New Physics Searches Using Muons
Preview of the Muon Working Group at the Proton Driver Workshop

Muon *g*-2	
Muon EDM	
Muon lifetime	MuLan @ PSI
Lepton Flavor Violation	
$\mu^+ \rightarrow e^+\gamma$	MEG @ PSI
$\mu^+ \rightarrow e^+e^+e^-$	
$\mu^- \rightarrow e^-$ conversion	MECO @ BNL PRIME @ JPARC

R. Ray
9/24/04

MUON WORKING GROUP

Preliminary Agenda

Thursday 7 Oct:	**Working Group Session 2**	Location: TBD
10:30 - 11:15	Theory	B. Marciano
11:15 - 12:00	Muon EDM, g-2 and flavor violation from beyond the SM	K. Babu
12:00 - 12:30	g-2	J. Miller
14:00 - 14:30	Mu lifetime measurement - Mulan	D. Hertzog
14:30 - 15:00	Mu EDM	J. Miller
15:50 - 16:20	mu e Conversion - MECO	TBD
16:20 - 16:50	mu e Conversion - PRIME	Y. Kuno
16:50 - 17:20	Mu --> e gamma - MEG	F. Cei

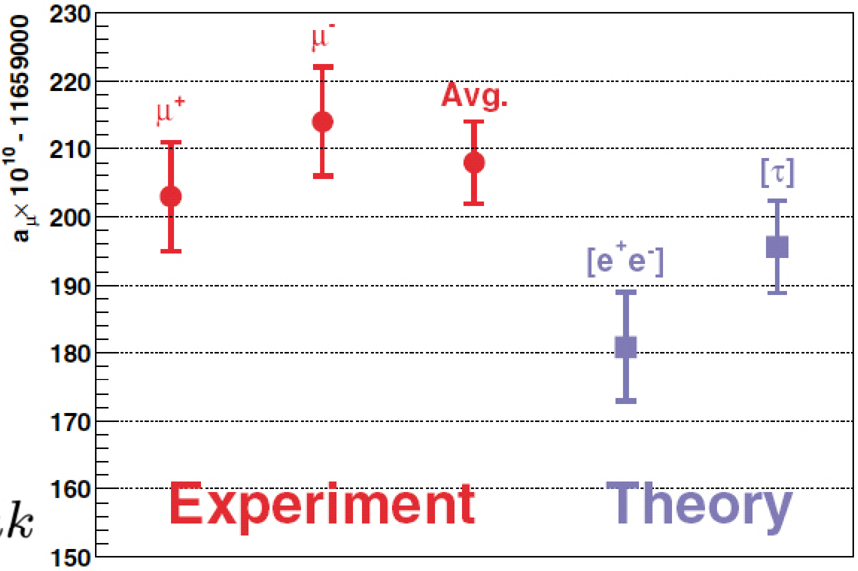
Muon g-2

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

A very precise test of the Standard Model sensitive to contributions from SUSY, WIMPs, extra dimensions, etc.

Most recent result from the BNL experiment

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



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.

K.Hagiwara's talk in W4

Muon EDM

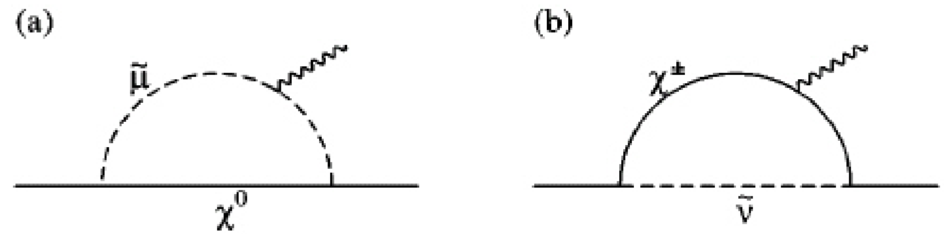
EDM of elementary particles violate both P and T, so CPT requires EDM to violate CP. EDMs provide information on additional CP violating phases.

SM EDMs are only generated at the multi-loop level and are are extremely suppressed, so observation would be a definitive indication of new physics.

Current bound on muon EDM is $O(10^{-19})$ e cm

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.

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

In simple cases,

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

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)

Muon Lifetime Measurement

Muon lifetime is used to determine $G_{F,}$ the fundamental parameter that governs the strength of electroweak processes.

$$\frac{1}{\tau_\mu} = \frac{G_F^{\,2}\, m_\mu^{\,2}}{192\pi^3} \times (1+\Delta q)$$

Δq are higher order QED and QCD corrections

The uncertainty of the theoretical corrections (< 1 ppm) are an order of magnitude smaller than the error on the measured value of the muon lifetime.

