Lepton Physics in Supersymmetric Models

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International Workshop on Nuclear and Particle Physics at 50-GeV PS
December 10-12, 2001
KEK, Tsukuba, Japan

Dipole operator of lepton

$$\mathcal{L} = e\frac{m_{l_j}}{2}\bar{l}_i\sigma_{\mu\nu}F^{\mu\nu}(L_{ij}P_L + R_{ij}P_R)l_j$$

where $P_{R/L} = (1 \pm \gamma_5)/2$

R_{ij}, L_{ij}

- Chiral symmetry and $SU(2)_L \times U(1)_Y$ breaking :
  - MDM : $a_{l_i}(\equiv \frac{g_{l_i}-2}{2}) = m_{l_i}^2(R_{ii} + L_{ii})$
- Lepton-Flavor violation :
  - $Br(\mu \to e\gamma) = \frac{48\pi^2\alpha}{G_F^2}(|R_{\mu e}|^2 + |L_{\mu e}|^2)$
- CP violation :
  - EDM : $d_{l_i} = m_{l_i}^2(R_{ii} - L_{ii})$

Muon $g-2$

BNL'98&'99+CERN'77 :

$$a_\mu^{\rm exp} = (116\ 592\ 023 \pm 151) \times 10^{-11}$$

The SM prediction :

$$a_\mu^{\rm SM} \left(\equiv \frac{(g_\mu - 2)}{2}\right) = a_\mu^{\rm QED} + \left\{a_\mu^{\rm Had}(\text{vac.pol.1}) + a_\mu^{\rm Had}(\text{vac.pol.2})\right\}$$
$$+ a_\mu^{\rm Had}(\text{light by light}) + a_\mu^{\rm EW}(\text{1loop+2loop})$$

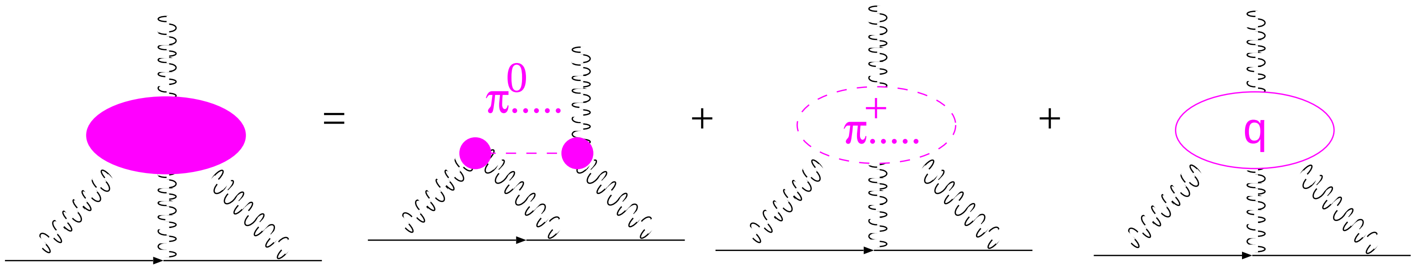
Theoretical calculation for $a_\mu^{\rm Had}$(light by light)

$-92(32) \times 10^{-11}$ (Bijnens *et al* (95))

$-79(15) \times 10^{-11}$ (Hayakawa & Kinoshita (95))

$\Rightarrow 89.6(15.4) \times 10^{-11}$ (Hayakawa & Kinoshita;hep-ph0112102)

Light-by-light scattering contribution



$$a_\mu^{\rm Had}(\text{light by light:}\pi^0) = \begin{cases} -59(\ 9)\times 10^{-11} & \text{(Bijnens } et\ al \text{ (95))} \\ -57(\ 3)\times 10^{-11} & \text{(HK (95))} \\ \Rightarrow +55.6(3)\times 10^{-11} & \text{(HK;hep-ph0112102)} \\ +58(10)\times 10^{-11} & \text{(Knecht \& Nyffeler (01);} \\ & \text{hep-ph/011058)} \end{cases}$$

$$\Rightarrow \quad a_\mu^{\rm NP}(\equiv a_\mu^{\rm exp} - a_\mu^{\rm SM}) = 255(162)\times 10^{-11} \text{ (Only 1.6 } \sigma \text{ away)}$$

