# 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

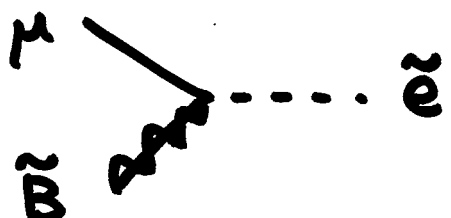
## LFV in SUSY

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

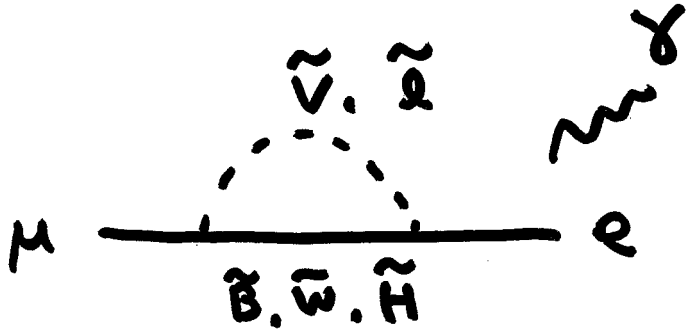
$$\ell = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \Leftrightarrow \tilde{\ell} = \begin{pmatrix} \tilde{\nu} \\ \tilde{e}_L \end{pmatrix}$$

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

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




flavor changing !




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

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

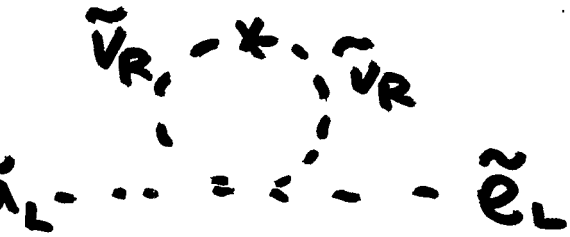
In order to satisfy $B(\mu \to e\gamma) < 10^{-11}$,

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.

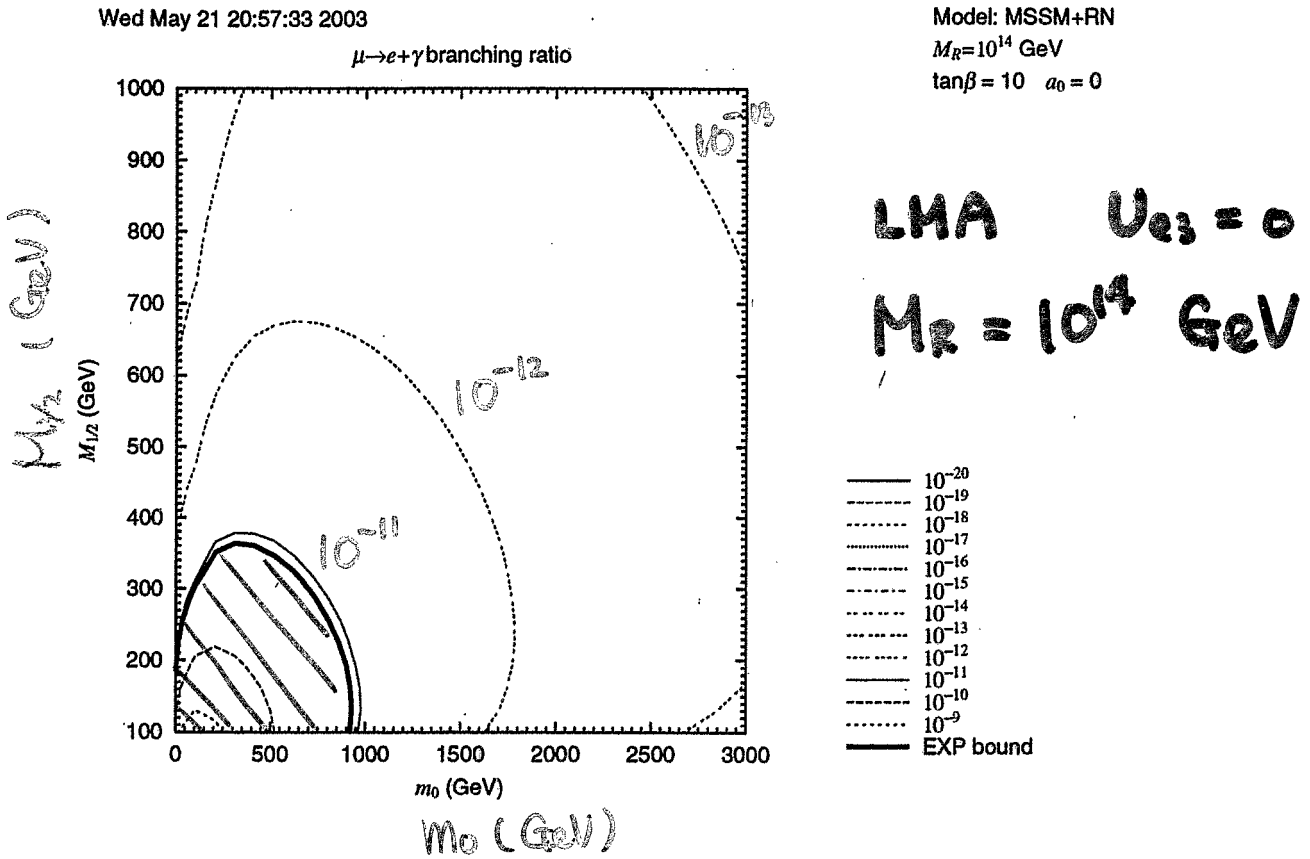
But mixing may be induced from neutrino interactions.