MuLan

10^{12} muon decays $\rightarrow$ 1 ppm determination of $\tau_{\leftarrow}$(> order of magnitude improvement over current PDG value)

Determine G_F to better than 1 ppm

LFV and new physics

- Many models beyond the Standard Model contain sources of LFV.
- Although the simple seesaw or Dirac neutrino model predictions are small, 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

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} ← Belle new results	
$\tau \to lll$	$1.4 - 3.1 \times 10^{-7}$ ← Belle new results	
$G_{Mu\overline{Mu}}/G_F$	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).

Y. Okada

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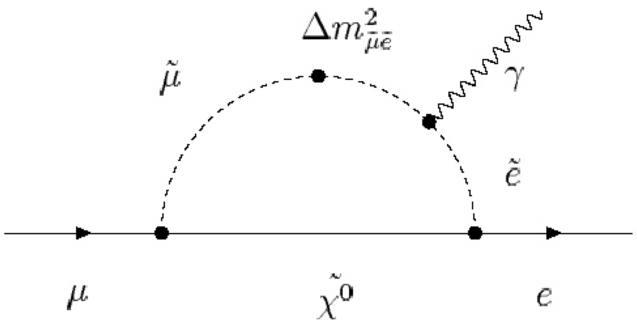
SUSY and LFV

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



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

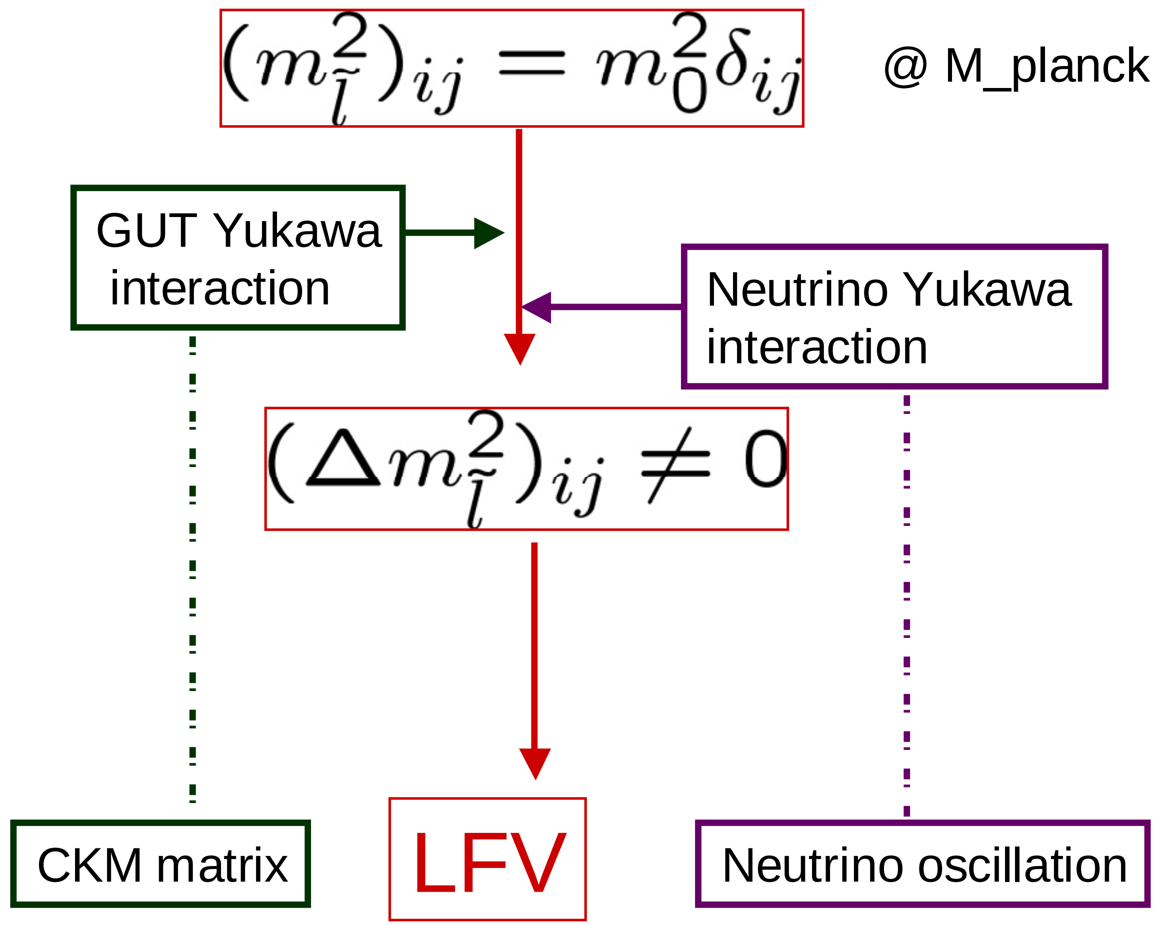
g-2: the diagonal term
EDM: complex phases
LFV: the off-diagonal term

