CLFV theory and prospect

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NuFact10

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Charged lepton flavor violation in the LHC era

- LHC will explore physics at the TeV scale, namely the physics of the electroweak symmetry breaking.
- Existence of lepton flavor violation in the charged lepton sector is a clear evidence of new physics.
- Two important issues

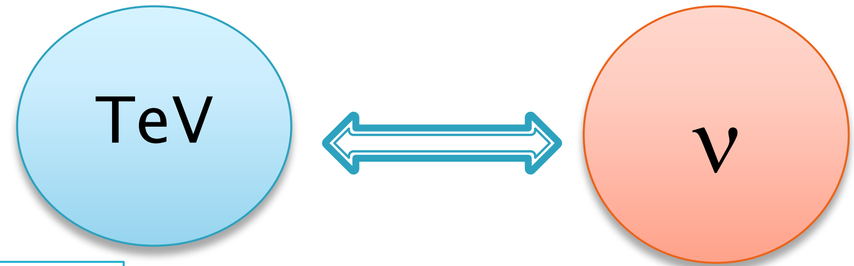
  Neutrino and CLFV

  SUSY and CLFV

Scale of the electroweak symmetry breaking

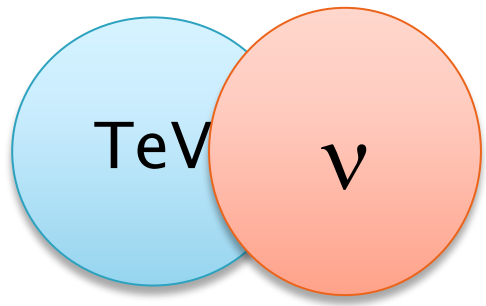
Scale of the neutrino mass generation

If two scales are well separated, LFVs are suppressed.



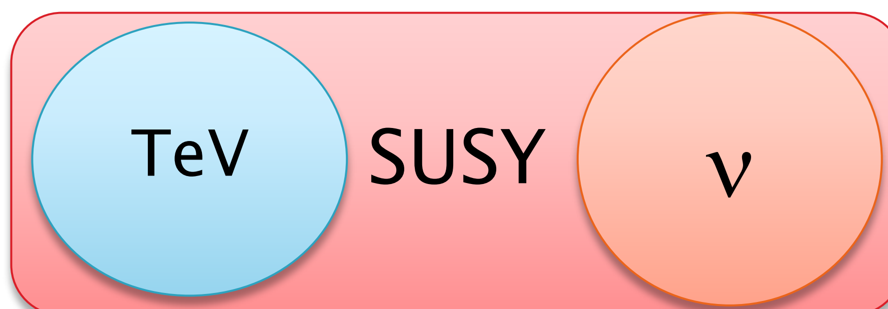
$$B(\mu \to e\gamma) < O(10^{-40})$$
for seesaw model with $M_R > 10^{10}$ GeV

If two scales are close, large LFVs are expected.



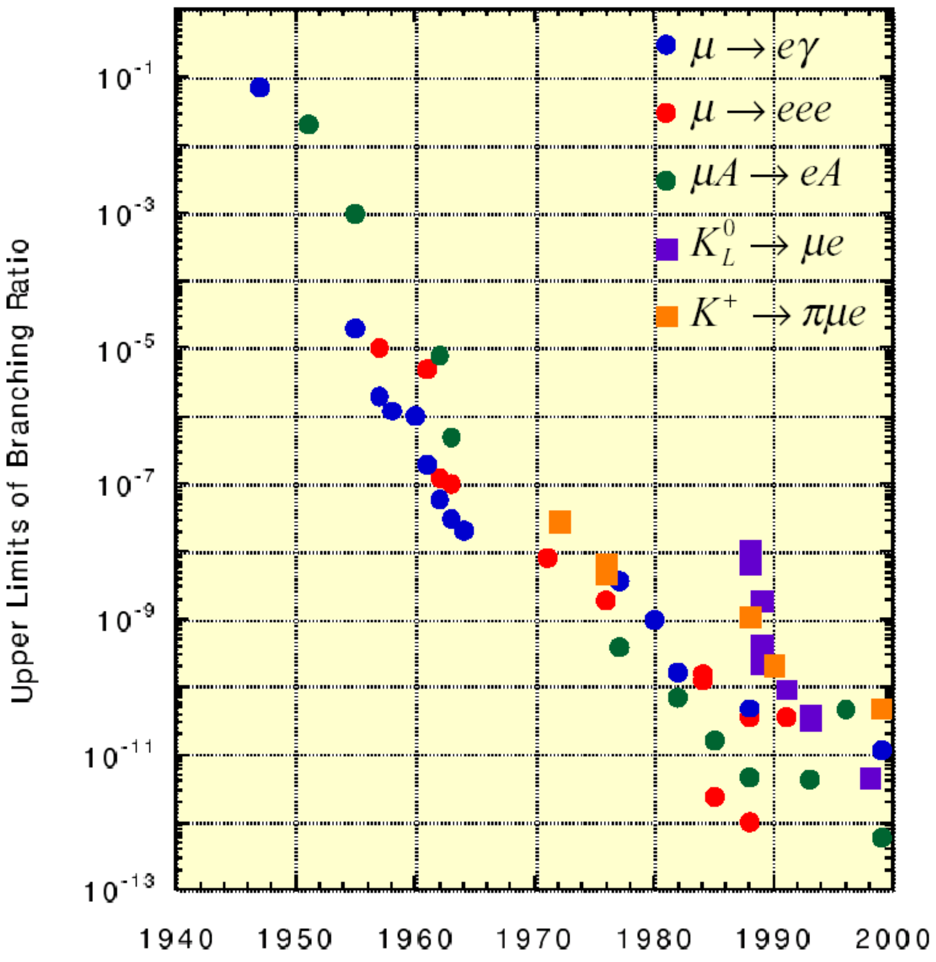
- Neutrino mass from loop
- Triplet Higgs for neutrino mass
- Left-right symmetric model

In supersymmetric models, large LFV signals are expected even if two scales are separated.



LFV searches

- Muon LFV search started in early days of muon experiments.
- Absence of μ->eγ indicated that the muon is not an excited state of the electron, but rather a new elementary particle.