BNL'00 result

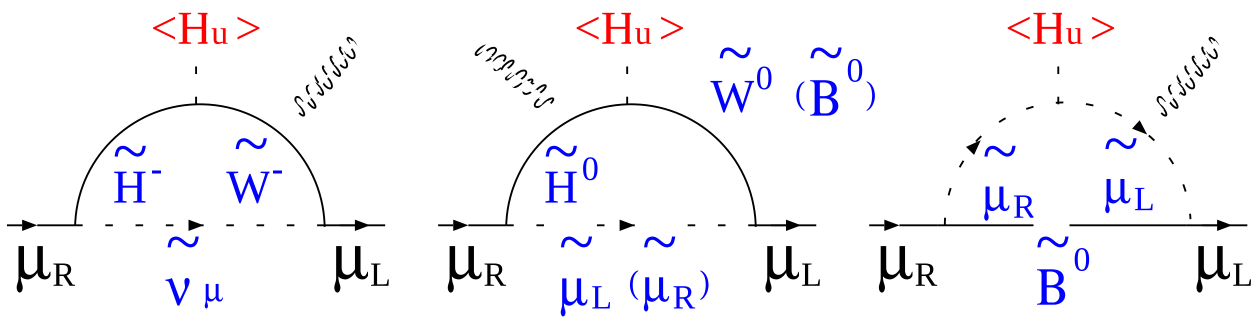
They have 4 times data.

Minimal SUSY SM (MSSM)

Two double Higgs bosons nature enhance $a_\mu^{\rm SUSY}$

$$m_\mu \sim f_\mu \langle H_d \rangle, \qquad a_\mu^{\rm SUSY} \sim \frac{m_\mu f_\mu \langle H_u \rangle}{m_{\rm NP}^2} = \frac{m_\mu^2}{m_{\rm SUSY}^2} \tan\beta$$

$$a_\mu^{\rm MSSM} \simeq \frac{5\alpha_2 + \alpha_Y}{48\pi} \frac{m_\mu^2}{m_{\rm SUSY}^2} \tan\beta \simeq 1.3 \times 10^{-9} \left(\frac{100{\rm GeV}}{m_{\rm SUSY}} \right)^2 \tan\beta$$



$a_\mu^{\rm MSSM} \sim 10^{-9}$ is expected.

Contents

· Lepton-Flavor Violation (LFV) of charged leptons

· Electric Dipole Moment (EDM) of charged leptons

Lepton-flavor violation

Origin of the Lepton-flavor violation;

- Neutrino masses
- GUTs

Neutrino oscillation: Lepton-flavor violating

- $\nu_\mu \to \nu_\tau$ in atmospheric neutrino
- $\nu_e \to \nu_\mu$ in solar neutrino

However, charged LFV processes, such as $\mu \to e\gamma$, induced by small neutrino masses are extremely small.

$$Br(\mu \to e\gamma) \quad \sim \quad \alpha\alpha_2 \left| \sum_i U_{\mu i} U^\dagger_{ei} \frac{m^2_{\nu_i}}{m^2_W} \right|^2 < 10^{-48} \left(\frac{m_\nu}{1\text{eV}} \right)^4$$

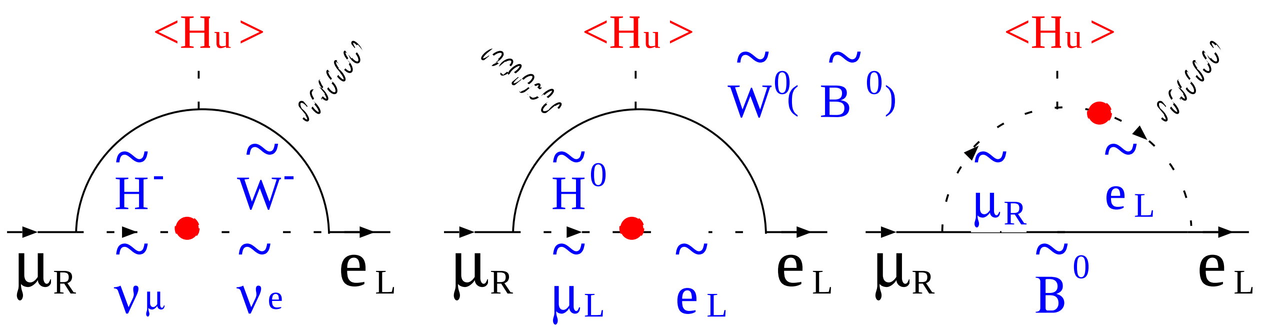
Minimal SUSY SM

Misalignment between slepton and lepton masses may lead to sizable lepton-flavor violating processes.