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

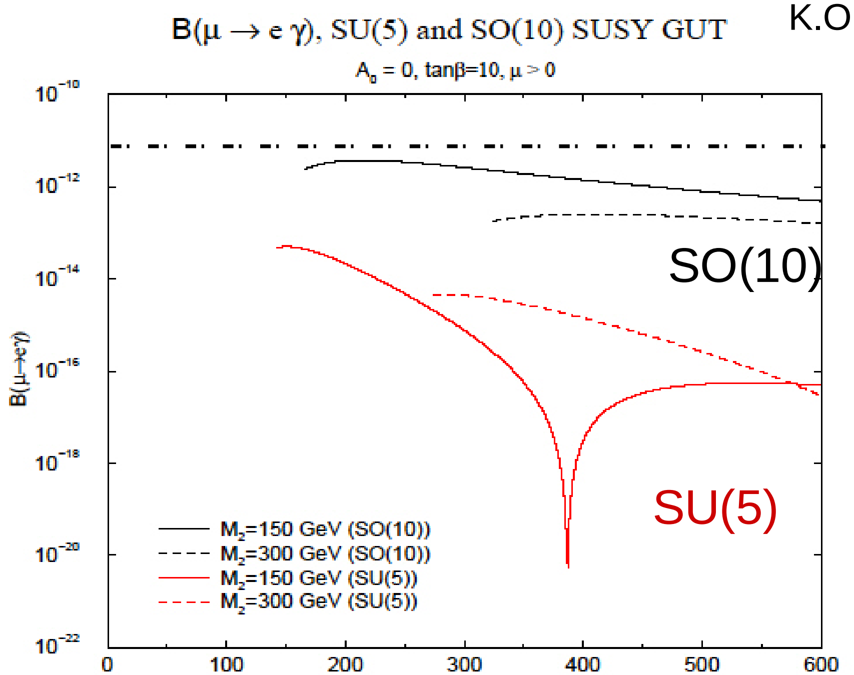
The flavor off-diagonal terms in the slepton mass matrix are induced by renormalization effects due to GUT and/or neutrino interactions.