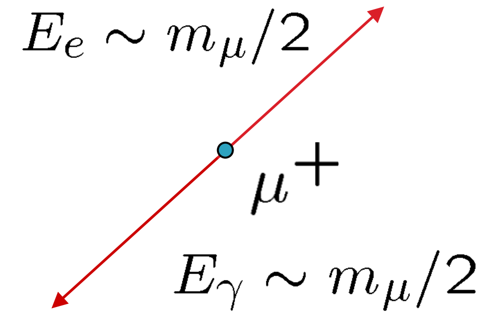
Phenomenology of LFV processes

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

$B < 1.2 \times 10^{-11}$ (MEGA)

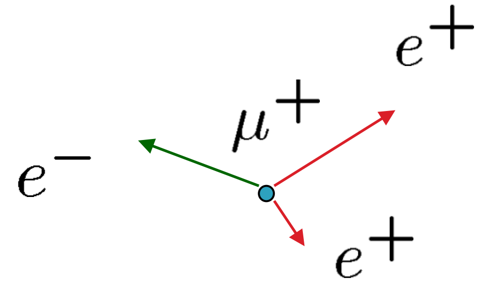
($< 1.5 \times 10^{-11}$ MEG 2009)

$\to 0(10^{-13})$ (MEG)



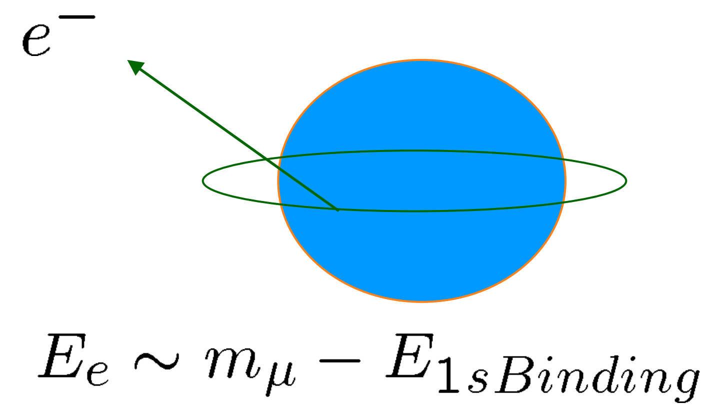
$$\mu^+ \to e^+ e^+ e^-$$ (SINDRUM)

$$B < 1.0 \times 10^{-12}$$



$$\mu^- A \to e^- A$$ (SINDRUMII)

$$B < 7 \times 10^{-13} (Au)$$

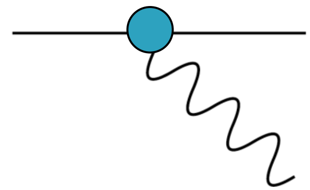


μ–e conversion search at $0(10^{-16})$ is planned at COMET(KEK) and Mu2e (Fermilab) experiments

$$\mu^- e^- \to e^- e^-$$ in muonic atoms (J.Sato's talk)

Effective interactions

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

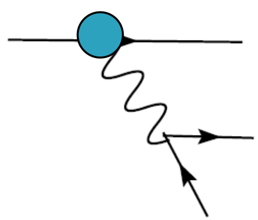


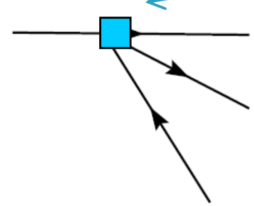
$\mu^+ \to e^+\gamma_R$ $\quad\quad$ $\mu^+ \to e^+\gamma_L$

$$-\frac{4G_F}{\sqrt{2}}(m_\mu A_R \overline{\mu} \sigma^{\mu\nu} P_L e F_{\mu\nu} + m_\mu A_L \overline{\mu} \sigma^{\mu\nu} P_R e F_{\mu\nu} + \text{H.c.})$$

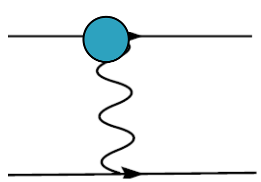
6 additional operators

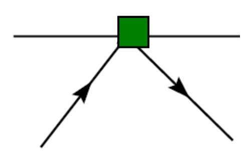
$\mu^+ \to e^+e^+e^-$





$\mu^- N \to e^- N$





Various llqq operators

Tau LFV processes

Current bounds for tau LFV processes: 10^{-7}– 10^{-8} from Belle and BaBar.
O(10^{-9}) at e^+e^- Super B factories.
CMS study: B(τ->3μ) < 3.8x10 $^{-8}$ at 30 fb^{-1} (R. Satinelli and M. Biasini 2002)
No obvious scaling between mu LFV and tau LFV.

