeV

RK (2000)

LFV in technicolor

technicolor : $\langle \bar{t}t \rangle \neq 0$ breaks $SU(2) \times U(1)$

no fundamental scalar field

$\Rightarrow$ no hierarchy problem

fermion masses

$$\frac{1}{\Lambda^2} \bar{q}_L u_R \bar{t} t \quad \Rightarrow \quad m_f \sim \frac{\langle \bar{t}t \rangle}{\Lambda^2}$$

$\Rightarrow$ There is no reason to forbid

$$\frac{v}{\Lambda^2} \bar{\mu} \sigma^{\mu\nu} e F_{\mu\nu} \quad \text{or} \quad \frac{1}{\Lambda} \bar{\mu} \gamma^\mu e \bar{q} \gamma_\mu q$$

too large $B(\mu \to e\gamma)$ or $B(\mu \to e; N)$

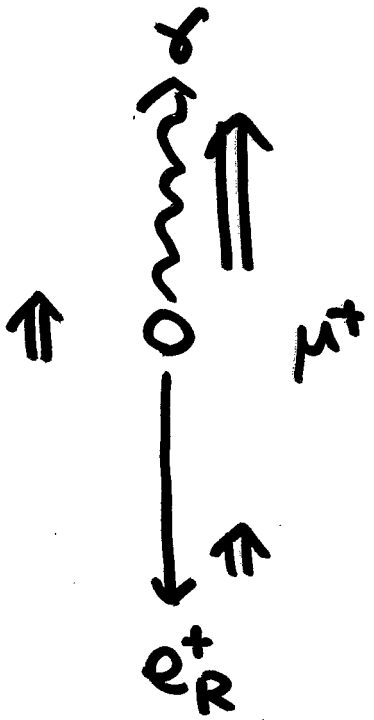
$\Rightarrow$ Major models of physics beyond the SM predict large (too large?) LFV.

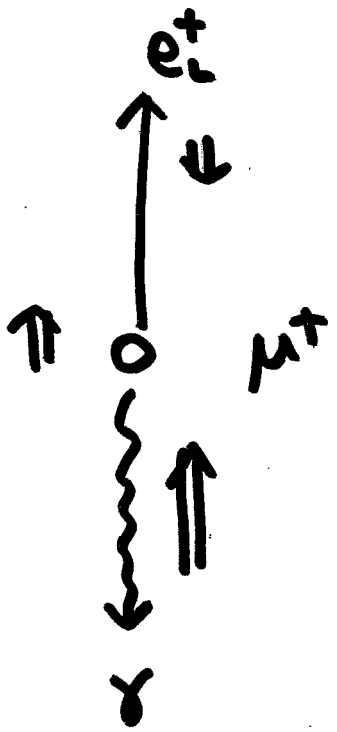
LFV processes

We learned LFV is important in physics beyond the SM. Now we try to extract information on new physics from LFV processes.

- $\mu \to e\gamma$ decay

$B(\mu \to e\gamma) < 1.2 \times 10^{-11}$ (MEGA, 1999)





