Muon Particle Physics

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Muon in the particle physics

- We have learned many important things from muons.

 (Generation structure, Lepton flavor conservation, V-A interaction, VEV of the Higgs field: $G_F = 1/\sqrt{2}v^2$,etc)
- Muon is simple. (almost 100% decay to

 e$\nu\nu$, a pure Dirac fermion)
- Muon is a clean laboratory for new physics.

New physics search from muons

Static properties

Muon g-2

Muon EDM

BNL E821 exp

Decay properties

Michel parameters $(\mu^+ \to e^+ \nu \bar{\nu})$

TWIST at TRIUMF

Lepton flavor violation

$$\mu^+ \to e^+ \gamma$$

MEG at PSI

$$\mu^+ \to e^+ e^+ e^-$$

$\mu^- - e^-$ conversion

MECO at BNL

Muonium - Anti-muonium conversion

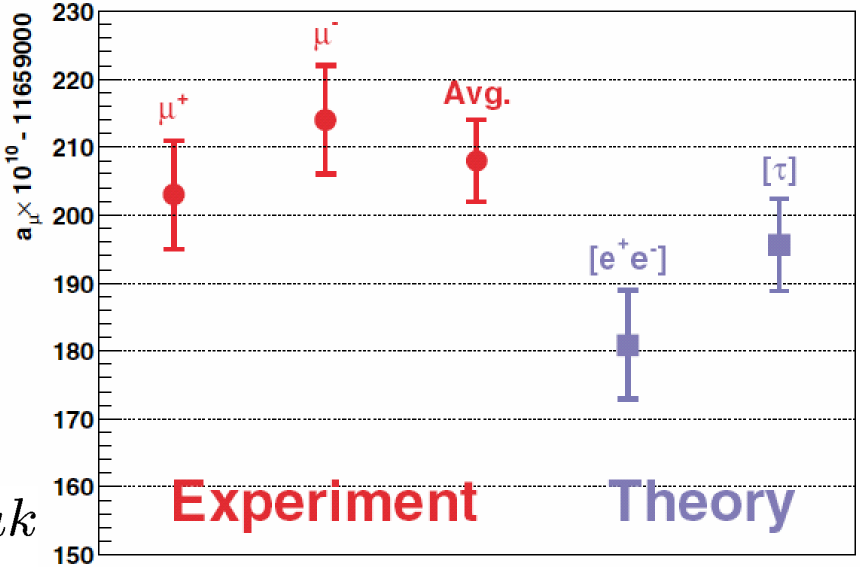
Muon g-2

A very precise test of the Standard Model

$$a_\mu \equiv (g-2)/2$$

Most recent result from the BNLexperiment

$$a_\mu = 11659208(6) \times 10^{-10}$$
$$(\mu^+, \mu^- \text{ combined})$$



Theoretical prediction

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{weak}$$

Low-energy e^+e^- annihilation cross section data from CMD-2
A new estimation of the light-by-light amplitude (K.Milnikov and A. Vainshtein)
A new evaluation on α^4 QED term (T.Kinoshita and M.Nio)

$$\delta a_\mu = (24.5 \pm 9.0) \times 10^{-10} \ (2.7\ \sigma)$$ (e^+e^- data used)

K.Hagiwara, A.D. Martin, D.Nomura, and T.Teubner.

Muon EDM

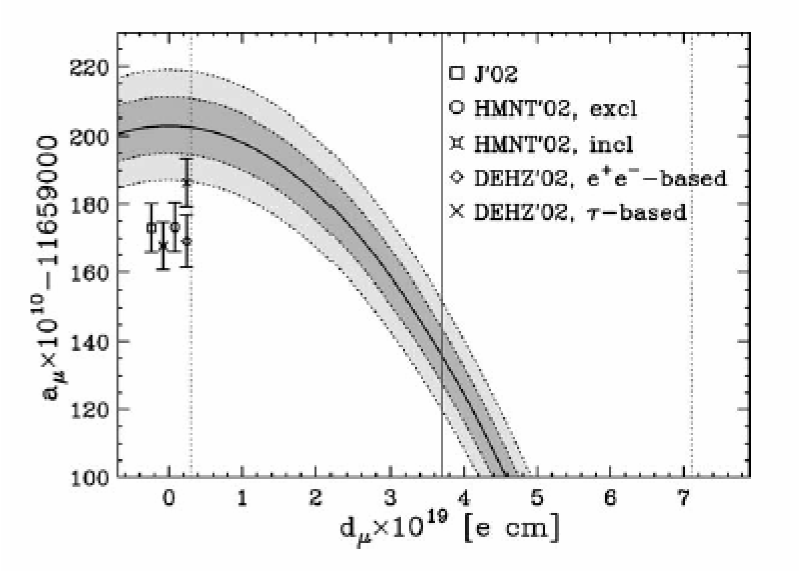
The SM contribution is extremely suppressed.
The previous bound of muon EDM is O(10^{-19}) e cm

In fact , the recent BNL experiment is sensitive to both g-2 and EDM.

$$\omega_a = -a_\mu \frac{e}{m_\mu} B - d_\mu \frac{2c}{\hbar} \beta \times B - \frac{e}{m_\mu c}\left(\frac{1}{\gamma^2 - 1} - a_\mu\right) \beta \times E - d_\mu \frac{2}{\hbar} E.$$

A new method is proposed to explore the muon EDM at the level of 10^{-24} e cm. (LoI to J-PARC)