$\tau \to \mu\gamma$

$\tau \to e\gamma$

$\tau \to \mu\mu\mu$

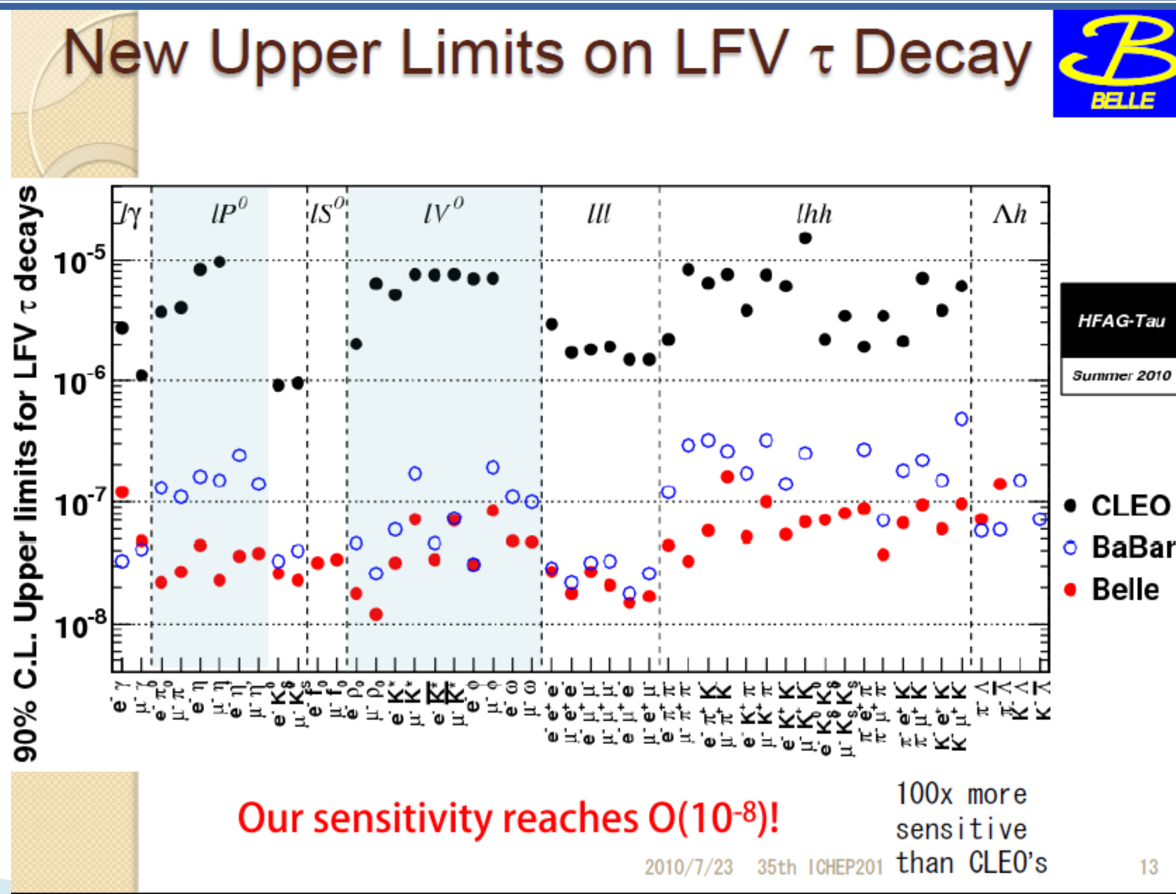
$\tau \to \mu ee$

…

$\tau \to \mu\pi$

$\tau \to \mu\eta$

…



K.Hayasaka, ICHEP 2010

Distinguishing various LFV interactions

- Comparison of three muon LFV processes.

  ($\mu \to e\gamma$, $\mu \to eee$, μ–e conversion)
- Angular distribution of polarized muon decays in $\mu \to e\gamma$, $\mu \to eee$.
- Atomic number dependence of the mu–e conversion rate.

(1) Comparison of three branching ratios

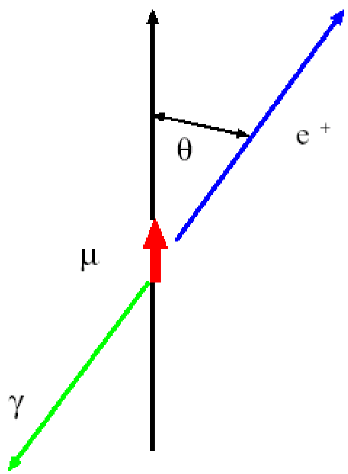
If the photon penguin process is dominant, there are simple relations among these branching ratios.

$$B(\mu \to 3e) \sim 6.1 \times 10^{-3} B(\mu \to e\gamma)$$
$$B(\mu Ti \to e Ti) \sim 4.0 \times 10^{-3} B(\mu \to e\gamma)$$
$$B(\mu Al \to e Al) \sim 2.6 \times 10^{-3} B(\mu \to e\gamma)$$

In many case of SUSY modes, this is true.
Other cases:
Additional Higgs exchange diagram (SUSY with large tan β)
Dominance of tree exchange diagrams (LR symmetric models)
Loop-induced but Z-penguin dominance (Little Higgs with T-parity)

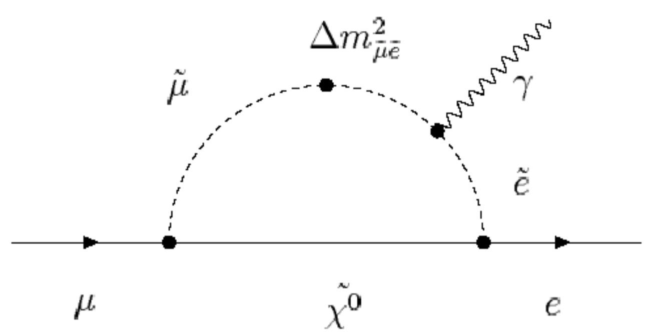
(2) Muon Polarization

- If the muon is polarized, we can define a P-odd asymmetry for μ -> e γ and T-odd and P-odd asymmetries for μ->3e. These asymmetries are useful to discriminate different models.

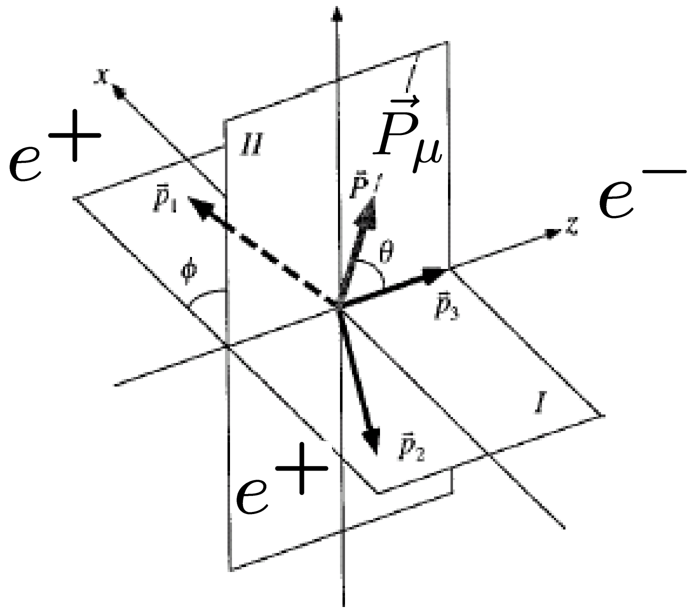


$$\frac{dB(\mu^+ \to e^+\gamma)}{d\cos\theta} \propto 1 + A_{\mu\to e\gamma} P_\mu \cos\theta$$

The SUSY seesaw model
Only LFV coupling for the left-handed slepton mixing
=> $\mu^+ \to e^+\gamma_R \Rightarrow (1-\cos\theta)$ distribution



μ–> 3e



Two P–odd and
one T–odd asymmetries

$$A_{P_1} = \frac{N(P_z > 0) - N(P_z < 0)}{N(P_z > 0) + N(P_z < 0)}$$
$$A_{P_2} = \frac{N(P_x > 0) - N(P_x < 0)}{N(P_x > 0) + N(P_x < 0)}$$
$$A_T = \frac{N(P_y > 0) - N(P_y < 0)}{N(P_y > 0) + N(P_y < 0)}$$

P and T–odd asymmetries in minimal SUSY GUT models

	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

(3) Atomic number dependence of the mu-e conversion rate for various LFV interactions

O.U.Shanker,1979
A.Czarnecki, W.J.Marciano, K.Melnikov, 1998
R.Kitano, M.Koike, Y.Okada, 2002

- Atomic number dependences for heavier nuclei are different for different types of LFV interactions.
  " Finite size effect", "Relativistic effect"
- Main sources of theoretical uncertainty are also different.