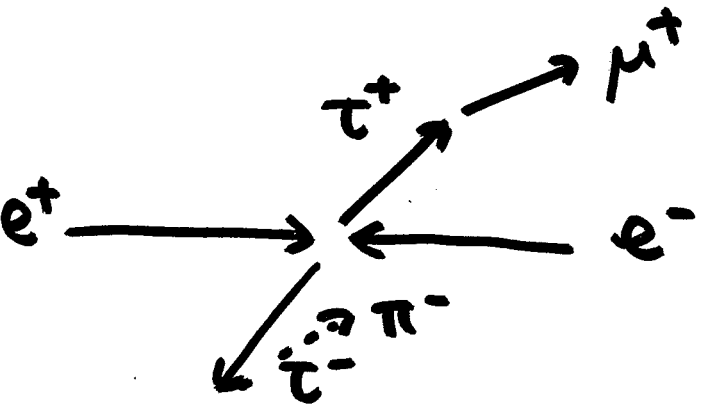
neutrino origin

$\bar{\mu}\sigma^{\mu\nu}P_L e$ $\qquad$ $\bar{\mu}\sigma^{\mu\nu}P_R e$

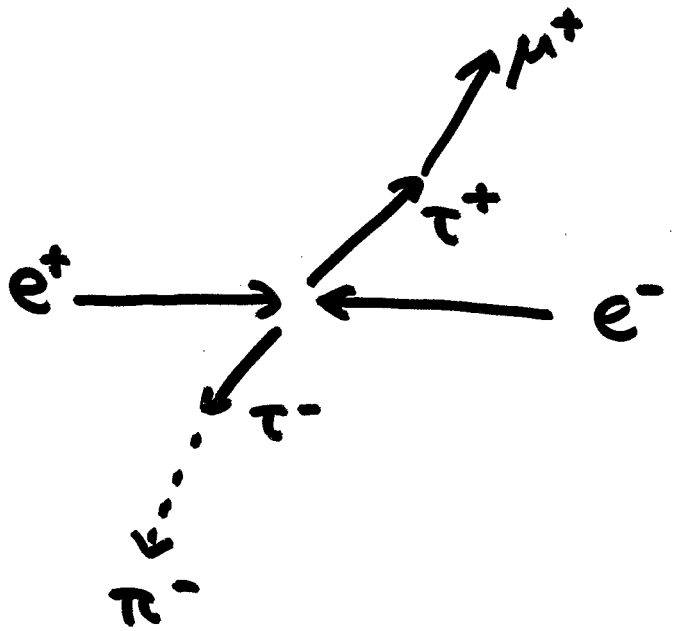
Okumura, Okada, Shimizu (2000)

- $\tau \to \mu\gamma$ decay RK, Okada (2001)

$B(\tau \to \mu\gamma) < 3.1 \times 10^{-7}$ (Belle, 2003)



$\bar{\tau}\sigma^{\mu\nu}P_L\mu$



$\bar{\tau}\sigma^{\mu\nu}P_R\mu$

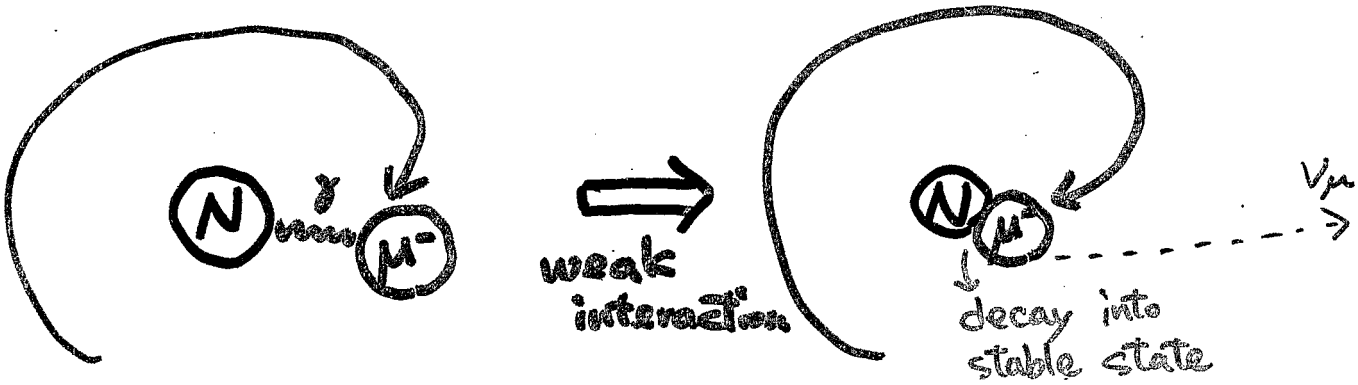
- $\mu \to e$ conversion in nuclei

$B(\mu \to e; T_i) < 6.1 \times 10^{-13}$

(SINDRUM II, 1998)

This process has rich information on new physics.

μ-e conversion in nuclei

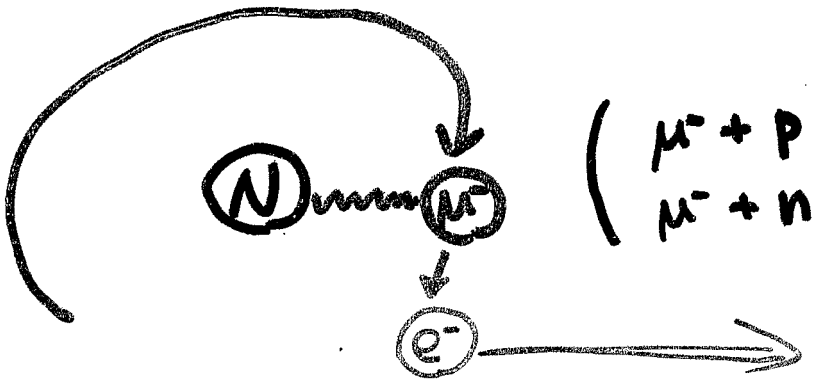


muonic atom

$(\mu^- + p \rightarrow \nu_\mu + n)$

muon capture

LFV interaction



$$\left(\begin{array}{l} \mu^- + p \rightarrow e^- + p \\ \mu^- + n \rightarrow e^- + n \end{array} \right)$$

μ-e conversion

$$E_e = m_\mu - E_{binding}$$

$\Uparrow$

clear signal

(kinematical endpoint of background process)

N: ground state
$\Downarrow$ transition
ground state

⇒ we can take coherent sum of the amplitudes.