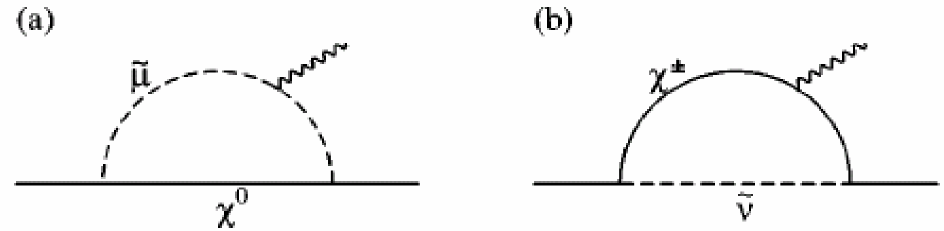
Apply a radial E field to cancel the spin precession due to the anomalous magnetic moment



J.Feng, K.Matchev, and Y.Shadmi, 2003

SUSY and g-2, EDM

Slepton-chargino (neutralino) loop diagrams contribute to g-2 and EDM at the one loop level.



SUSY contribution to g-2: enhanced for a large value of the ratio of two Higgs VEVs ($\tan\beta = < H_2^0 > / < H_1^0 >$).

$$|a_\mu^{SUSY}| \sim 13 \times 10^{-10} \tan\beta \left(\frac{100GeV}{M_{SUSY}}\right)^2$$

$$\leftrightarrow a_\mu^{SM,weak} = 15.4 \times 10^{-10}$$

SUSY contribution to EDM.

Naively muon EDM is expected as large as 0(10^{-22}) e cm.

$$d_\mu^{\mathrm{NP}} = 4.0 \times 10^{-22}\, e\,\mathrm{cm} \frac{a_\mu^{\mathrm{NP}}}{43 \times 10^{-10}} \tan\phi_{\mathrm{CP}}.$$

In simple cases,

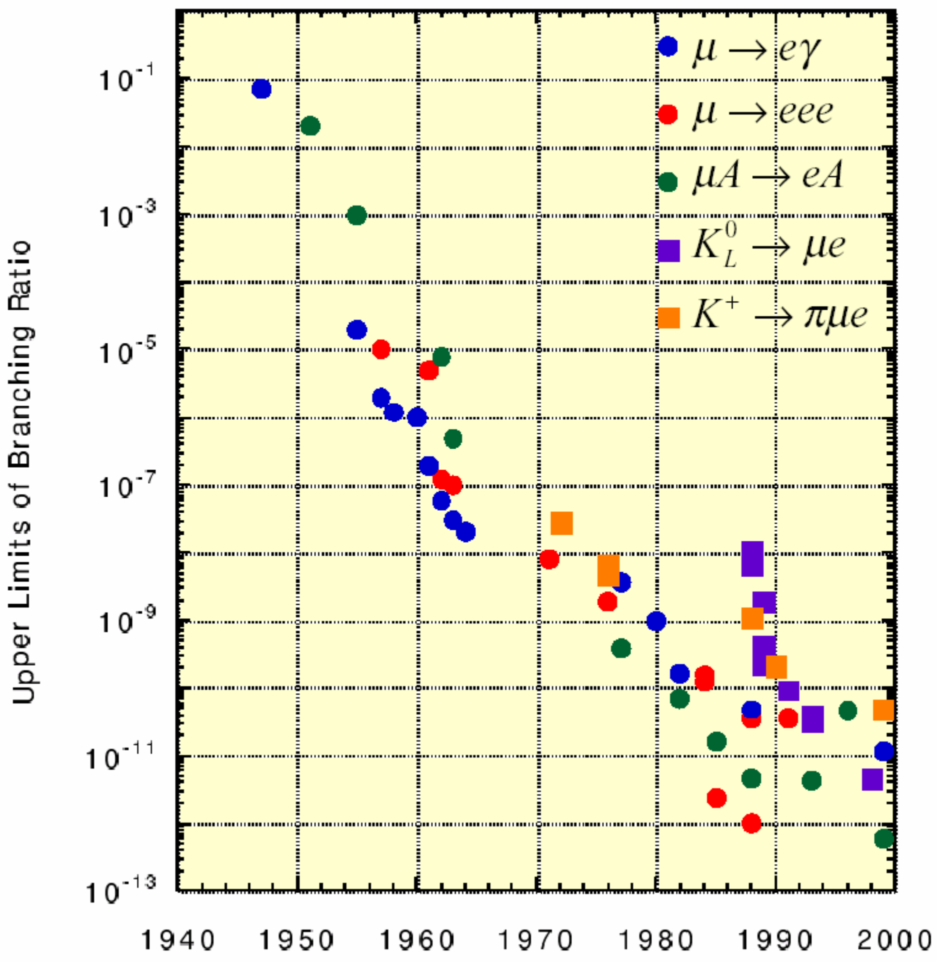
$$|d_\mu / d_e| \sim m_\mu / m_e \rightarrow d_\mu < 0(10^{-25})\ e\ \mathrm{cm}$$

We need source of the lepton-universality violation to enhance muon EDM.

(Left-right symmetric seesaw model, K.S.Babu, B.Dutta, R.N.Mohapara 2000, etc)

Lepton Flavor Violation

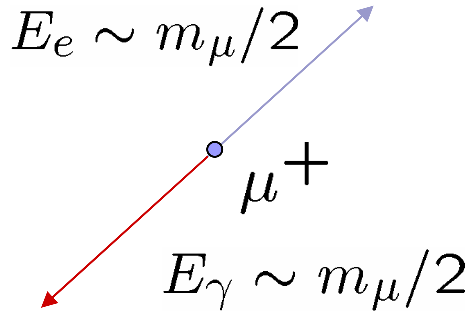
- No lepton flavor violation (LFV) in the Standard Model.
- LFV in charged lepton processes is negligibly small for a simple seesaw neutrino model.