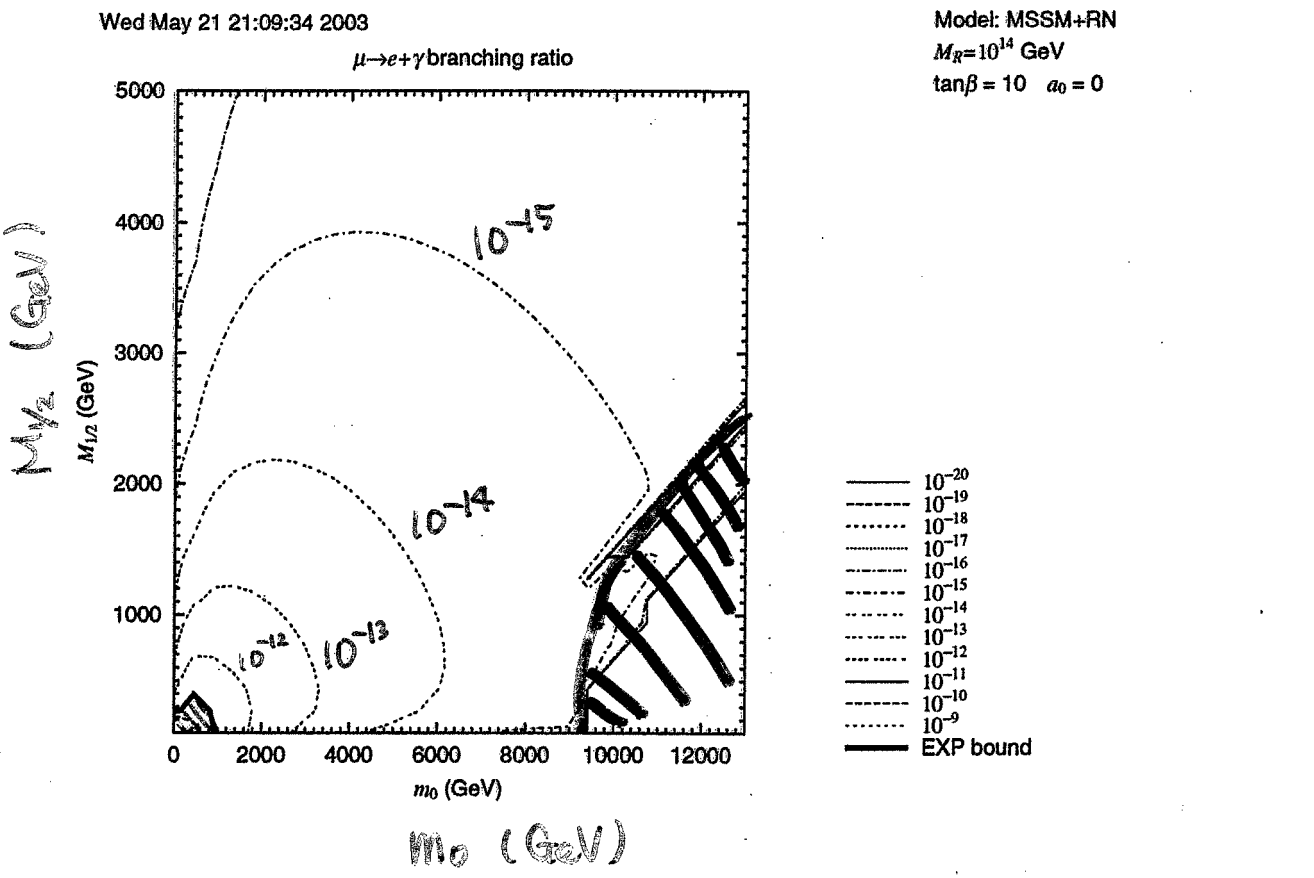



$$\Rightarrow \delta_{\tilde{\mu}\tilde{e}} \simeq \frac{1}{8\pi^2} (f_\nu^\dagger f_\nu)_{e\mu} \times \log \frac{M_{\nu_R}}{M_{pl}}$$