⇒ factor of Z larger than other transitions.

What's interesting ?

- Target atom dependence of the branching ratio.
- relative size compared to $\mu \to e\gamma$ decay.

$\Rightarrow$ We need detailed calculation for various nuclei.

Previous calculations

- 1959 Weinberg and Feinberg
  non-relativistic calculation
- 1979 Shanker
  relativistic effect, Coulomb distortion
- 1997 Czarnecki, Marciano, Melnikov
  correct the calculation of the photonic transition.

We follow the method of CMM and evaluate the conversion rate for various nuclei with up-dated nuclear data.

General LFV interactions

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\left[m_\mu A_R \, \bar{\mu}\sigma^{\mu\nu} P_L e \, F_{\mu\nu} + (L \leftrightarrow R) \right]$$

$$- \frac{G_F}{\sqrt{2}} \sum_q \Big[g_{LS}(q) \, \bar{e} P_R \mu \cdot \bar{q} q + (L \leftrightarrow R)$$

$$+ g_{LV}(q) \, \bar{e} \gamma^\mu P_L \mu \cdot \bar{q} \gamma_\mu q + (L \leftrightarrow R) \Big]$$

$$+ \text{H.c.}$$

(effective Lagrangian for coherent conversion)

to get amplitudes

$$\bar{q} q \rightarrow \langle N | \bar{q} q | N \rangle = C_p^S \rho_p + C_n^S \rho_n$$

$$\bar{q} \gamma^0 q \rightarrow \langle N | \bar{q} \gamma^0 q | N \rangle = C_p^V \rho_p + C_n^V \rho_n$$

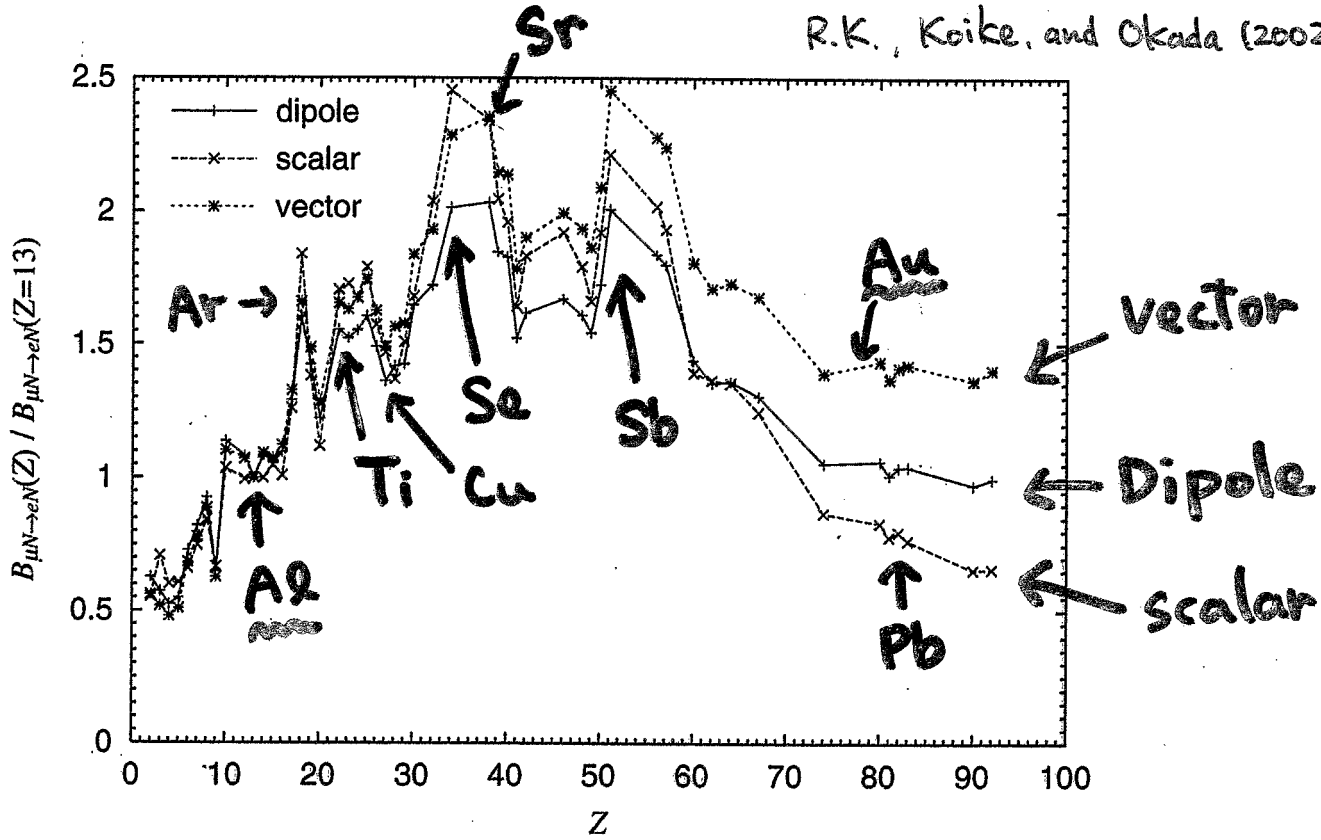
$$F^{0r} \rightarrow \langle N | F^{0r} | N \rangle = \frac{Ze}{r^2} \int_0^r r'^2 \rho_p(r') \, dr'$$