$$
\begin{aligned}
\mathcal{L}_{\rm eff}^{(q')} = & -\frac{1}{\Lambda^2}\Big[\left(C_{DR} m_\mu\, \bar{e}\sigma^{\rho\nu} P_L \mu + C_{DL} m_\mu\, \bar{e}\sigma^{\rho\nu} P_R \mu\right) F_{\rho\nu} \\
& + \sum_{q=u,d,s} \left(C_{VR}^{(q)}\, \bar{e}\gamma^\rho P_R \mu + C_{VL}^{(q)}\, \bar{e}\gamma^\rho P_L \mu\right) \bar{q}\gamma_\rho q \\
& + \sum_{q=u,d,s} \left(C_{SR}^{(q)} m_\mu m_q G_F\, \bar{e} P_L \mu + C_{SL}^{(q)} m_\mu m_q G_F\, \bar{e} P_R \mu\right) \bar{q} q \\
& + \left(C_{GQR} m_\mu G_F\, \bar{e} P_L \mu + C_{GQL} m_\mu G_F\, \bar{e} P_R \mu\right) \frac{\beta_L}{2 g_s^3} G_a^{\rho\nu} G_{\rho\nu}^a + h.c. \Big]
\end{aligned}
$$

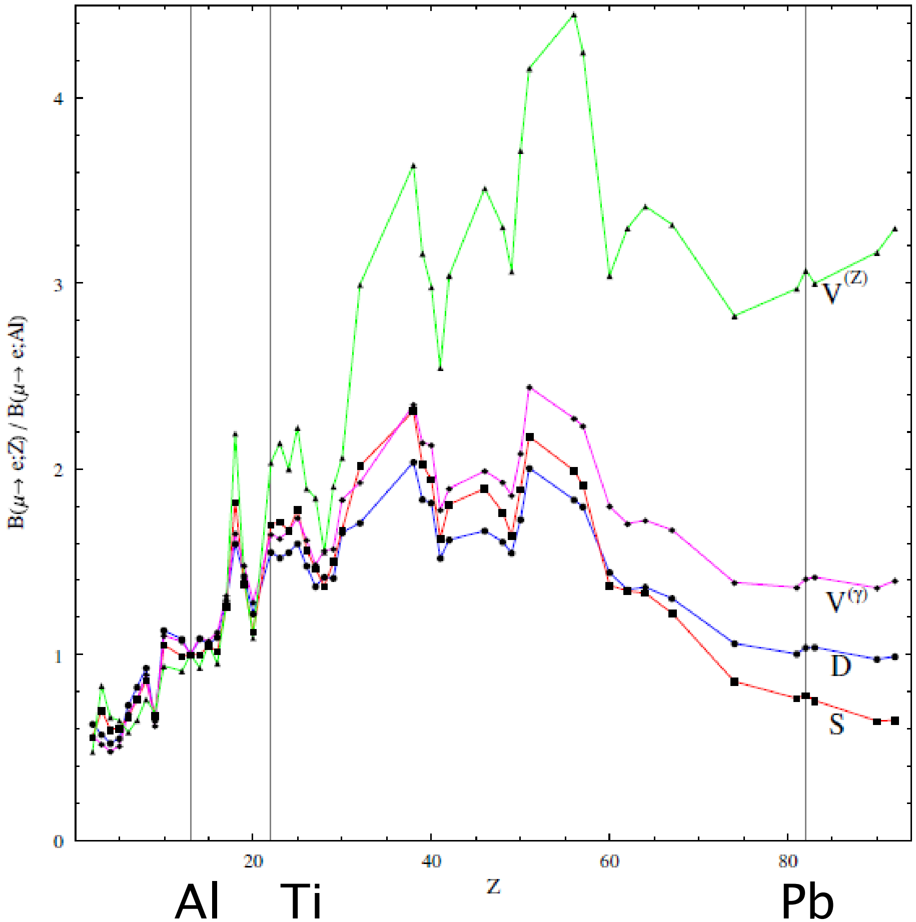
Photonic dipole

Vector

Scalar

gluonic

Atomic number dependence of the mu-e conversion rate



Z-like vector

Photon-like vector

Photonic dipole

Higgs-like scalar

- Maximal in the intermediate nuclei.
- Different Z dependence for heavy nuclei.
- Large enhancement in the Z-like vector case (neutron-rich for heavy nuclei).

Theoretical uncertainty
Photonic: negligible
Vector: 5% level for heavy nuclei from neutron density
Scalar: additional uncertainty from s-quark density in a nulceon

V. Cirigliano, R.Kitano, Y.Okada, and P.Tuson, 2009

New physics examples

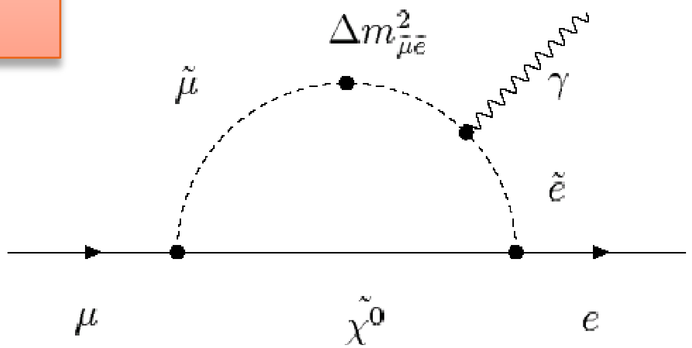
- In order to discriminate theoretical models , comparison of various signals is important.

- SUSY Seesaw with/without SU(5) GUT model
- The Littlest Higgs Model with T parity
- Neutrino mass from TeV physics and LFV

SUSY and LFV

quark/lepton ⇔ squark/slepton
W,Z,Higgs ⇔ chargino, neutralino
gluon ⇔ gluino
graviton ⇔ gravitino

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



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

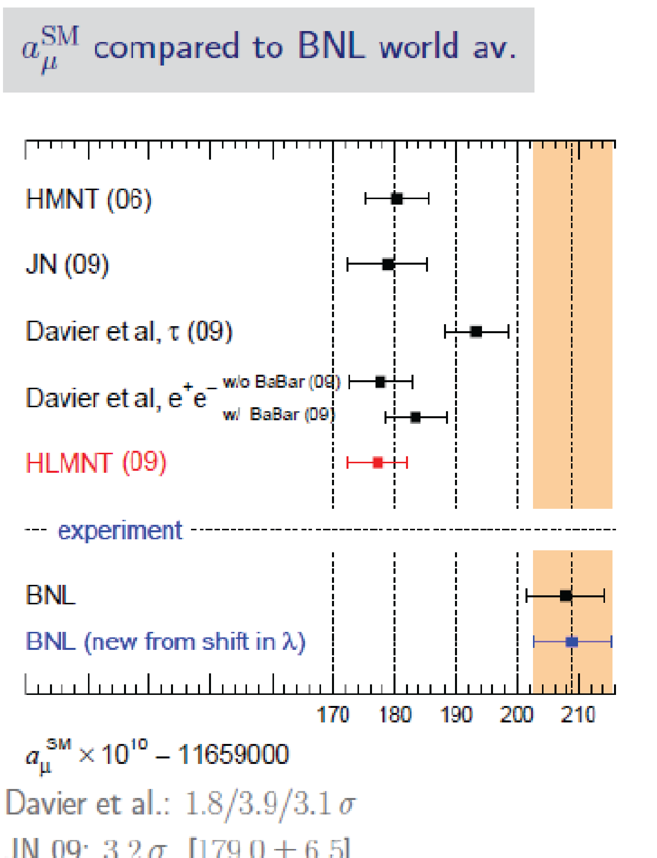
g-2: the diagonal term
EDM: complex phases
LFV: the off-diagonal term