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

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


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

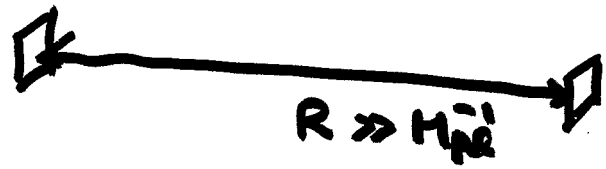
$\Rightarrow$ Prediction on LFV

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

# 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

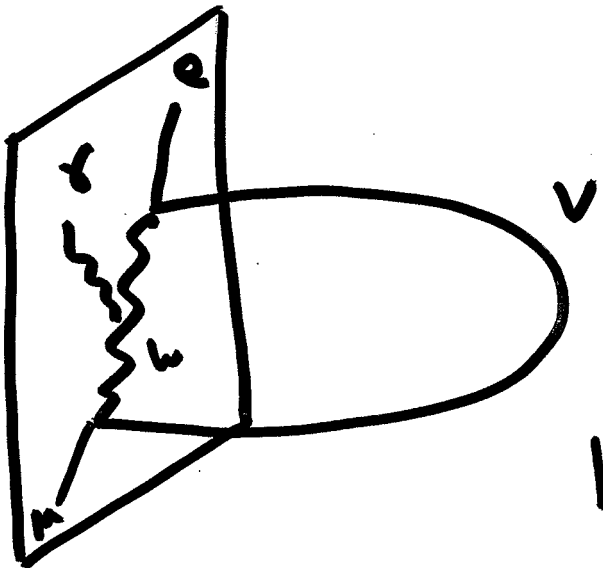
$\Rightarrow$ We expect

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

$\Rightarrow$ 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 $B(\mu \to e; N)$

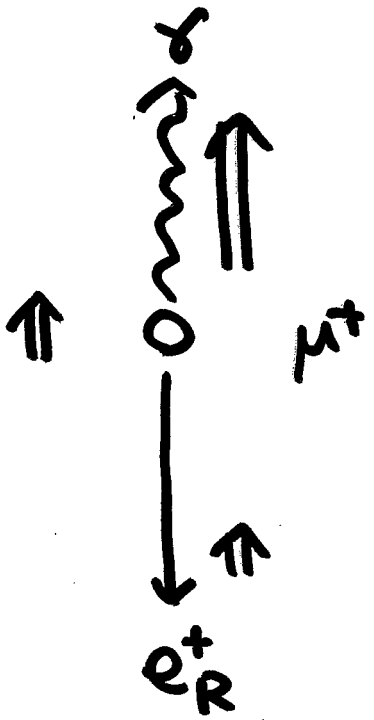
$\Rightarrow$ Major models of physics beyond the SM predict large (too large?) LFV.

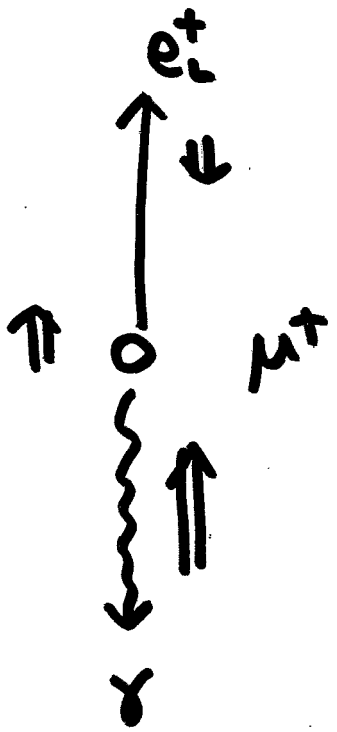
# LFV processes

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)



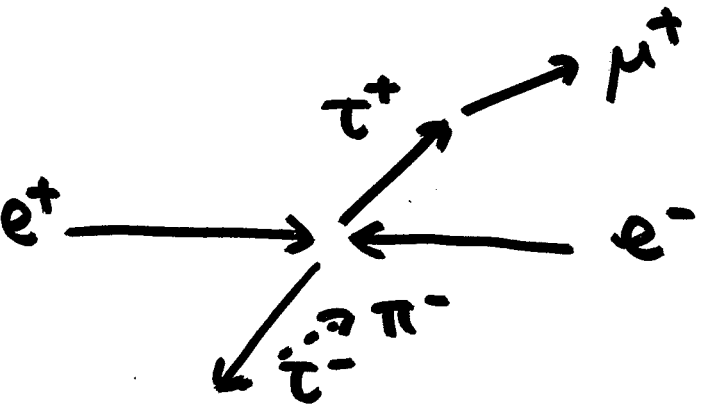

neutrino origin

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

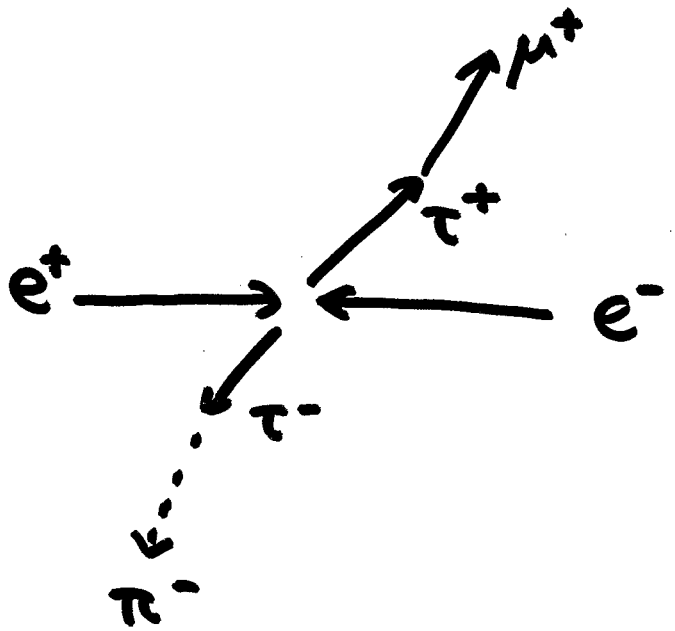
Okumura, Okada, Shimizu (2000)