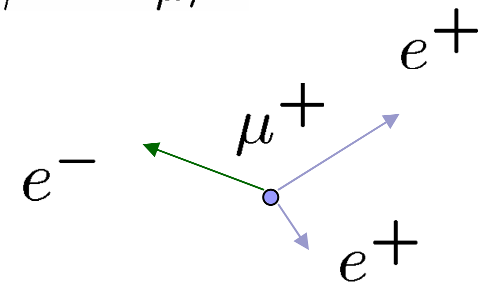
Three muon LFV processes

$$\mu^+ \to e^+\gamma$$

Back to back emission of a positron and a photon with an energy of a half of the muon mass.



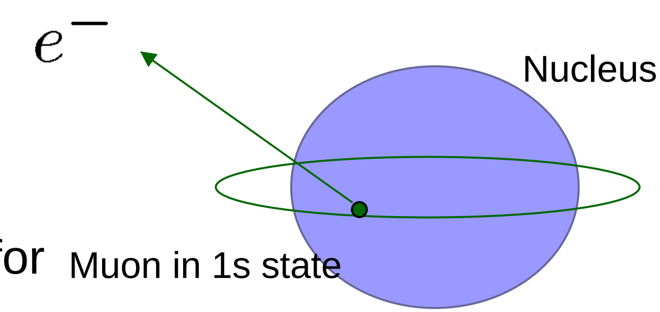
$$\mu^+ \to e^+e^+e^-$$



$$\mu^- A \to e^- A$$

$$E_e \sim m_\mu - E_{1sBinding}$$

A monochromatic energy electron emission for the coherent mu-e transition.



Experimental bounds

Process	Current	Future
$\mu^+ \to e^+\gamma$	1.2×10^{-11}	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	1.0×10^{-12}	
$\mu^- A \to e^- A$ (Ti)	6.1×10^{-13}	
$\mu^- A \to e^- A$ (Al)		$< 10^{-16}$(MECO)
$\tau \to \mu\gamma$	3.2×10^{-7}	
$\tau \to lll$	$1.4 - 3.1 \times 10^{-7}$	
$G_{Mu\overline{Mu}}/G_F$	3×10^{-3}	$\Delta L_f = 2$

Belle new results

Mu-e conversion search at the level of 10^{-18} is proposed in the future muon facility at J-PARC (PRIME).

LFV and new physics

- Many models beyond the Standard Model contain sources of LFV.
- Although the simple seesaw or Dirac neutrino model predicts too small generate branching ratios for the charged lepton LFV, other models of neutrino mass generation can induce observable effects.

Generalized Zee model (K.Hasagawa, C.S.Lim, K.Ogure, 2003)

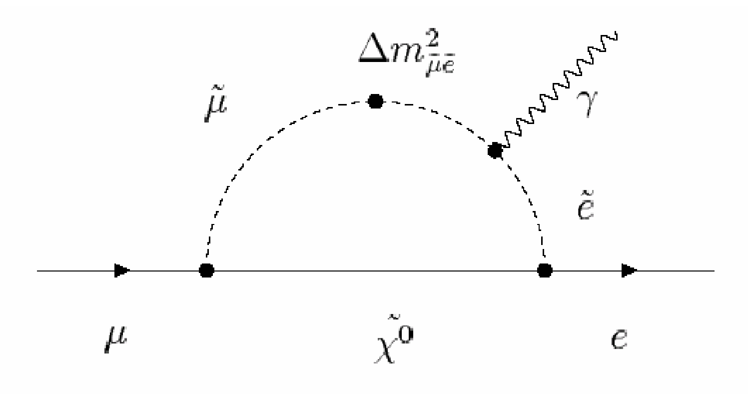
Neutrino mass from the warped extra dimension (R.Kitano,2000)

R-parity violating SUSY model (A.de Gouvea, S.Lola, K.Tobe,2001)

SUSY seesaw model

SUSY and LFV

In SUSY models, LFV processes are induced by the off-diagonal terms in the slepton mass matrixes



