Rare muon decays and physics beyond the SM

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Lepton Flavor Violation (LFV) in charged lepton processes

$\Delta L_f = 1$

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

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

$\mu^- - e^-$ conversion in atoms

$\Delta L_f = 2$

Muonium (μ^+e^-) - Anti-Muonium (μ^-e^+) conversion

The Minimal Standard Model $\Longrightarrow$ No LFV

The simplest extension of SM with Sea-Saw or Dirac neutrino

$\Longrightarrow$ Charged-lepton LFV is negligibly small

$(B(\mu \to e\gamma) < 10^{-40})$

A clear signal of physics beyond the SM (with neutrino oscillation)

Experimental Bounds

Process	Current	Future
$B(\mu^+ \to e^+\gamma)$	1.2×10^{-11}	10^{-14}(PSI)
$B(\mu^+ \to e^+e^+e^-)$	1.0×10^{-12}	
$\frac{\sigma(\mu^- T_i \to e^- T_i)}{\sigma(\mu^- T_i \to capture)}$	6.1×10^{-13}	10^{-16}(MECO)
$G_{Mu\overline{Mu}}/G_F$	3×10^{-3}	

$$(H_{Mu\overline{Mu}} = \frac{G_{Mu\overline{Mu}}}{\sqrt{2}}\overline{\mu}\gamma_\lambda(1-\gamma_5)e\overline{\mu}\gamma^\lambda(1-\gamma_5)e + H.c.)$$

Examples of New Physics

$\Delta L_f = 1$

SUSY (SUSY GUT, SUSY model with right-handed neutrino)

R-parity violating SUSY model

Model with extra-dimension

Model with violation of Lorentz invariance

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$\Delta L_f = 2$

R-parity violating SUSY model

Left-Right Model with triplet Higgs field

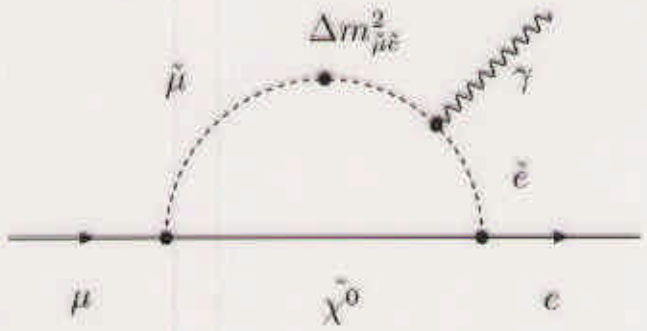
Model with bilepton

.....

SUSY and LFV

Slepton mass matrices are new source of flavor mixing in the lepton sector.
General SUSY breaking terms induce large LFV.

$$\mathcal{L}_{soft} = -(m_E^2)_{ij}\tilde{e}^*_{Ri}\tilde{e}_{Rj} - (m_L^2)_{ij}\tilde{l_{Li}}^*\tilde{l_{Lj}} \\ -\{m_0(A_e)_{ij}H_1\tilde{e}^*_{Ri}\tilde{l}_{Lj} + H.c.\}$$



The experimental bound of $B(\mu \to e\gamma)$ implies

$$\frac{\Delta m^2_{\tilde{\mu}\tilde{e}}}{m^2_{\tilde{l}}} < 10^{-3}\left(\frac{m_{\tilde{l}}}{100GeV}\right)^2$$

The branching ratios of LFV processes depend on

- SUSY breaking mechanism
- Interaction at high energy scale

Interesting examples

- SUSY GUT

  Ordinary Yukawa coupling constants becomes a source of flavor mixing for the lepton/slepton sector.

$$W_{SU(5)} = \frac{1}{8}(y_u)_{ij} T_i \cdot T_j \cdot H(5) + (y_d)_{ij} \bar{F}_i \cdot T_j \cdot \bar{H}(5)$$
$$T_i \ni (q_{iL}, u^c_{iL}, e^c_{iL}),\ \bar{F}_i \ni (d^c_{iL} l_{iL})$$

L.J.Hall, V.Kostelecky and S.Raby, 1986; R.Barbieri and L.J.Hall 1994; R.Barbieri, L.J.Hall and A.Strumia 1995; J.Hisano, T.Moroi, K.Tobe and M.Yamaguchi 1997 ....