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

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




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




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

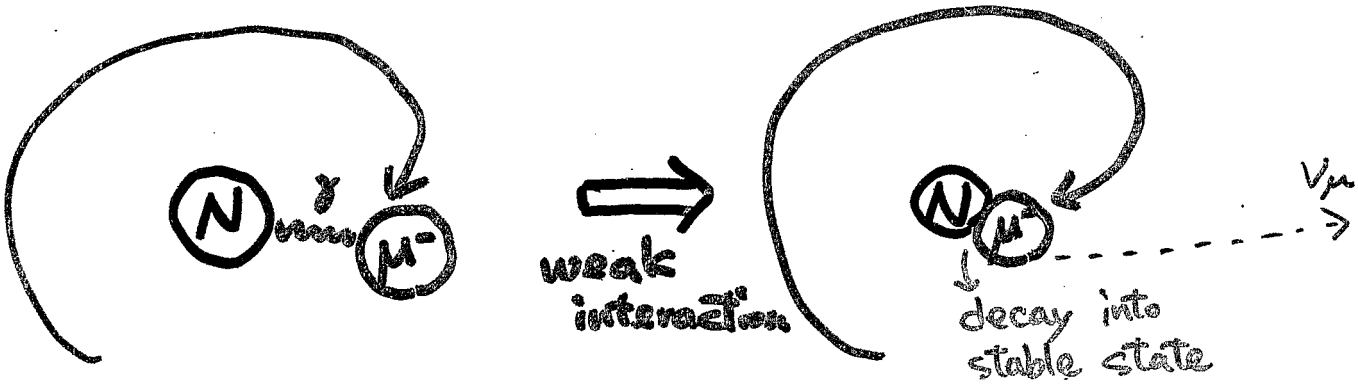
- $\mu \to e$ conversion in nuclei

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

(SINDRUM II, 1998)

This process has rich information on new physics.

# μ-e conversion in nuclei

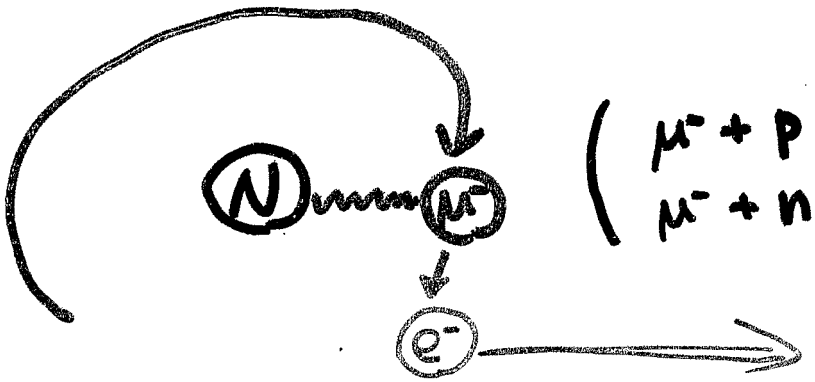



**muonic atom**

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

**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

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

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

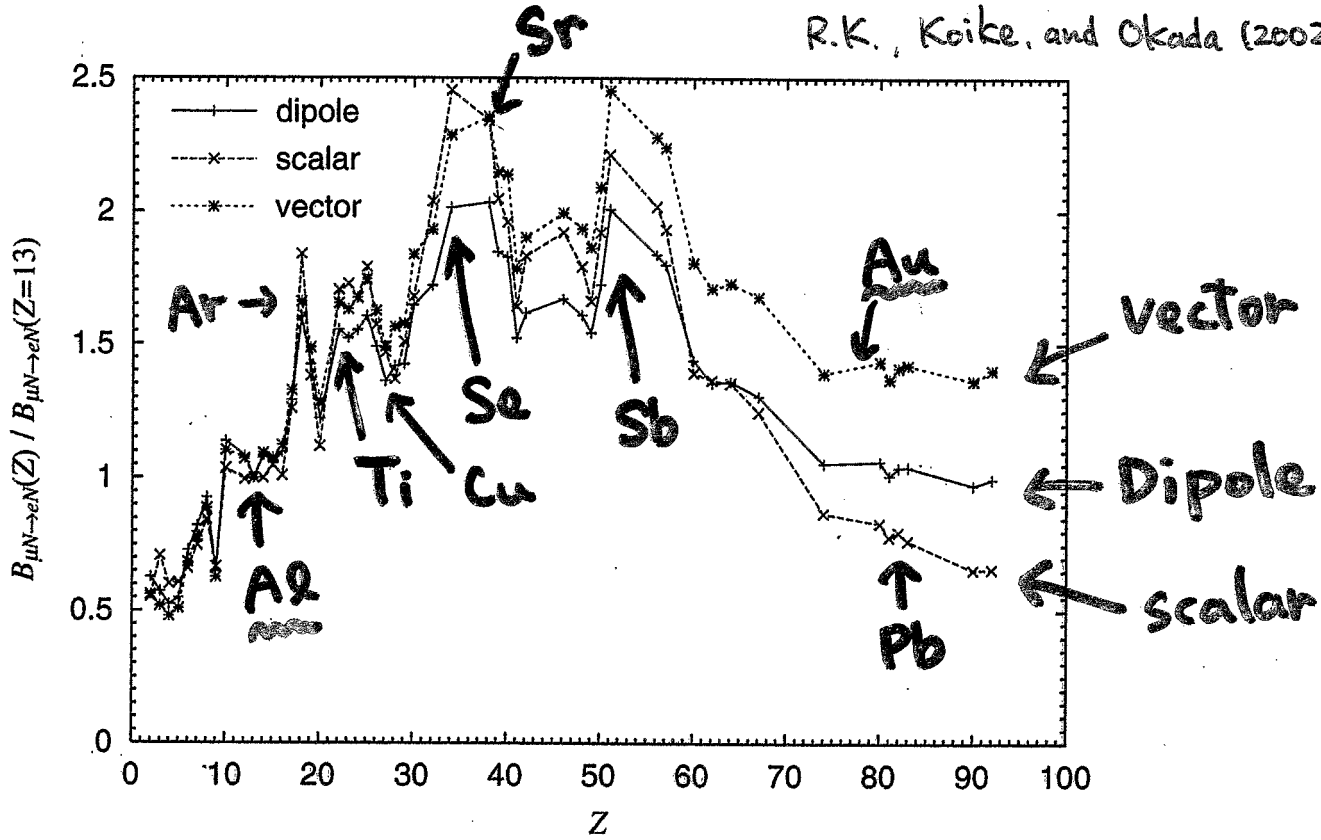
$$F^{0r} \rightarrow \langle N | F^{0r} | N \rangle = \frac{Ze}{r^2} \int_0^r r'^2 \rho_p(r') \, dr'$$