$$m^2_{\tilde{l}} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

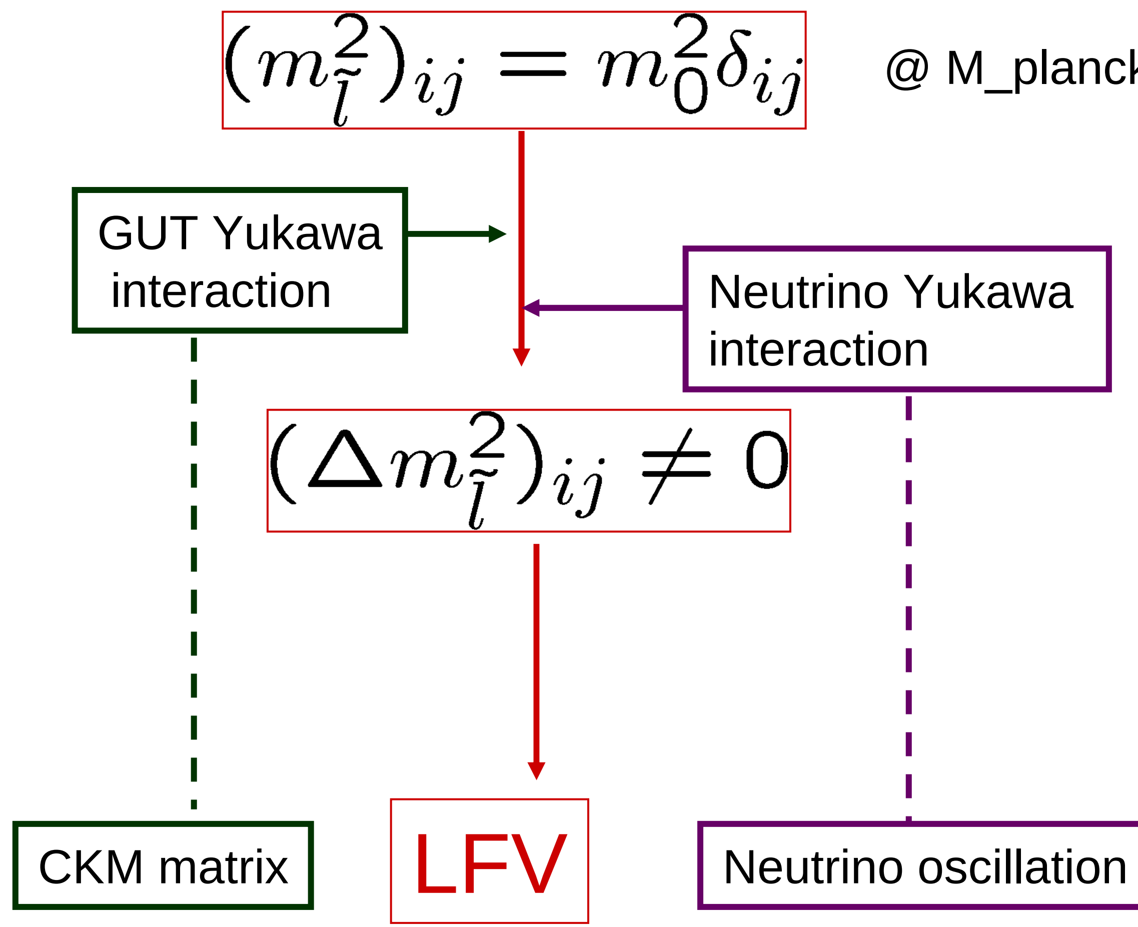
g-2: the diagonal term
EDM: complex phases
LFV: the off-diagonal term

Off-diagonal terms depend on how SUSY breaking is generated and what kinds of LFV interactions exist at the GUT scale.

SUSY GUT and SUSY Seesaw model

L.J.Hall,V.Kostelecky,S.Raby,1986;A.Masiero, F.Borzumati, 1986

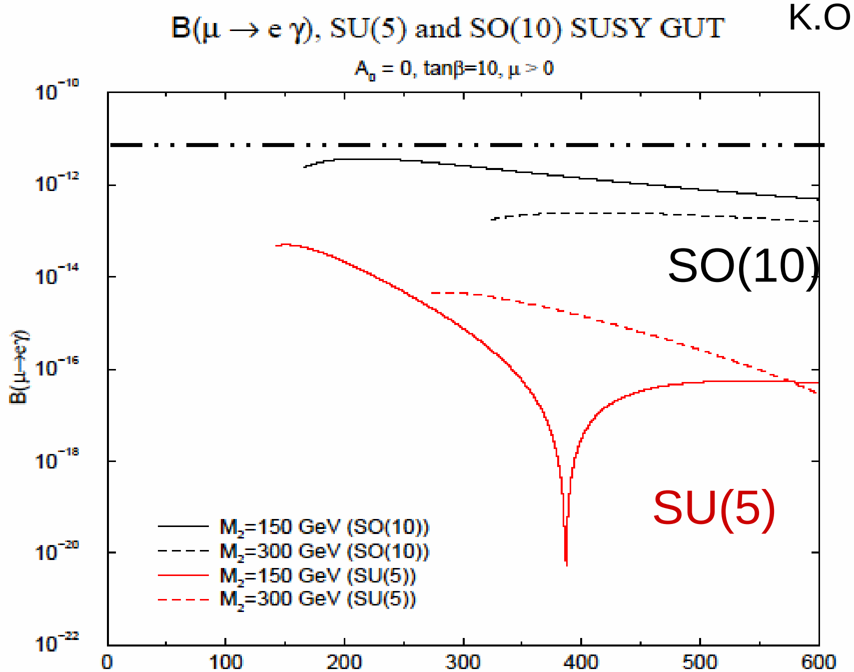
The flavor off-diagonal terms in the slepton mass matrix are induced by renormalization effects due to GUT and/or neutrino interactions.