$\mu, e \rightarrow$ wave functions obtained by solving Dirac eq. in the electric potential.

$\Rightarrow$ All we need is $\rho_p(r)$ and $\rho_n(r)$

We take these densities from the experimental data.

R.K., Koike, and Okada (2002)



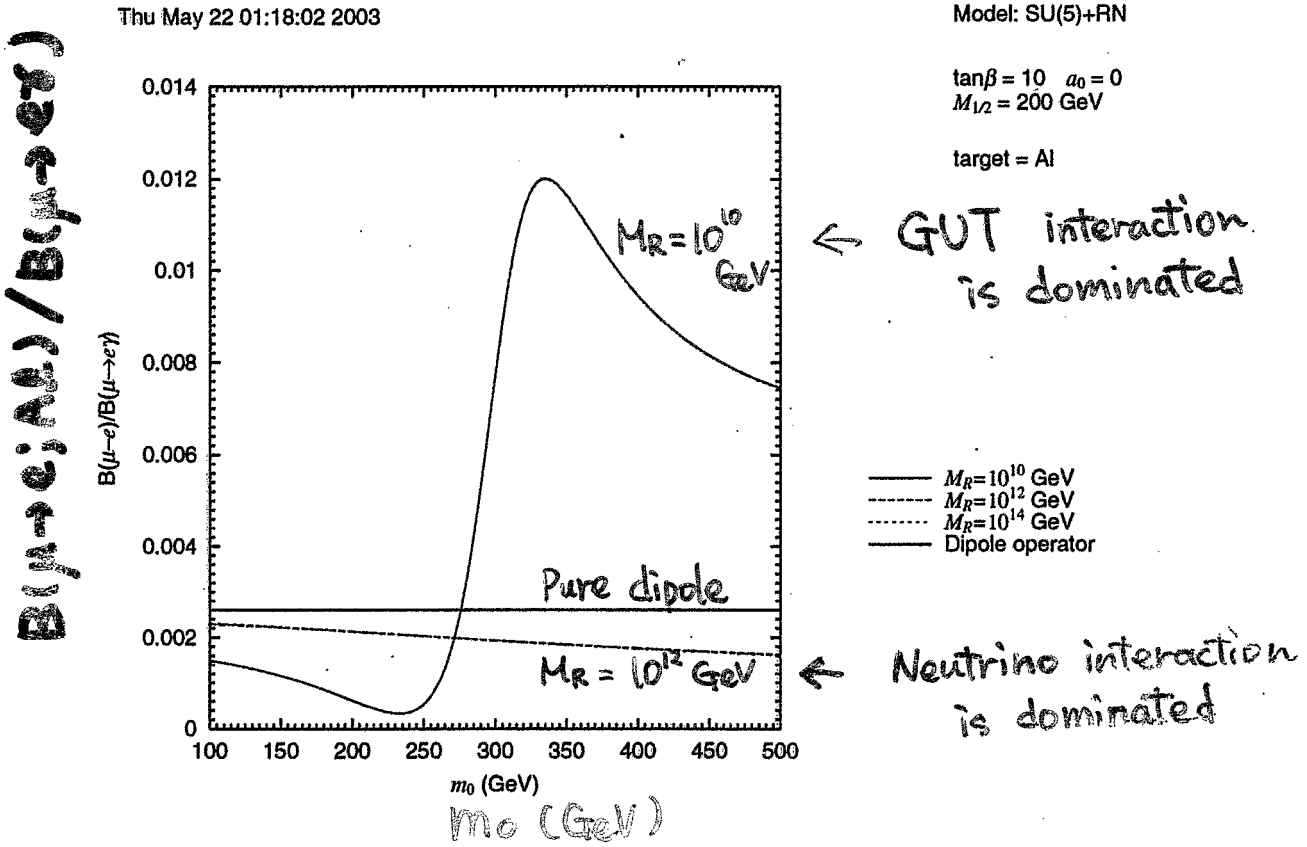
conversion branching ratio ($\equiv \dfrac{\omega_{conv}}{\omega_{capture}}$)
normalized by $B_{\mu N\to eN}(Z=13)$