μ -> e γ branching ratio

SU(5) and SO(10) SUSY GUT

K.Okumura

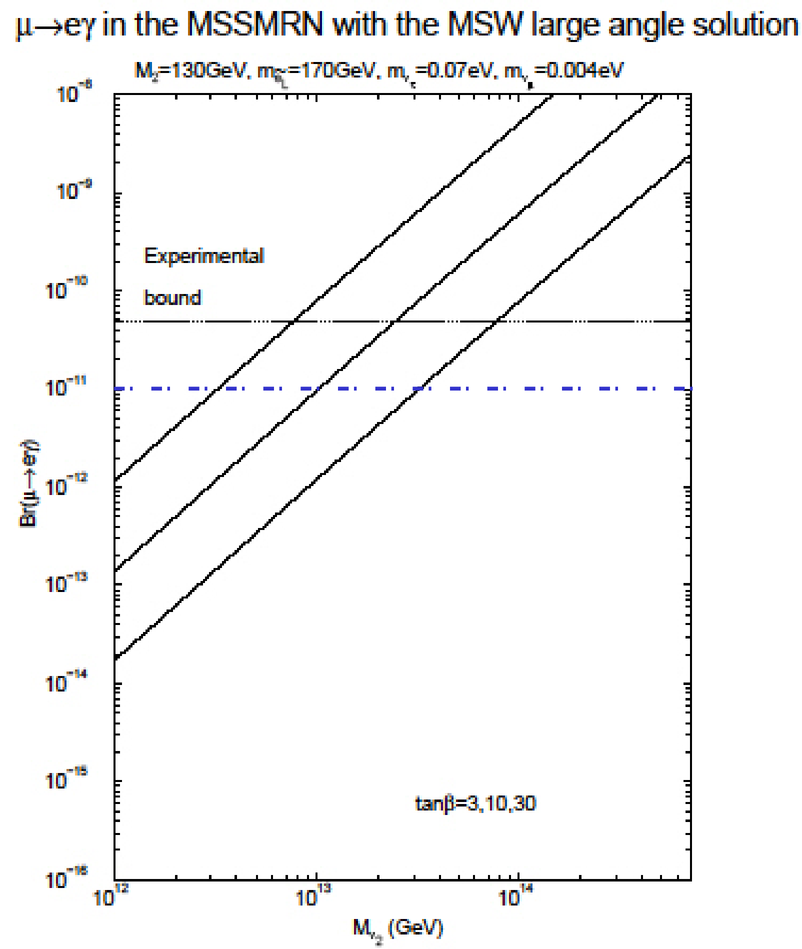


Right-handed selectron mass

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

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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

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

Dipole

Scalar

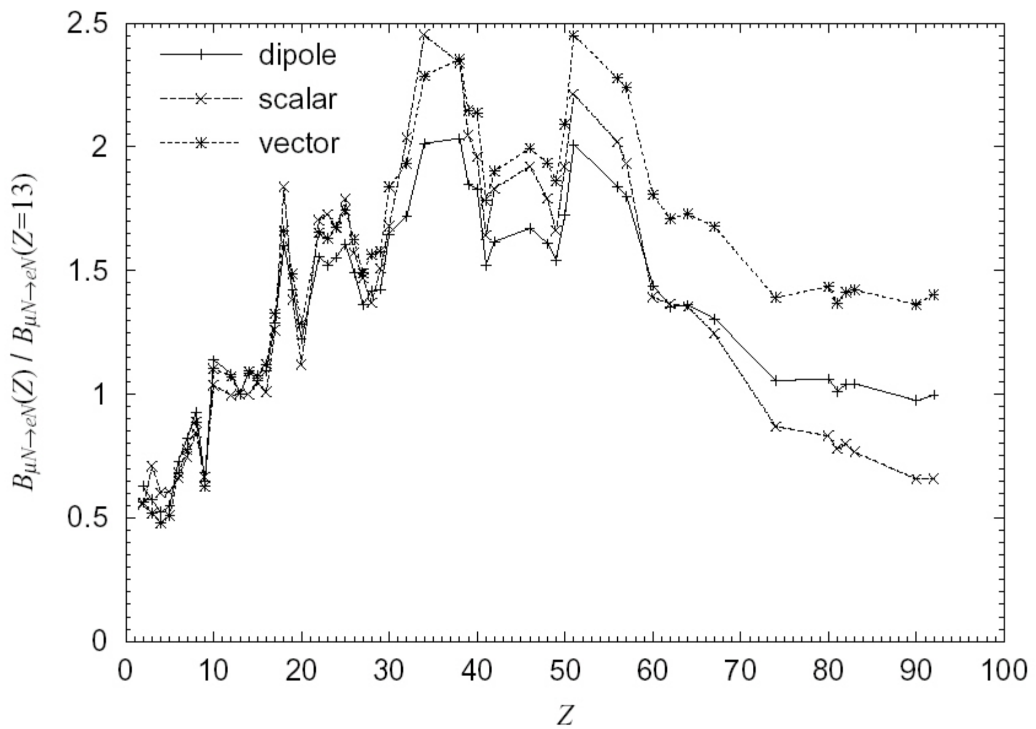
Vector

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.



$(\rho_p = \rho_n)$

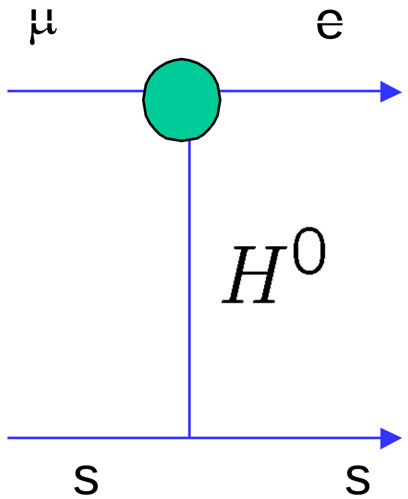
$$B(\mu Pb \to e Pb)/B(\mu Al \to e Al) = 1.0,\ 0.77,\ 1.4$$

dipole scalar vector

Another way to discriminate different models

Higgs-mediated contribution to μ-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