- SUSY model with right-handed neutrinos

  Neutrino Yukawa coupling constants becomes a new source of flavor mixing.

$$W_N = (y_e)_{ij} H_1 E^c_i L_j + (y_\nu)_{ij} H_2 N_i L_j + \frac{1}{2}(M_R)_{ij} N_i N_j$$

F.Borzumati and A.Masiero, 1986; J.Hisano, D.Nomura and T.Yanagida, 1998; J.Hisano and D.Nomura, 1999; J.Ellis et al.,1999; J.L.Feng, Y.Nir and Y.Shadmi, 1999; W.Buchmüller et al, 1999 ....

LFV for SU(5) and SO(10) SUSY GUT

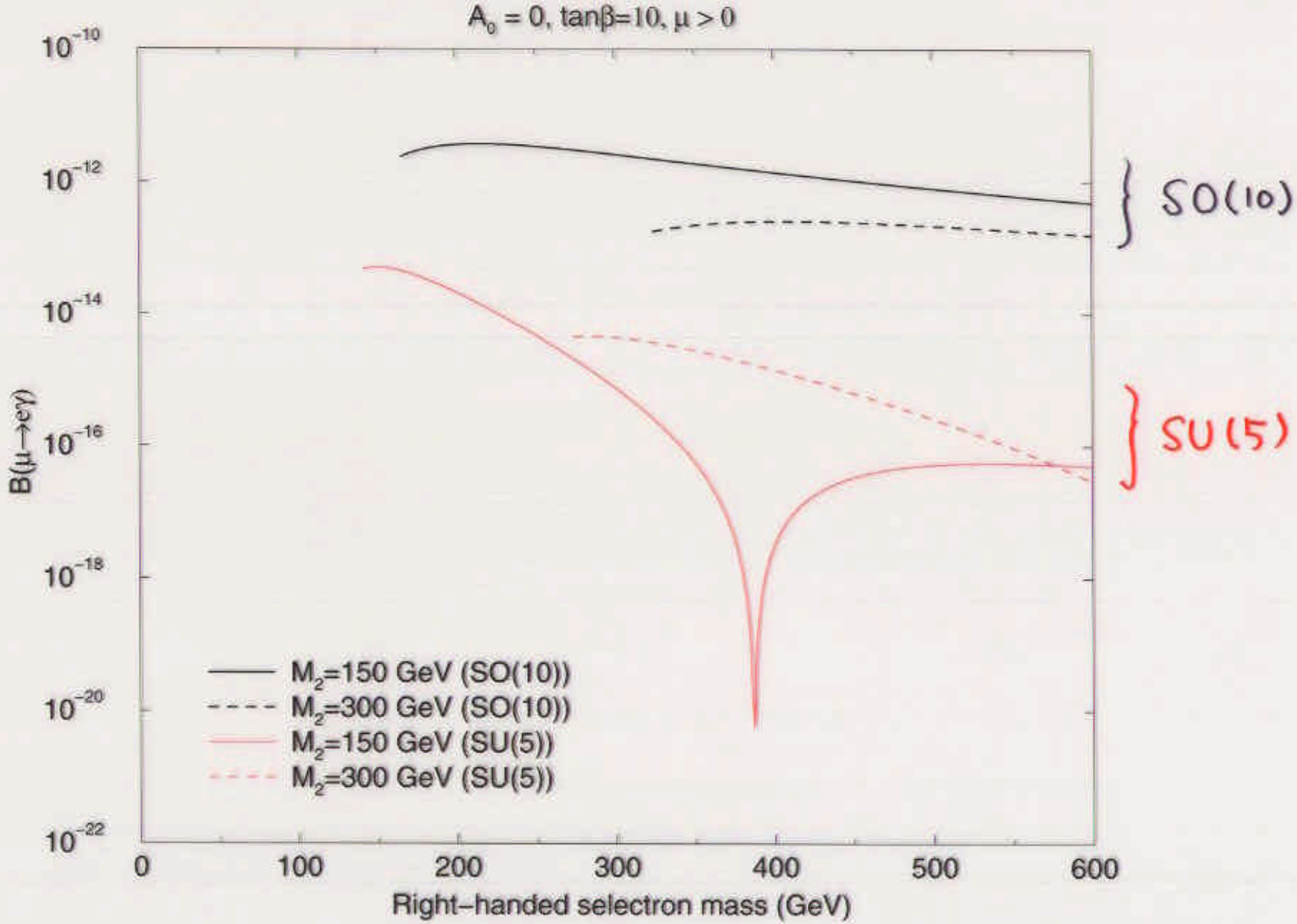
- In SU(5) SUSY GUT, $B(\mu \to e\gamma)$ depends on detailed structure of Yukawa coupling constants at the GUT scale, but typically $O(10^{-14})$.
  (Could be enhanced for a large value of $\tan\beta = < H_1^0 > / < H_2^0 >$.)