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

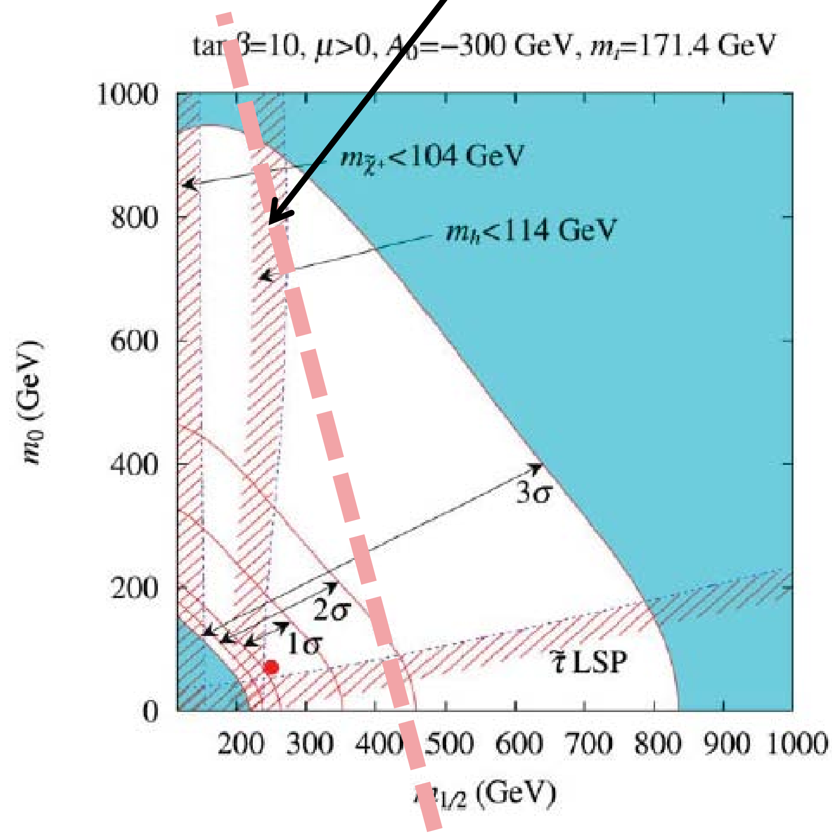
Muon g-2 and SUSY

- Muon g-2 has 3-4 sigma deviation from the SM prediction.
- If this is explained by SUSY, there is a good chance that SUSY is discovered in the 7 TeV run at LHC.

LHC 7TeV 1fb^{-1}



Hagiwara, Liao,Martin,Nomura, Teubner 2010

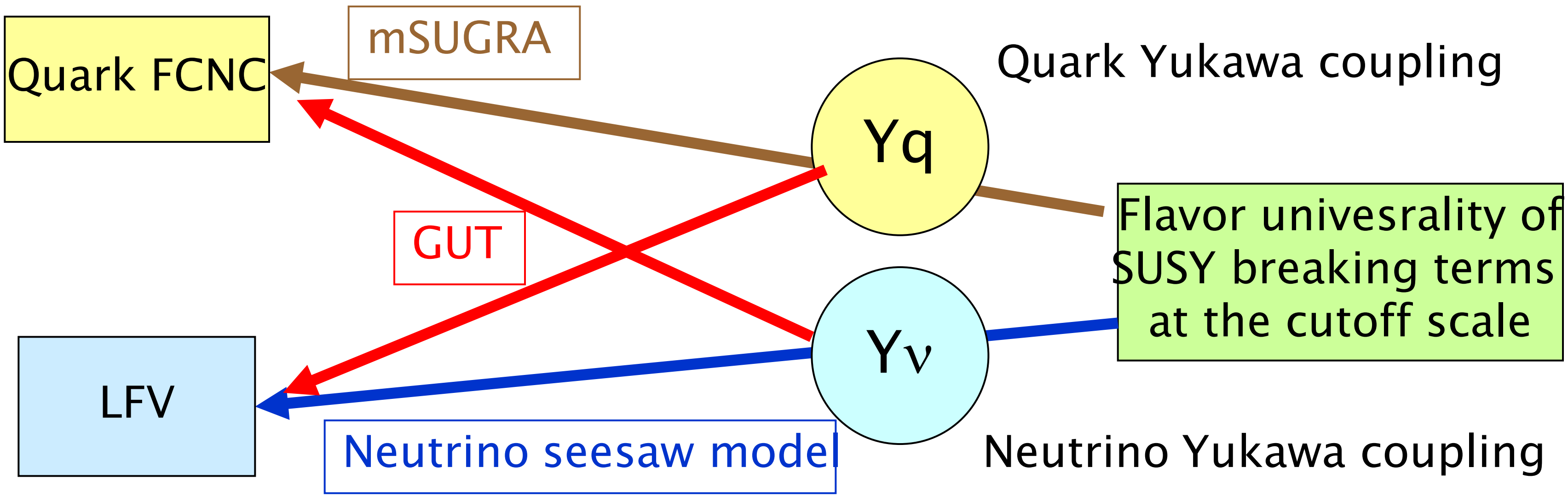


Hagiwara, Martin, Nomura, Teubner, 2007

SUSY GUT and SUSY Seesaw model

- Quark and neutrino Yukawa couplings are sources of squark and slepton flavor mixings.
- There are many new sources of new CP violation.