μ -> e γ branching ratio

SU(5) and SO(10) SUSY GUT

K.Okumura

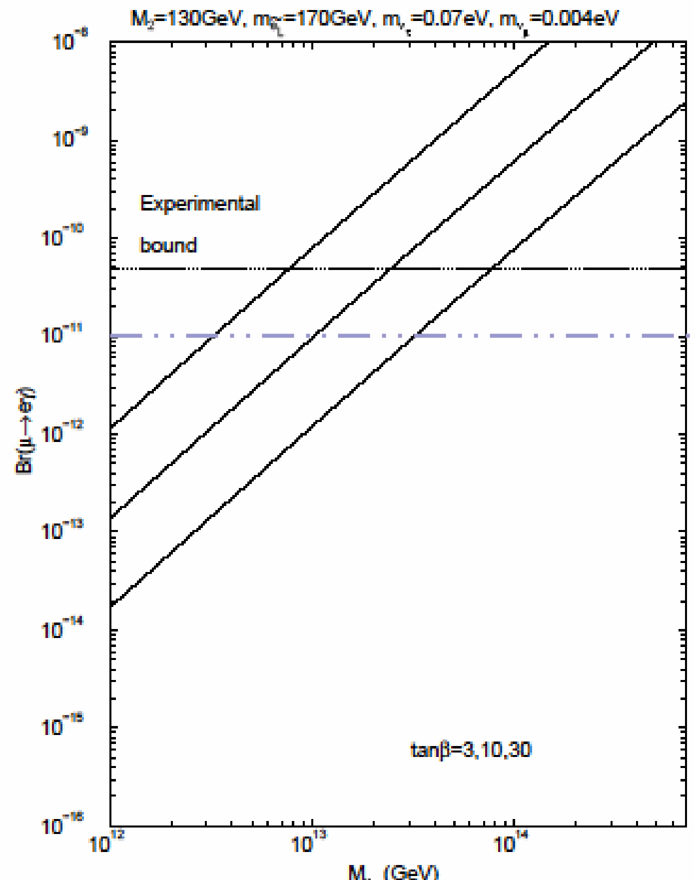


Right-handed selectron mass

The branching ratio can be large
in particular for SO(10) SUSY GUT model.

SUSY seesaw model

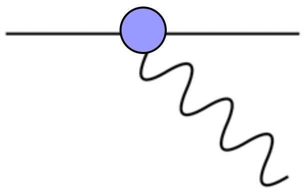
J.Hisano and D.Nomura,2000



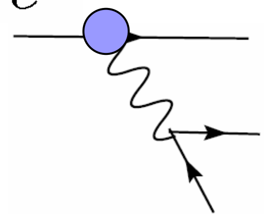
Right-handed neutrino mass

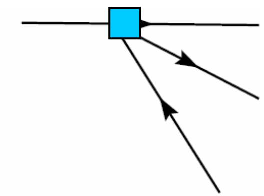
Comparison of three processes

$\mu^+ \to e^+ \gamma$

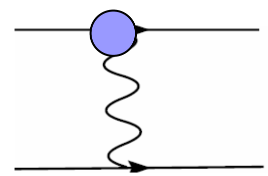


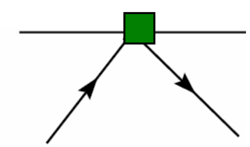
$\mu^+ \to e^+ e^+ e^-$





$\mu^- A \to e^- A$





If the photon penguin process is dominated, there are simple relations among these branching ratios.

$$B(\mu^+ \to e^+ e^+ e^-) \sim 6 \times 10^{-3} B(\mu \to e\gamma)$$

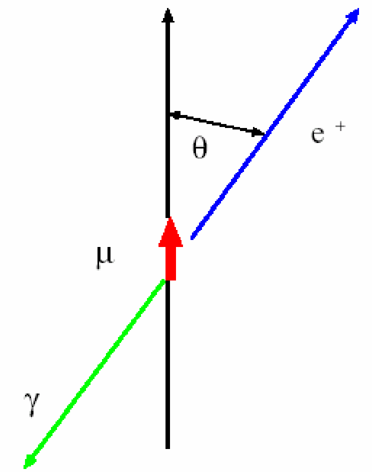
$$\frac{\sigma(\mu^- Ti \to e^- Ti)}{\sigma(\mu^- Ti \to capture)} \sim 4 \times 10^{-3} B(\mu \to e\gamma)$$

In many case of SUSY modes, this is true, but there is an important case
In which these relations do not hold.

Muon polarization

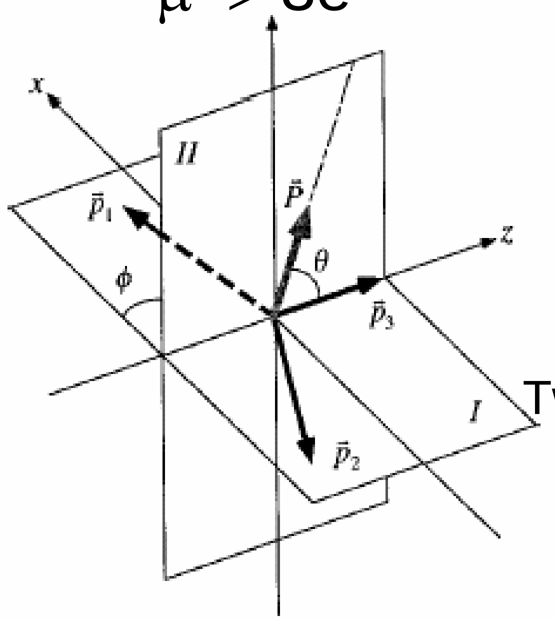
- If the muon is polarized, we can define a P-odd asymmetry for mu -> e gamma and T-odd and P-odd asymmetries for mu ->3e. These asymmetries are useful to distinguish different models.
- For example, the parity asymmetry in mu ->e gamma reflects whether left-handed or right-handed sleptons have flavor mixing.

μ–> eγ



$$\frac{dB(\mu^+ \to e^+\gamma)}{d\cos\theta} \propto 1 + A_{\mu\to e\gamma} P_\mu \cos\theta$$