- In SO(10) SUSY GUT, $B(\mu \to e\gamma)$ can be close to the experimental bound, typically $O(10^{-12})$.
  Relations among $\mu \to e\gamma$, $\mu^+ \to e^+e^+e^-$ and $\mu - e$ conversion branching ratios.

$$B(\mu^+ \to e^+e^+e^-) \sim \frac{1}{160} B(\mu \to e\gamma)$$

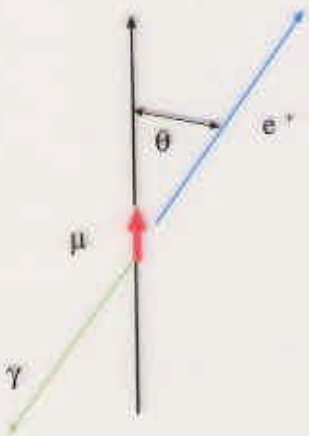
$$\frac{\sigma(\mu^- T_i \to e^- T_i)}{\sigma(\mu^- T_i \to capture)} \sim \frac{1}{240} B(\mu \to e\gamma)$$

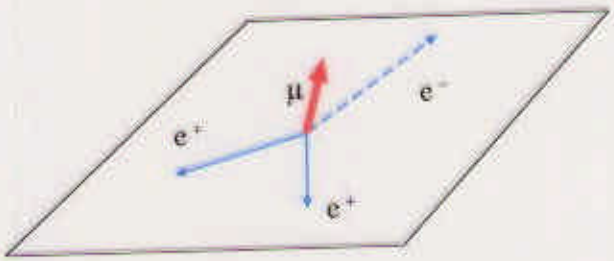
$B(\mu \to e\,\gamma)$, SU(5) and SO(10) SUSY GUT



Polarized muon and P and T odd asymmetries

If the muon is polarized we can define P-odd asymmetry for $\mu^+ \to e^+\gamma$ and T-odd and P-odd asymmetries for $\mu^+ \to e^+e^+e^-$.





- For $\mu^+ \to e^+\gamma$:

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

- For $\mu^+ \to e^+e^+e^-$:
  T-odd asymmetry (A_T) and two P-odd asymmetries (A_Z, A_X).

These asymmetries have different features for SU (5)& SO (10) models

	SU (5)	SO (10)
$A_{\mu\to e\gamma}$	+100%	-100% – +100%
A_Z	-30% – +40 %	$\simeq -A_{\mu\to e\gamma}/10$
A_X	-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 PRD 61 (2000) 094001

SUSY model with right-handed neutrino

- If the neutrino Yukawa coupling constant is large, the slepton mass matrices can receive large radiative corrections responsible for LFV.

  The See-Saw relation: $m_\nu = y_\nu^T \frac{1}{M_R} y_\nu (v^2 \sin^2\beta/2)$

  $\Longrightarrow$ The neutrino Yukawa coupling constant is $O(1)$ for $M_R = O(10^{14})$ GeV.

- Large flavor mixing in the slepton sector is naturally expected from neutrino mixing parameters suggested by atmospheric and solar neutrino experiments.