$\mu, e \rightarrow$ 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)



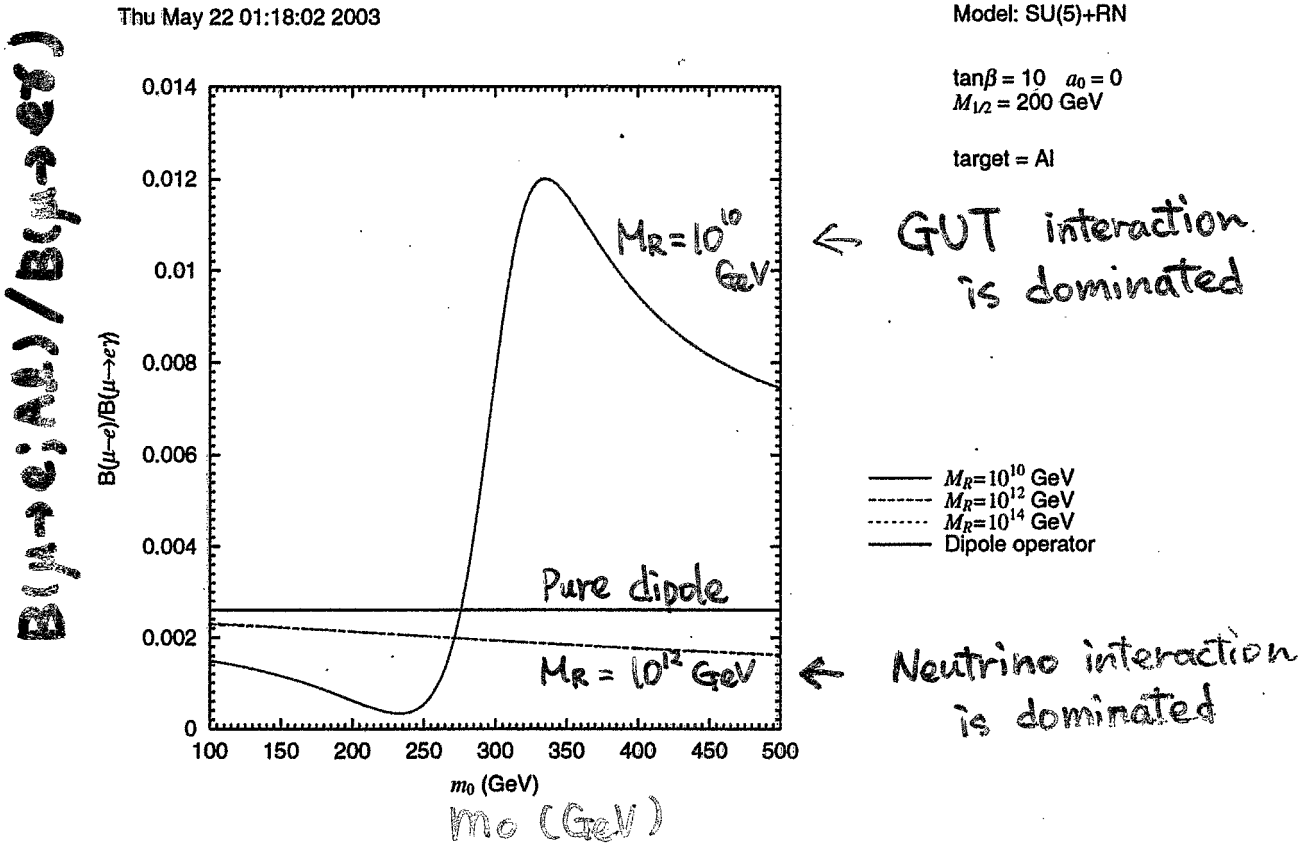

conversion branching ratio ($\equiv \dfrac{\omega_{conv}}{\omega_{capture}}$)
normalized by $B_{\mu N\to eN}(Z=13)$