(Universal SUSY breaking terms, GUT and/or neutrino Yukawa coupling constants)

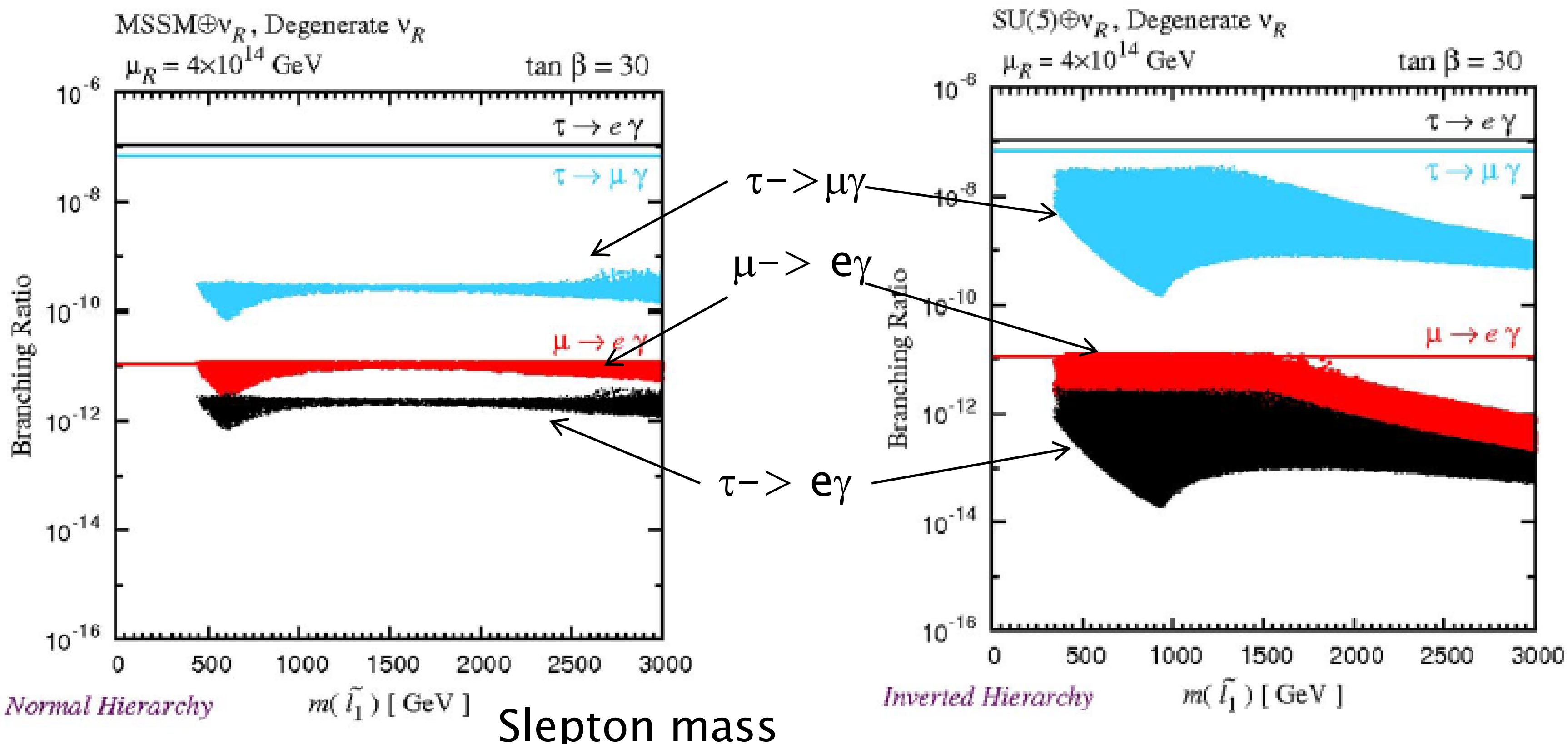


L.J.Hall,V.Kostelecky,S.Raby,1986;A.Masiero, F.Borzumati, 1986

μ−> eγ, τ−> eγ, τ−>μγ

SUSY Seesaw model

SUSY Seesaw +SU(5) GUT

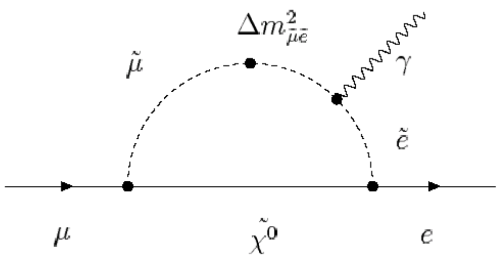


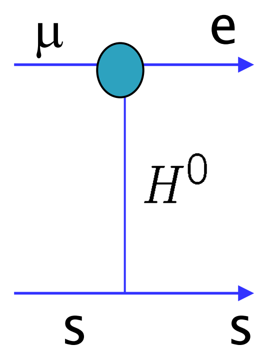
Neutrino normal hierarchy
=> Large μ−>eγ

Neutrino inversed hierarchy
=> τ−>μγ is also large

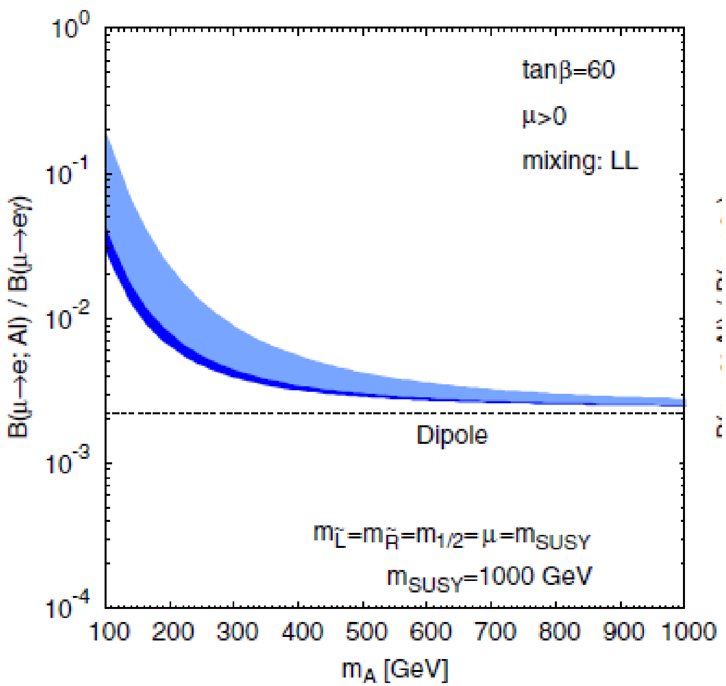
T.Goto, Y.Okada,T.Shindou,M.Tanaka, 2008