μ–> 3e



Two P-odd and one T-odd asymmetries

P and T-odd asymmetries in SUSY GUT models

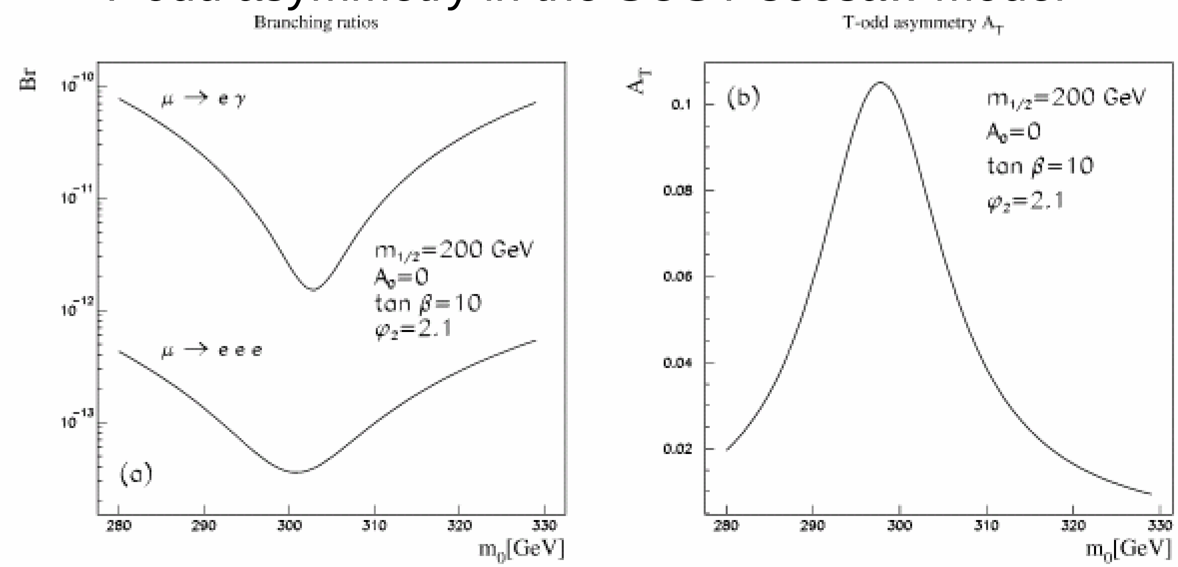
The T-odd asymmetry can be 10 % level for some parameter space of the SU(5) SUSY GUT and the SUSY seesaw model.

Information on lepton sector CP violation

	SU (5)	SO (10)
$A_{\mu\to e\gamma}$	$+100\%$	$-100\% - +100\%$
A_{P_1}	$-30\% - +40\ \%$	$\simeq -A_{\mu\to e\gamma}/10$
A_{P_2}	$-20\% - +20\ \%$	$\simeq -A_{\mu\to e\gamma}/6$
$\lvert A_T\rvert$	$\lesssim 15\%$	$\lesssim 0.01\%$

Y.Okada,K.Okumura,and Y.Shimizu, 2000

T-odd asymmetry in the SUSY seesaw model



J.Ellis,J.Hisano,S.Lola, and M.Raidal, 2001

Z dependence of mu-e conversion branching ratio

R.Kitano, M.Koike and Y.Okada. 2002

We have calculated the coherent mu-e conversion branching ratios in various nuclei for general LFV interactions to see:

(1) which nucleus is the most sensitive to mu-e conversion searches,

(2) whether we can distinguish various theoretical models by the Z dependence.

Relevant quark level interactions

$$
\begin{aligned}
\mathcal{L}_{\rm int} = & -\frac{4G_F}{\sqrt{2}}\left(m_\mu A_R \bar{\mu}\sigma^{\mu\nu}P_L e F_{\mu\nu} + m_\mu A_L \bar{\mu}\sigma^{\mu\nu}P_R e F_{\mu\nu} + \text{h.c.}\right) \\
& -\frac{G_F}{\sqrt{2}}\sum_{q=u,d,s}\Big[\left(g_{LS(q)}\bar{e}P_R\mu + g_{RS(q)}\bar{e}P_L\mu\right)\bar{q}q \\
& \quad + \left(g_{LV(q)}\bar{e}\gamma^\mu P_L\mu + g_{RV(q)}\bar{e}\gamma^\mu P_R\mu\right)\bar{q}\gamma_\mu q \\
& \quad + \text{h.c.} \Big],
\end{aligned}
$$

Dipole

Scalar

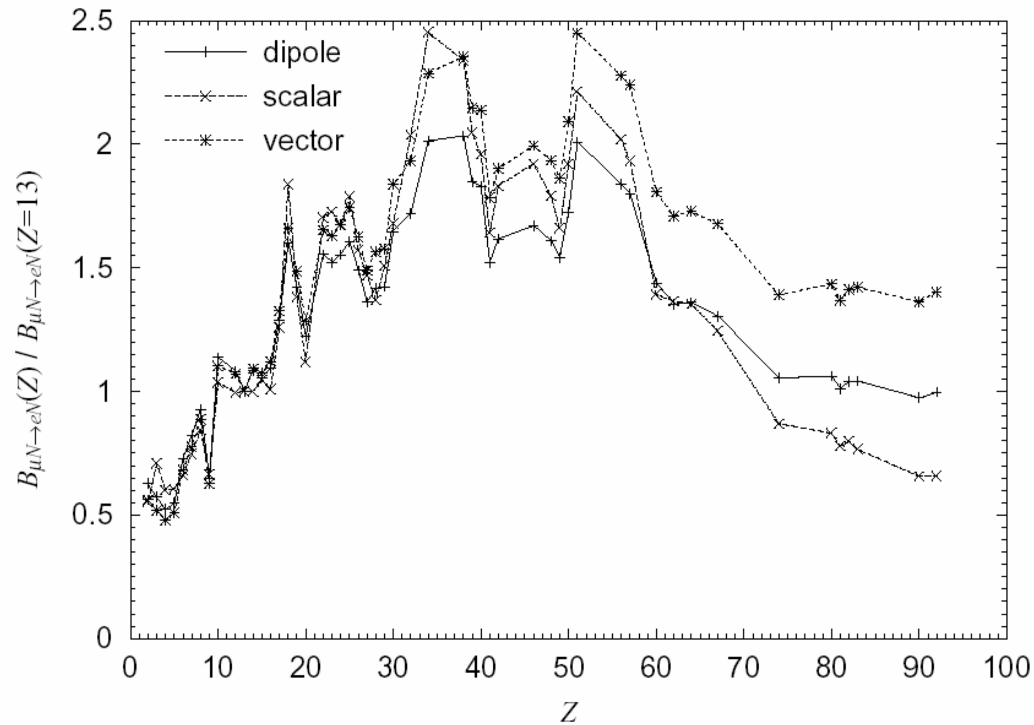
Vector

mu-e conversion rate normalized at Al.