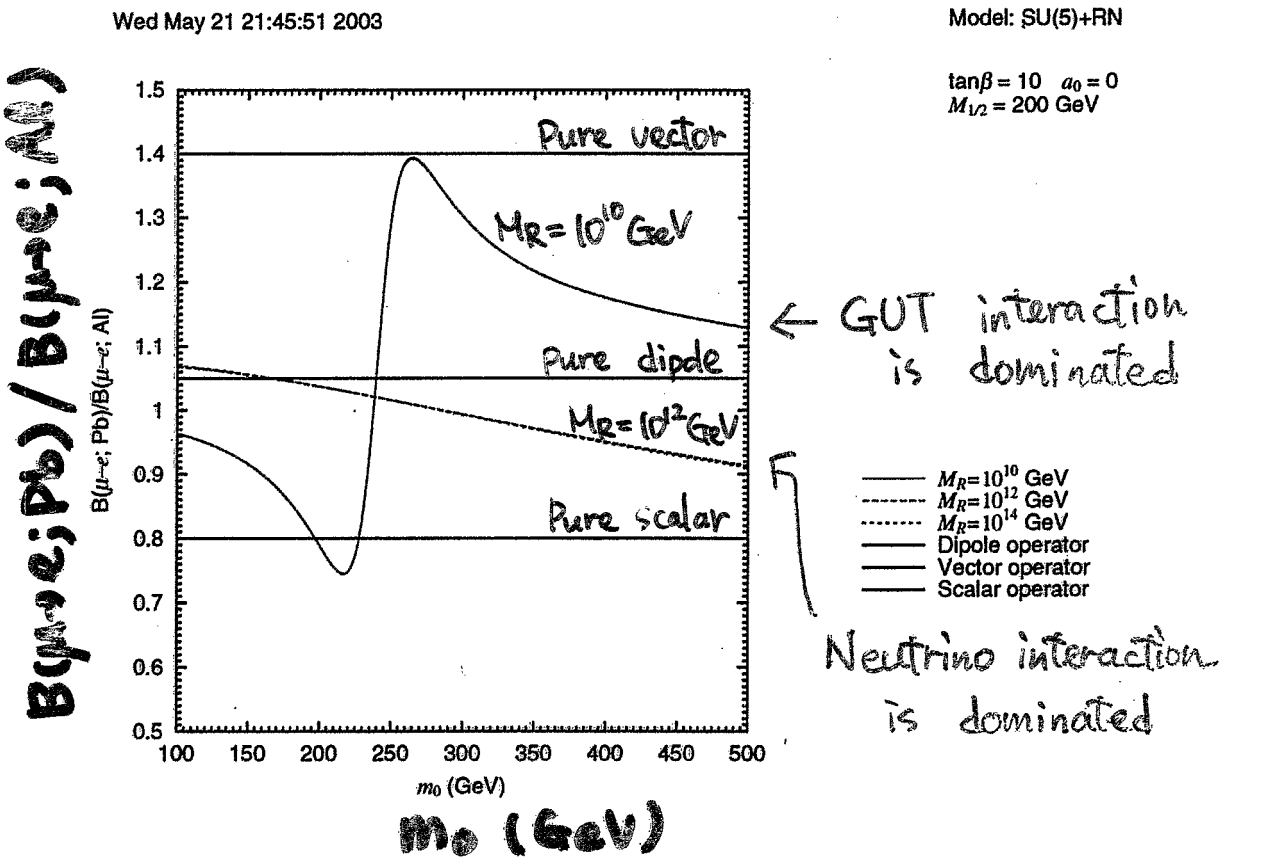
- $Z = 30-60$ give large branching ratio
- $\dfrac{B(Z:\text{heavy})}{B(Z:\text{light})}$ has significant model dependence.

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)

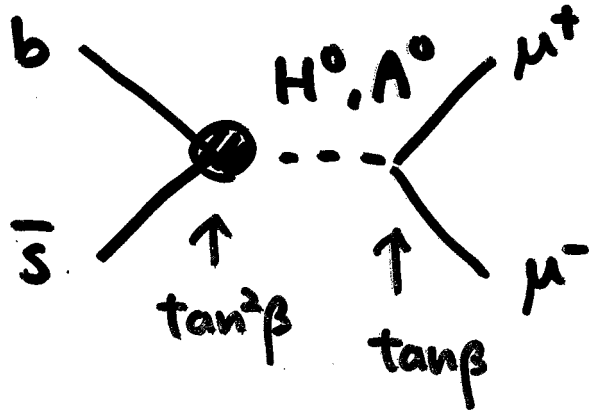

Wed May 21 21:45:51 2003
Model: SU(5)+RN
tanβ = 10 a0 = 0
M1/2 = 200 GeV
B(μ→e; Pb)/B(μ→e; Al)
B(μ→e; Pb)/B(μ→e; Al)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
100 150 200 250 300 350 400 450 500
m0 (GeV)
Pure vector
MR=10^10 GeV
Pure dipole
MR=10^12 GeV
Pure scalar
← GUT interaction is dominated
MR=10^10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