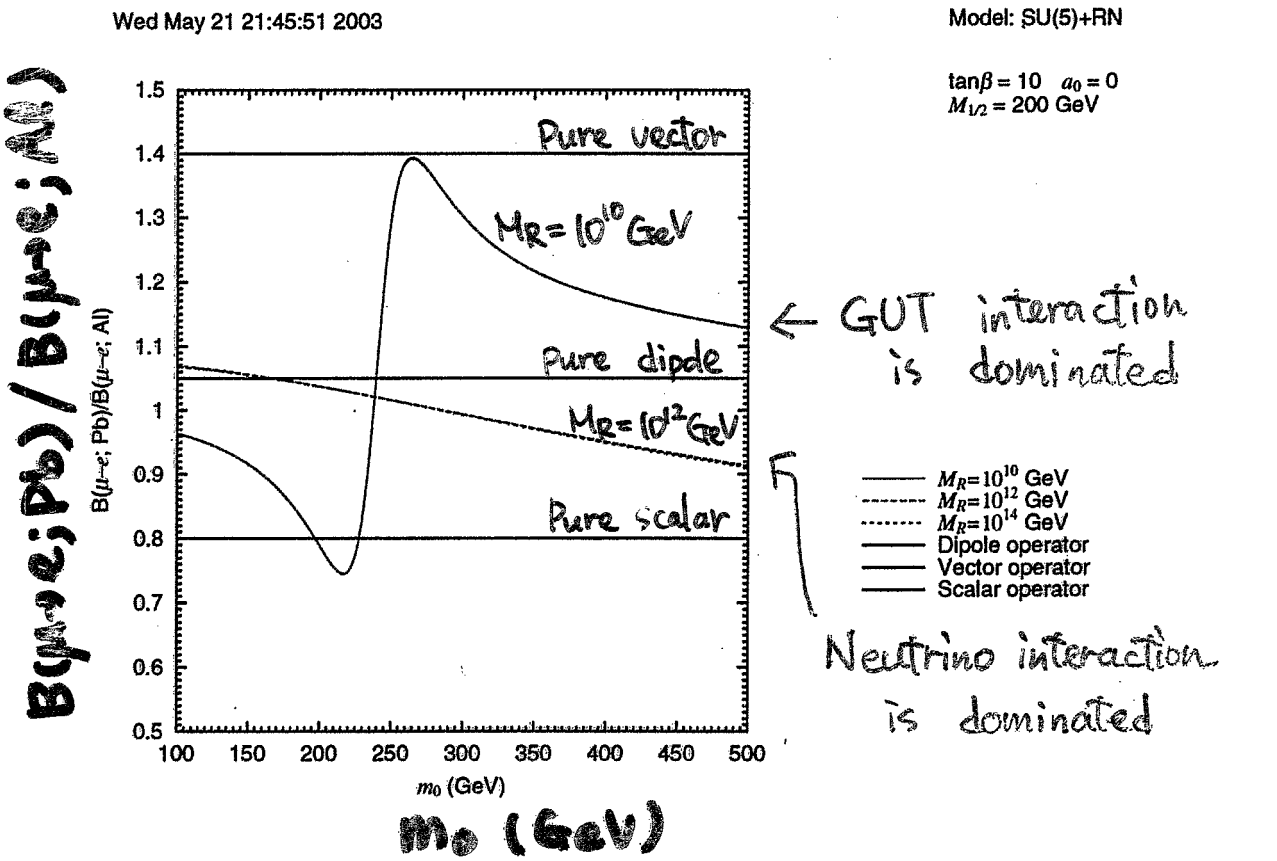
- $Z = 30-60$ give large branching ratio
- $\dfrac{B(Z:\text{heavy})}{B(Z:\text{light})}$ has significant model dependence.

vector : SU(5) GUT

scalar : R-parity violation, Higgs exchange

dipole : SO(10) GUT, MSSM + V_R


Thu May 22 01:18:02 2003
Model: SU(5)+RN
tanβ = 10 a0 = 0
M1/2 = 200 GeV
target = Al
B(μ→e; Al)/B(μ→eγ)
B(μ→e)/B(μ→eγ)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
100 150 200 250 300 350 400 450 500
m0 (GeV)
MR=10^10 GeV
Pure dipole
MR = 10^12 GeV
← GUT interaction is dominated
← Neutrino interaction is dominated
MR=10^10 GeV
MR=10^12 GeV
MR=10^14 GeV
Dipole operator
m0 (GeV)