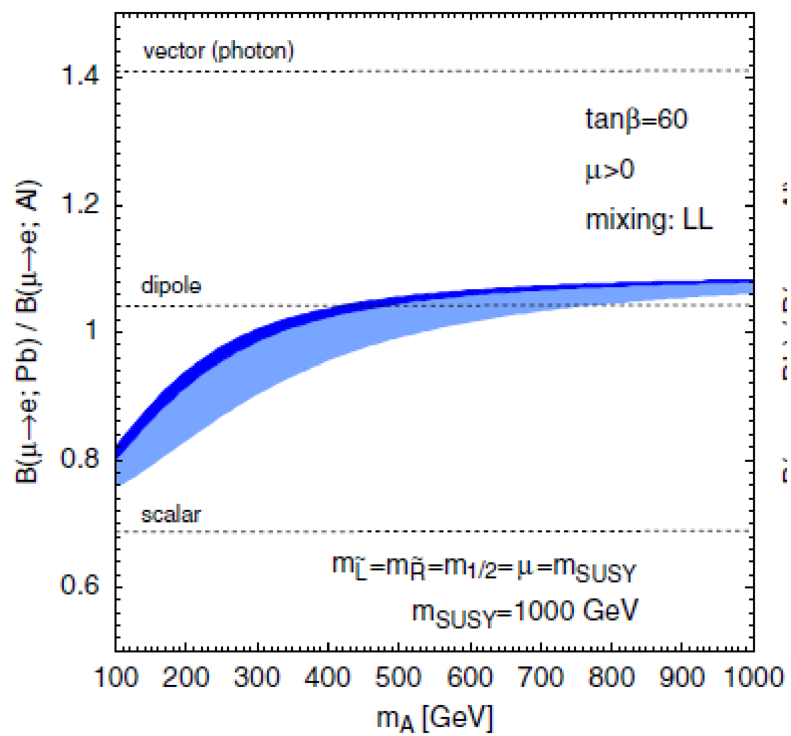
Higgs exchange contribution in SUSY seesaw model with a large "tanβ"





Blue band :
Uncertainty from "y"
Light: 0<y<0.4
Dark:0<y<0.05





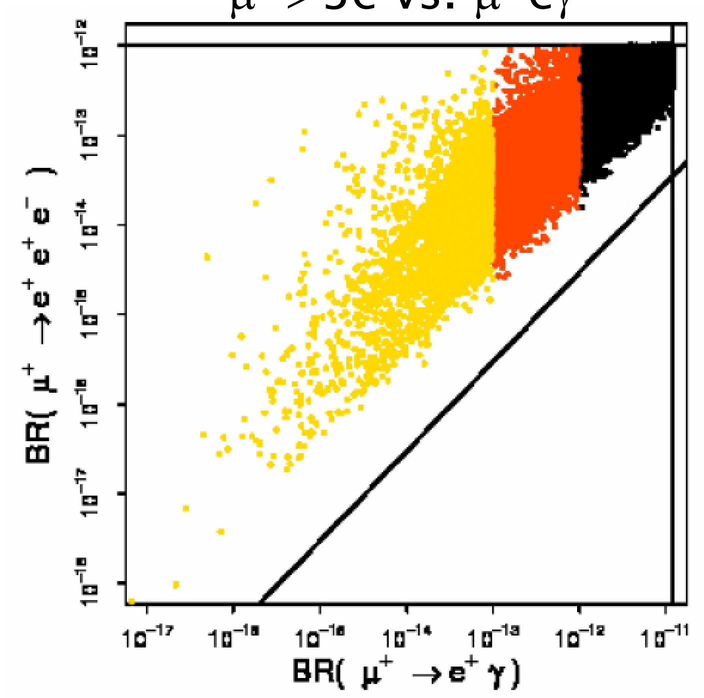
V. Cirigliano, R.Kitano, Y.Okada, and P.Tuson, 2009

Little Higgs Model with T parity

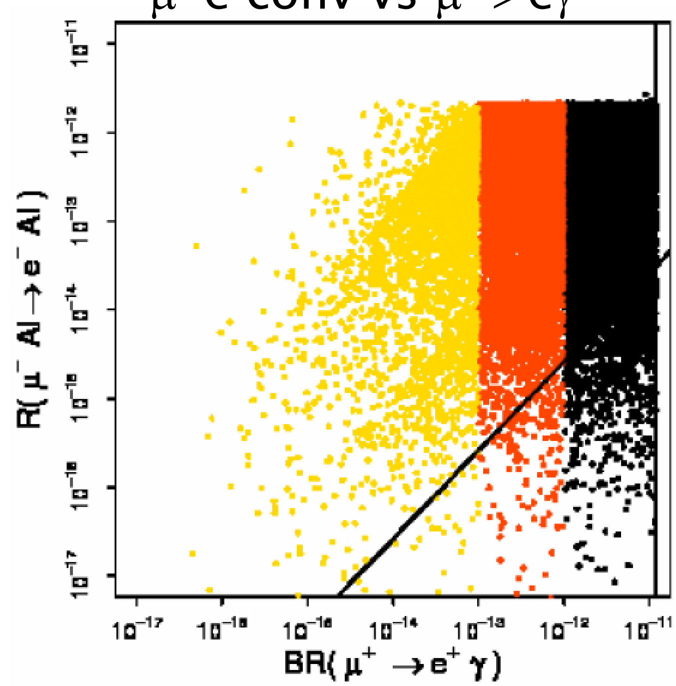
- The Higgs boson is a pseudo Nambu-Goldstone boson of some strong dynamics at ~10 TeV.
- New gauge bosons and a top partner to stabilize the Higgs potential against large radiative corrections without fine-tuning.
- T-odd heavy quarks and leptons are introduced. New flavor mixing matrixes induce FCNC and LFV.

J.Hubisz,S.J.Lee,G.Paz, 2005 ;M.Blanke,et al. 2006-2009;
S.Rai Choudhury, et al. 2007;T.Goto, Y.Okada, Y.Yamamoto, 2009
F.del Aguila, J.I.Illana, M.D.Jenkins,2009,2010

μ->3e vs. μ-eγ



μ-e conv vs μ->eγ



T.Goto, Y.Okada, Y.Yamamoto, 2010

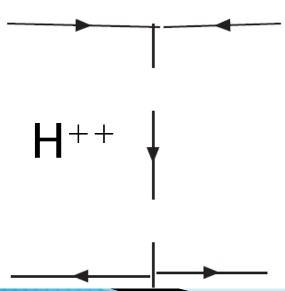
Neutrino mass from TeV physics and LFV

- If the origin of neutrino mass comes from TeV physics, a large LFV is expected.
- Each model shows a characteristic feature in branching ratios, angular distributions, etc.