The branching ratio is largest for the atomic number of Z=30 – 60.

For light nuclei, Z dependences are similar for different operator forms.

Sizable difference of Z dependences for dipole, scalar and vector interactions. This is due to a relativistic effect of the muon wave function.



$(\rho_p = \rho_n)$

$$B(\mu Pb \to e Pb)/B(\mu Al \to e Al) = 1.0,\ \ 0.77,\ \ 1.4$$

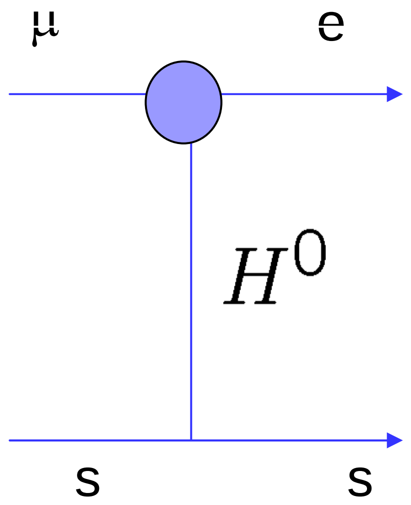
Another way to discriminate different models

dipole scalar vector

Higgs-mediated contribution to mu-e conversion in SUSY seesaw model

R.Kitano,M.Koike,S.Komine, and Y.Okada, 2003

SUSY loop diagrams can generate
a LFV Higgs-boson coupling
for large tan β cases. (K.Babu, C.Kolda,2002)



The heavy Higgs-boson exchange provides
a new contribution of a scalar type.

Higgs-exchange contribution

$$B(\mu \mathrm{Al} \to e \mathrm{Al})_{H^0} \sim O(10^{-13}) \cdot \left(\frac{200\mathrm{GeV}}{m_{H^0}}\right)^4 \cdot \left(\frac{\tan\beta}{60}\right)^6$$

Photon-exchange contribution

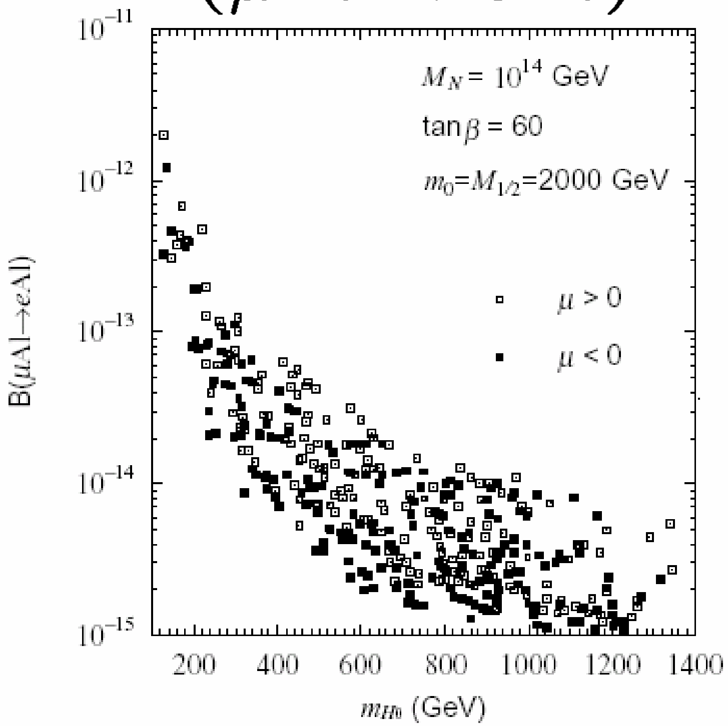
$$B(\mu \mathrm{Al} \to e \mathrm{Al})_{\gamma} \sim O(10^{-13}) \cdot \left(\frac{1000\mathrm{GeV}}{M_S}\right)^4 \cdot \left(\frac{\tan\beta}{60}\right)^2$$

Numerical results : SUSY seesaw model

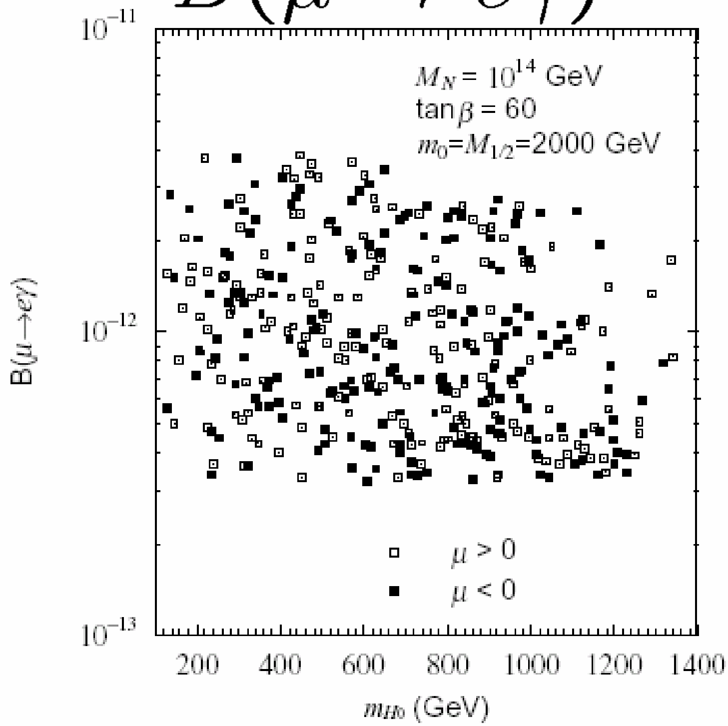
We calculated the mu-e conversion, mu > e gamma and, mu->3e branching ratios in the SUSY seesaw model.