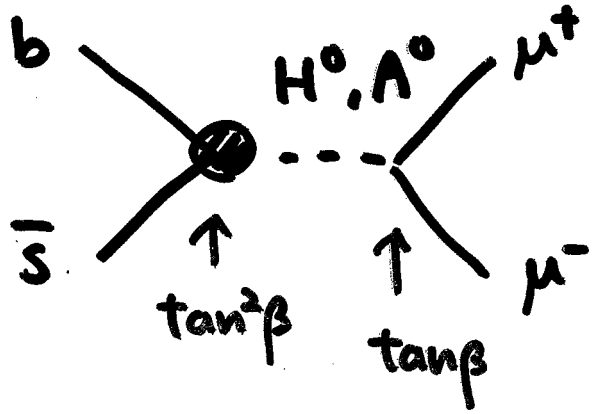

Wed May 21 21:45:51 2003
Model: SU(5)+RN
tanβ = 10 a0 = 0
M1/2 = 200 GeV
B(μ→e; Pb)/B(μ→e; Al)
B(μ→e; Pb)/B(μ→e; Al)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
100 150 200 250 300 350 400 450 500
m0 (GeV)
Pure vector
MR=10^10 GeV
Pure dipole
MR=10^12 GeV
Pure scalar
← GUT interaction is dominated
MR=10^10 GeV
MR=10^12 GeV
MR=10^14 GeV
Dipole operator
Vector operator
Scalar operator
Neutrino interaction is dominated
m0 (GeV)

Higgs-mediated μ-e conversion

Choudhury, Gaur (1999)
Hamzaoui, Pospelov, Toharia (1999)
Babu, Kolda (2000)

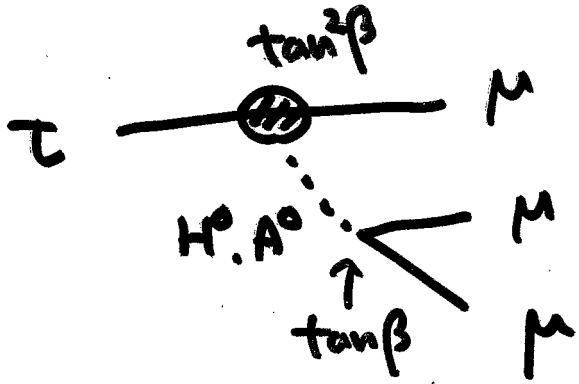
Higgs-mediated FCNC

It is pointed out that



is large for small m_{A^0} and large $\tan\beta$.

Also



Babu, Kolda (2002)
Dedes, Ellis, Raidal (2002)

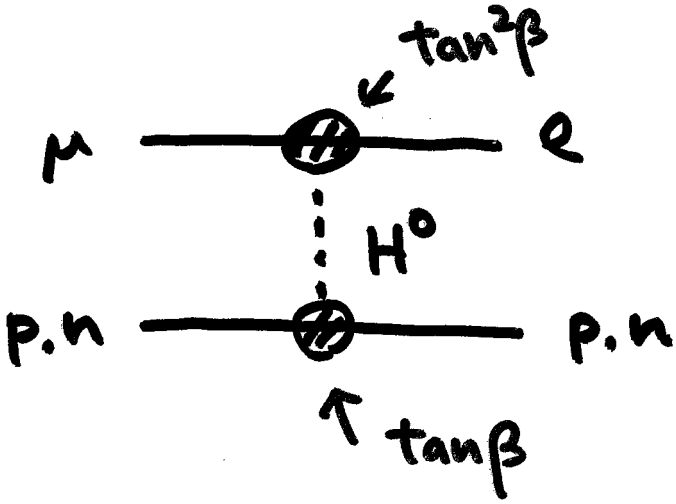
is large

because of $B \propto (\tan\beta)^6 \frac{1}{m_A^4}$

$\Rightarrow$ For large $\tan\beta$ and $m_A \ll m_{SUSY}$, this effect becomes more important than the other diagrams such as photon exchange contribution.

μ-e conversion

RK, Koike, Komine, Okada (2003)



H^0-p-p coupling is NOT suppressed by quark masses. The contribution from strange quark dominates.