  Atmospheric neutrino (2-3 mixing) $\Leftrightarrow \tau \to \mu\gamma$

  Solar neutrino (1-2 mixing) $\Leftrightarrow \mu \to e\gamma$

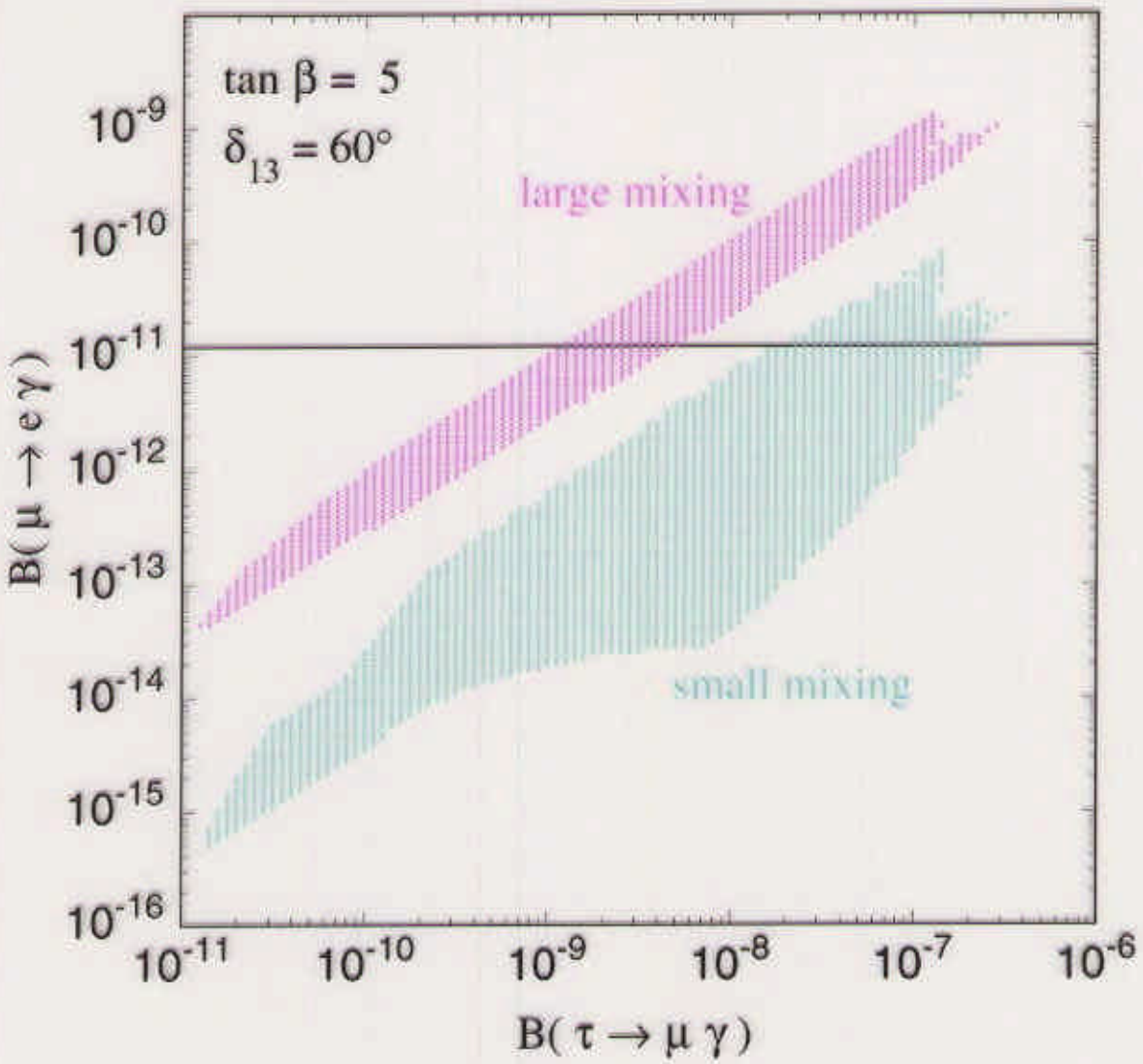
- B($\mu \to e\gamma$) and B($\mu \to e\gamma$) can be close to the current experimental bounds.

SU(5) SUSY GUT with Right-handed Neutrino

large mixing : MSW large mixing angle solution

small mixing : MSW small mixing angle solution

$(M_R)_{ij} = (4 \times 10^{14}\ \text{GeV})\delta_{ij}$, $m_0 < 1$ TeV, $M_{1/2} < 1$ TeV, $|\frac{A_0}{m_0}| < 5$



Current bound $B(\tau \to \mu\gamma) < 1.1 \times 10^{-6}$

S.Baek, T.Goto, Y.Okada and K.Okumura ~~and Y.Shimizu~~ hep-ph/0002141

Summary

- Muon LFV processes are important to search for physics beyond the SM.

- Branching ratios for LFV processes can be close to the present experimental bounds for SUSY GUT and the SUSY model ~~model~~ with See-Saw neutrino.

- To distinguish various models, it is important to search for all three processes, $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^+e^-$ and $\mu^- - e^-$ conversion. Polarized muon experiments are also useful.