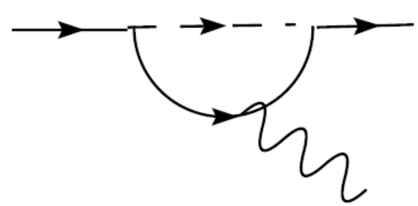
Examples

Radiative neutrino mass generation (Zee model, etc)
Neutrino mass in the warped extra dimension
R-parity violating SUSY model
Triplet Higgs model
Left-right symmetric model

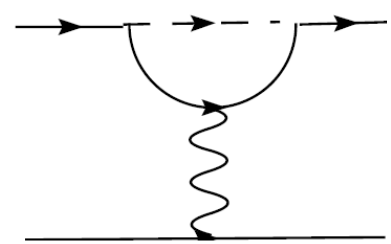
μ->3e



μ ->eγ

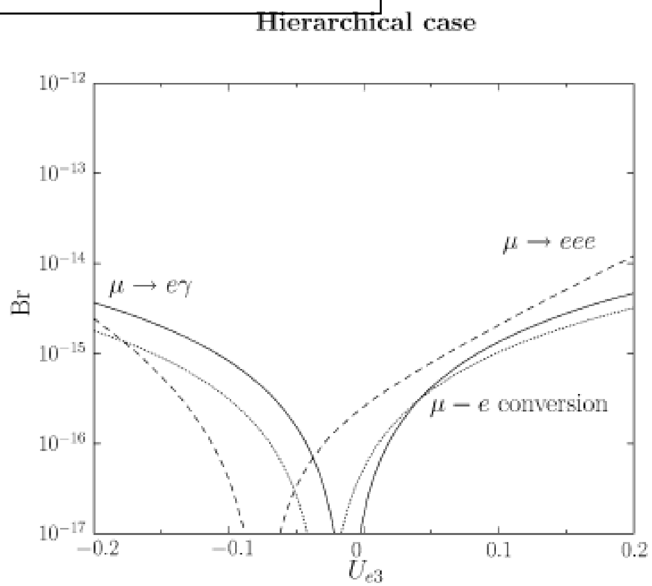


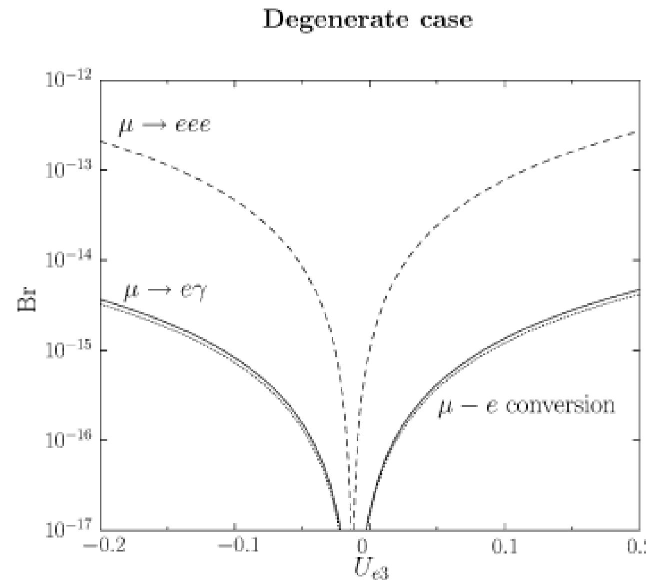
μ-e conv



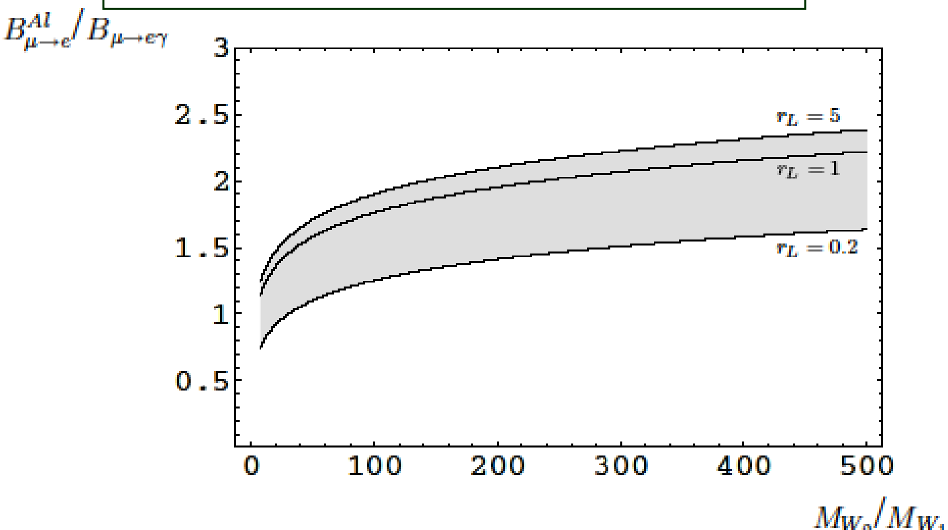
Triplet Higgs model

N.Kakizaki,Y.Ogura, F.Shima, 2003



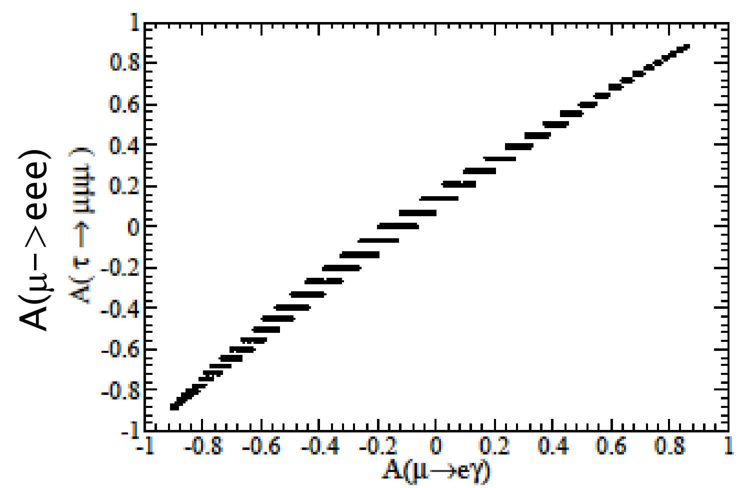


Left-Right symmetric model



V.Cirigliano, A.Kurylov, M.J.Ramsey-Musolf, P.Vogel, 2004

μ->eγ and μ->3e asymmetries



A.Akeroyd, M.Aoki and Y.Okada,2006

Pattern of CLFV signals

SUSY GUT/Seesaw	B(μ->e γ) >> B(μ->3e) ~B(μA-eA) Various asymmetries in polarized μ decays
SUSY with large tan β	μ-e conv. can be enhanced Z-dependence in the μ-e conv. branching ratio
The littlest Higgs model with T-parity	B(μ->3e) ~ B(μ->eγ) B(μA-eA) can be larger or smaller than B(μ->eγ)
Triplet Higgs for neutrino	B(μ->3e) ~ B(μ->eγ) ~B(μA-eA) or B(μ->3e) >> B(μ->eγ) ~B(μA-eA)
Left-right symmetric model	B(μ->3e) >> B(μ->eγ) ~B(μA-eA) Asymmetries in μ->3e, μ->eγ

Various possibilities to distinguish new physics models

Summary

- LFV processes are important probes to New Physics at the TeV scale.
- Well-motivated models like SUSY, Little Higgs models, and neutrino mass generation from TeV physics predict interesting range of signals.
- Correlations among various signals including angular distribution of $\mu \to e\gamma$ and $\mu \to 3e$ and atomic number dependence of μ-e conversion rates are useful in discriminating different theoretical models.