# Higgs-mediated $\mu$-e conversion

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

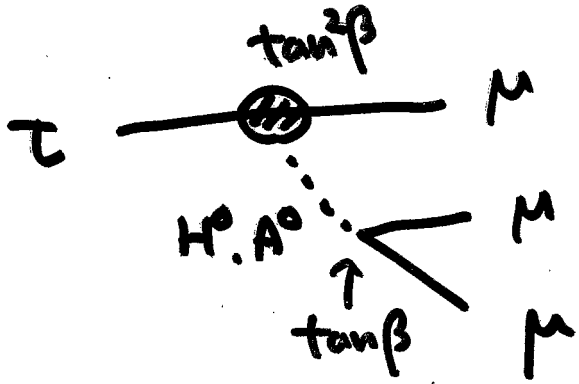
## Higgs-mediated FCNC

It is pointed out that




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

Also




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

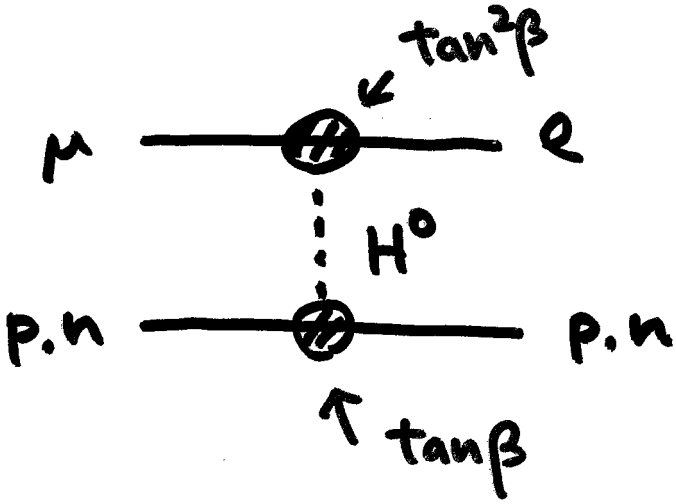
is large

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.

# $\mu$-e conversion

RK, Koike, Komine, Okada (2003)




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

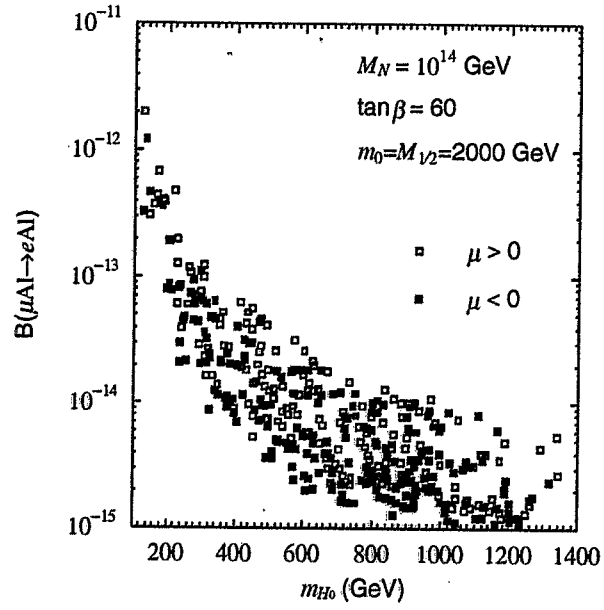
$$\Rightarrow B(\mu \to e; Al)_H \simeq O(10^{-13}) \left[\frac{200\,\mathrm{GeV}}{m_{H^0}}\right]^4 \left[\frac{\tan\beta}{60}\right]^6$$