(Universal slepton masses at the GUT scale. Hierarchical neutrino masses. A large tan β (tan β = 60). The Majorana neutrino mass = 10^14 GeV .)

$B(\mu Al \rightarrow eAl)$

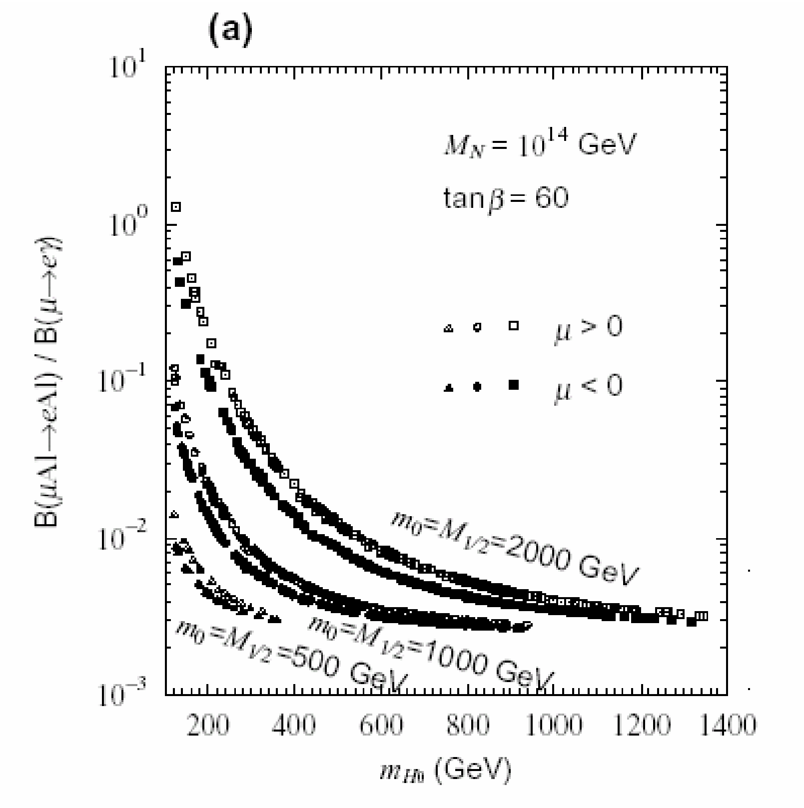


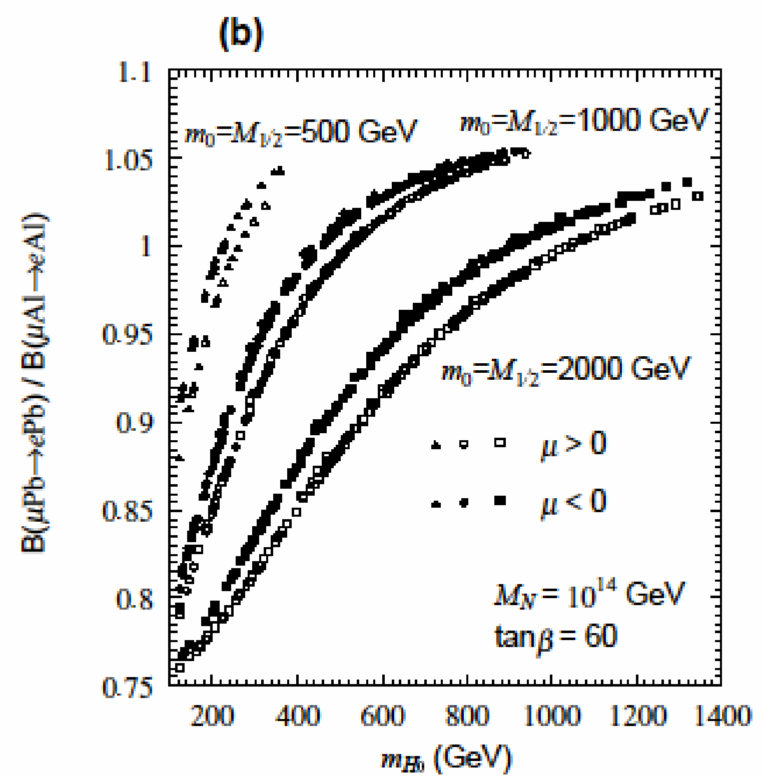
$B(\mu \rightarrow e\gamma)$



Ratio of the branching ratios and Z-dependence of mu-e conversion rates

$$B(\mu Al \to eAl)/B(\mu \to e\gamma) \qquad B(\mu Pb \to ePb)/B(\mu Al \to eAl)$$





mu-e conversion is enhanced.
Z-dependence indicates the scalar exchange contribution.

Summary

- Muon experiments provide various opportunities to search for new physics effects.
- Large effects are expected in well-motivated models of SUSY for LFV processes.
- Comparison of muon g-2, EDM, and various LFV processes is important to distinguish different models.