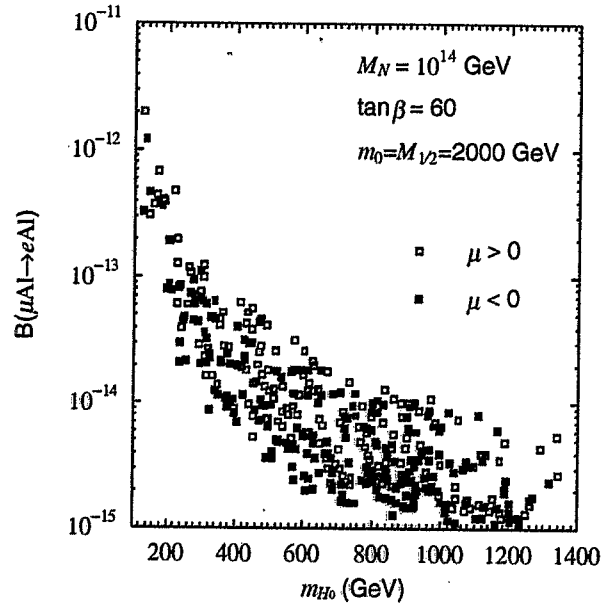
$$\Rightarrow B(\mu \to e; Al)_H \simeq O(10^{-13}) \left[\frac{200\,\mathrm{GeV}}{m_{H^0}}\right]^4 \left[\frac{\tan\beta}{60}\right]^6$$

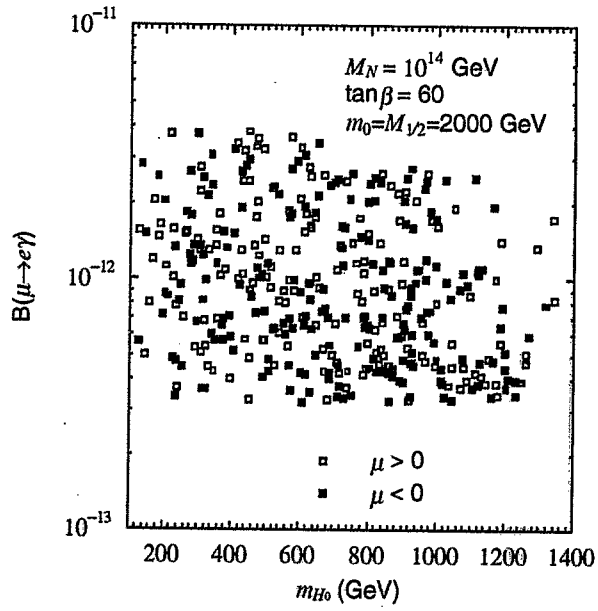
in SUSY-seesaw model

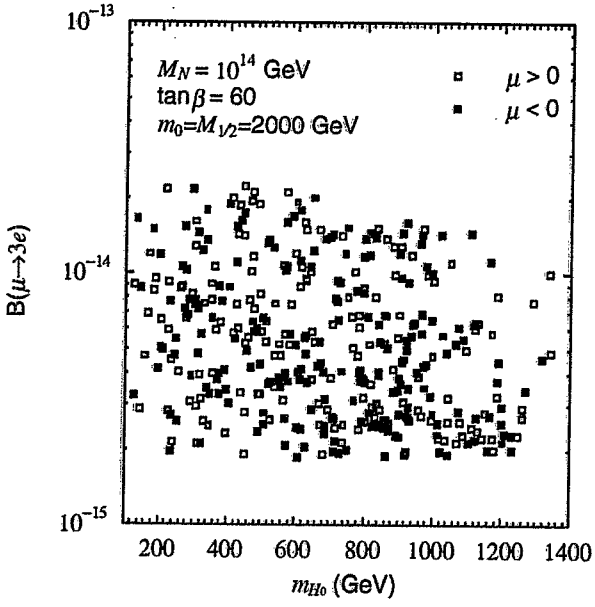
whereas

$$B(\mu \to e; Al)_\gamma \simeq O(10^{-13}) \left[\frac{1000\,\mathrm{GeV}}{m_{SUSY}}\right]^4 \left[\frac{\tan\beta}{60}\right]^2$$