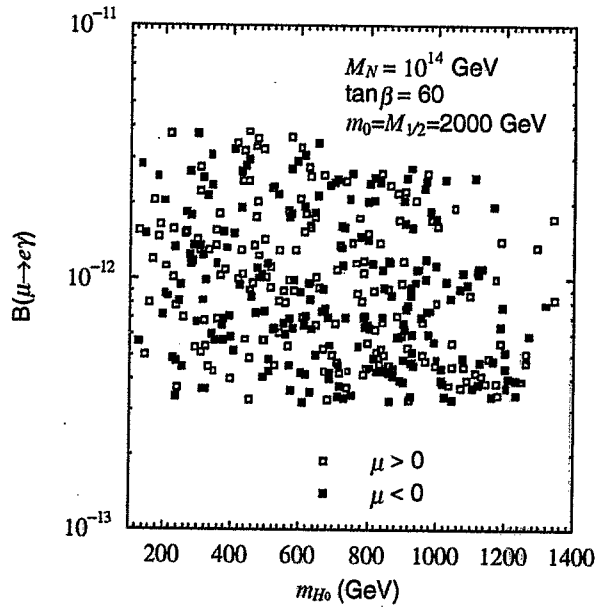
in SUSY-seesaw model

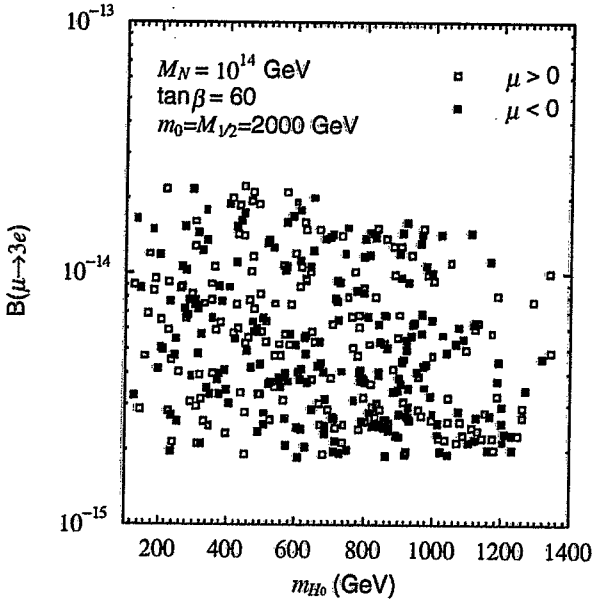
whereas

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

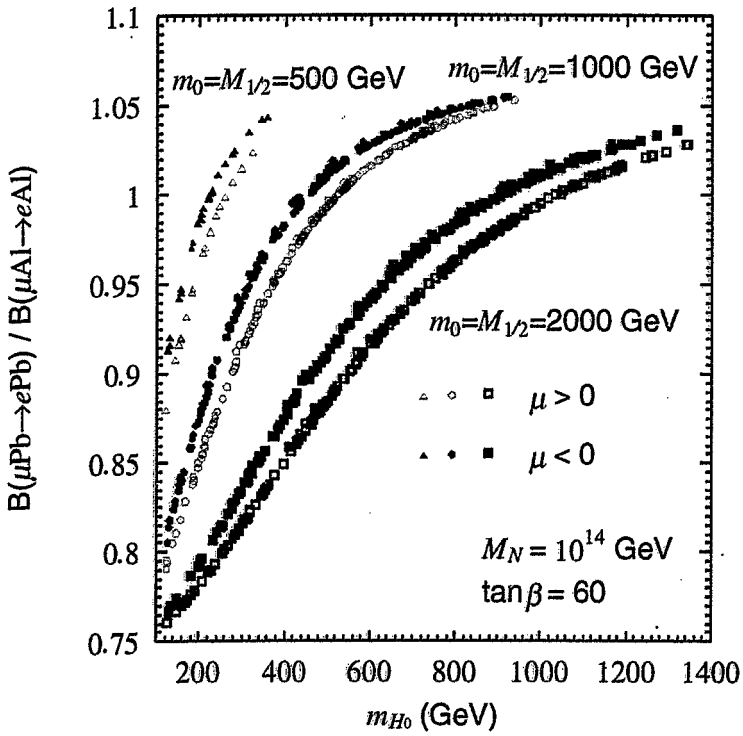
# Branching ratios



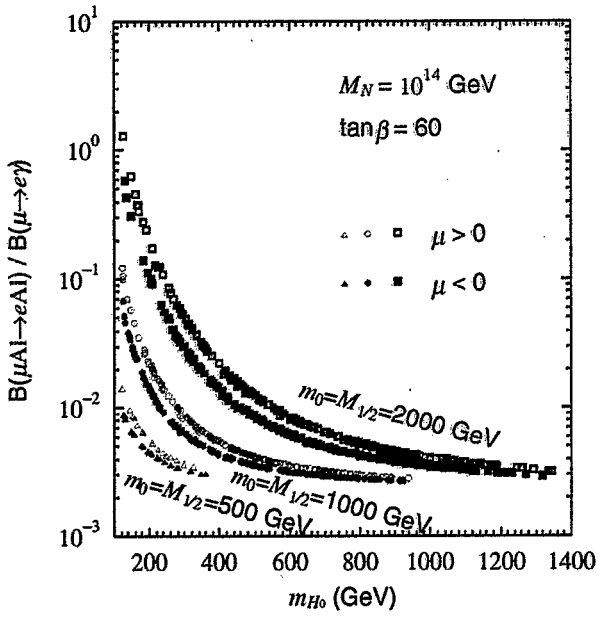



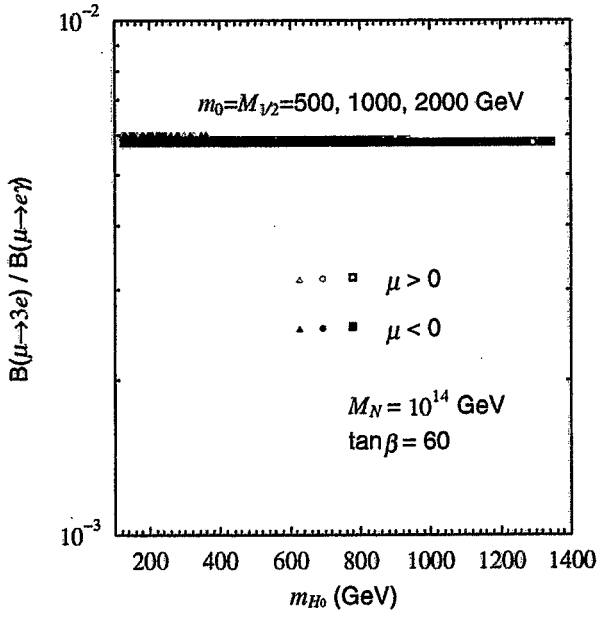

- We can see the enhancement of $B(\mu\mathrm{Al} \to e\mathrm{Al})$ in $m_{H^0} \lesssim$ 600GeV region.
- The enhancement is absent in $\mu \to e\gamma$ decay.
- We cannot see the effect of the Higgs-mediation in $\mu \to 3e$ decay, because of the small Yukawa coupling of the electron.




- 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.