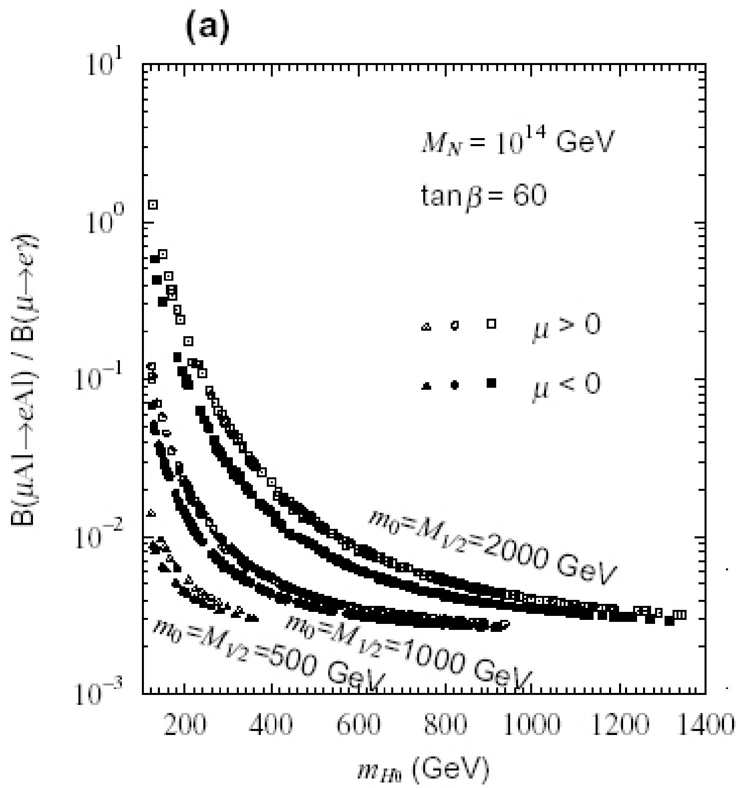
$$B(\mu\text{Al} \to e\text{Al})_{H^0} \sim O(10^{-13}) \cdot \left(\frac{200\text{GeV}}{m_{H^0}}\right)^4 \cdot \left(\frac{\tan\beta}{60}\right)^6$$

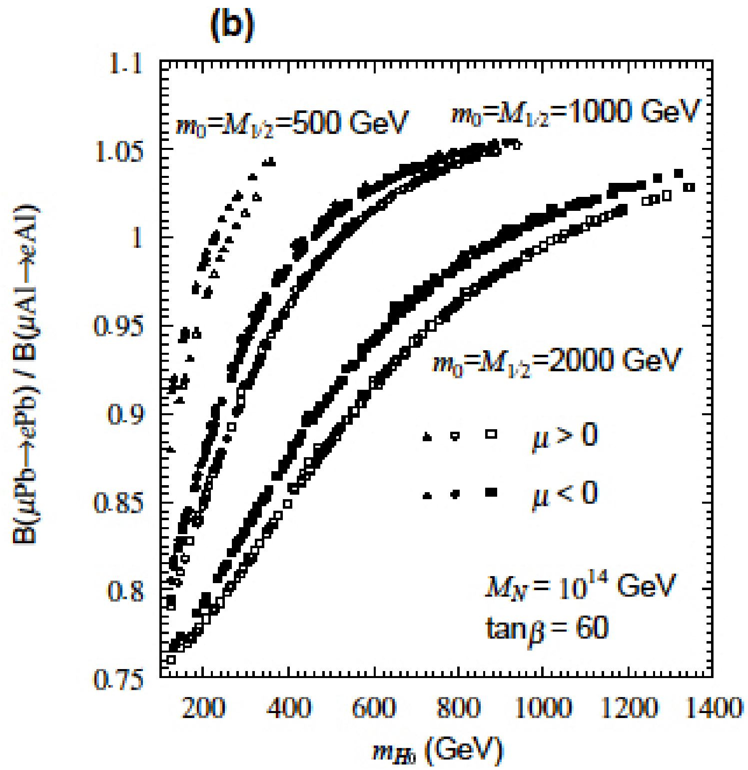
Photon-exchange contribution

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

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

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





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

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Summary

Many opportunities available in muon physics to observe physics beyond the SM

Observable effects are predicted by various models

Comparison of g-2, EDM and various LFV processes along with significant theoretical input will be necessary to distinguish between different models.