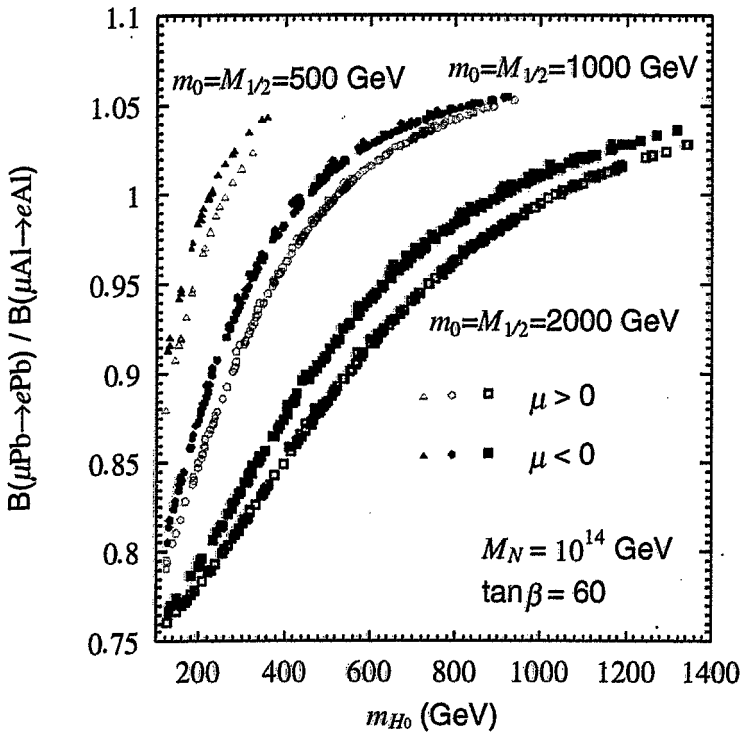
Branching ratios





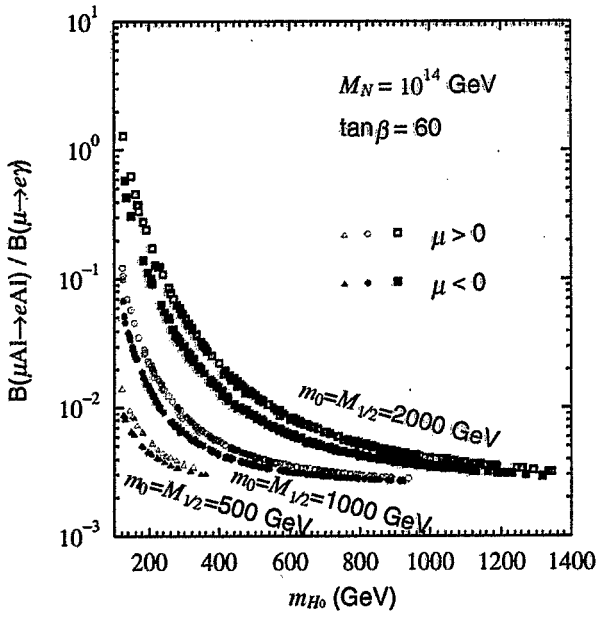


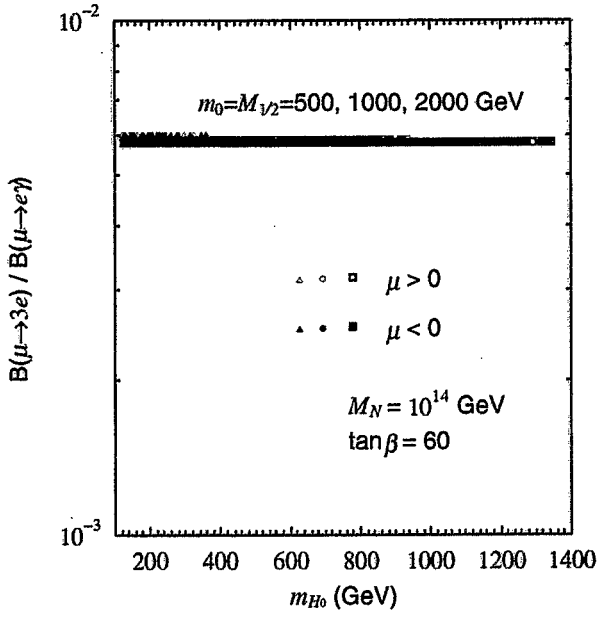
- We can see the enhancement of $B(\mu\mathrm{Al} \to e\mathrm{Al})$ in $m_{H^0} \lesssim$ 600GeV region.
- The enhancement is absent in $\mu \to e\gamma$ decay.
- We cannot see the effect of the Higgs-mediation in $\mu \to 3e$ decay, because of the small Yukawa coupling of the electron.



- For small m_{H^0}, the value approaches to the scalar prediction (0.70), and as increasing m_{H^0} the value increase and approaches to the dipole prediction (1.1).
- We can confirm the existence of the scalar operator.
- This ratio gives us the size of the Higgs mediation effect.

Ratio of the branching ratios





- $B(\mu\mathrm{Al} \to e\mathrm{Al})/B(\mu \to e\gamma)$ can reach $O(1)$ for small m_{H^0}.
- For large m_{H^0}, the ratio approaches to 0.0026 which is the value of dipole operator dominated case.
- We cannot see the enhancement in the $\mu \to 3e$ decay.
- These figures don't depend on the source of LFV.

Summary

- LFV is very important. Many new physics predict large LFV.
- LFV processes have useful information on new physics. The impact of the discovery is very big. I think bigger than that of the Higgs boson.
- $\mu \to e$ conversion is interesting. $B(\mu \to e; N) / B(\mu \to e\gamma)$ and the target atom dependence may reveal the nature of LFV.