When left-handed slepton matrix has off-diagonal component $(m^2_{\tilde{L}})_{12}$,

$$Br(\mu \to e\gamma) \simeq \frac{\pi\alpha}{75} \frac{(\alpha_2 + \frac{5}{4}\alpha_Y)^2}{(G_F m^2_{\rm SUSY})^2} \tan^2\beta \left(\frac{(m^2_{\tilde{L}})_{12}}{m^2_{\rm SUSY}} \right)^2$$

$$= 3 \times 10^{-5} \left(\frac{a_\mu^{\rm MSSM}}{10^{-9}} \right)^2 \left(\frac{(m^2_{\tilde{L}})_{12}}{m^2_{\rm SUSY}} \right)^2$$



Experimental status

	Current	Present Activities	Future
$Br(\tau \to \mu\gamma)$	1.0×10^{-6}	$\sim 10^{-7}$ (B-factory)	$10^{-(8-9)}$(?)
$Br(\mu \to e\gamma)$	1.2×10^{-11}	2×10^{-14} (PSI)	10^{-15}(?)
$Br(\mu \to 3e)$	1.0×10^{-12}		$10^{-(15-16)}$(?)
$Br(\mu^- N \to e^- N)$	6.1×10^{-13}	5×10^{-17} (BNL)	10^{-18} (?)

Future experiments for muon: PRISM, NuFACT

Future experiments for tau: super B-factory

When $\tan\beta \gtrsim 1$, $\mu \to e$ conversion rate is given

$$R(\mu^- \mathrm{Ti(Al)} \to e^- \mathrm{Ti(Al)}) \simeq 5(3) \times 10^{-3} Br(\mu \to e\gamma).$$

Sensitivity of 10^{-18} for $\mu \to e$ conversion is comparable to $Br(\mu \to e\gamma) \sim 10^{-16}$

Relation between $\mu \to e\gamma$ and muon $(g-2)$

$$Br(\mu \to e\gamma) \simeq 3 \times 10^{-5} \left(\frac{a_\mu^{\rm MSSM}}{10^{-9}} \right)^2 \left(\frac{(m^2_{\tilde{L}})_{12}}{m^2_{\rm SUSY}} \right)^2$$

From $Br(\mu \to e\gamma) < 1.2 \times 10^{-11}$,

$$\frac{(m^2_{\tilde{L}})_{12}}{m^2_{\rm SUSY}} \lesssim 6 \times 10^{-4} \left(\frac{\delta a_\mu^{\rm SUSY}}{10^{-9}} \right)^{-1} \left(\frac{{\rm Br}(\mu \to e\gamma)}{1.2 \times 10^{-11}} \right)^{\frac{1}{2}} .$$

$$\sim 10^{-5} \text{ for PSI, BNL}$$

$$\sim 10^{-6} \text{ for PRISM, NuFACT}$$

If the deviation of muon $g-2$ is confirmed, the future LFV experiments will give stringent tests of the universality of slepton masses.

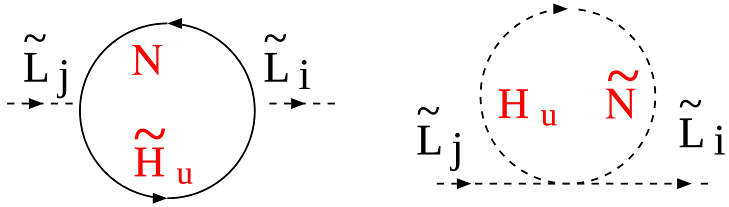
Charged LFV in MSSM depends

origin of SUSY breaking and physics beyond the MSSM.

See-Saw mechanism in the minimal supergravity

Right-handed neutrinos (N) have lepton-flavor violating Yukawa coupling (Y_ν).

$$\Delta(m^2_{\tilde{L}})_{ij} =$$



$$\simeq -\frac{1}{8\pi^2}(Y_\nu^\dagger Y_\nu)_{ij} \log\frac{\tilde{M}_X}{M_N}(3m_0^2 + A_0^2) \qquad (i \neq j)$$

M_X: the scale of SUSY breaking messenger to MSSM.

Typically, $M_X = 2 \times 10^{18}$GeV in minimal supergravity.

LOG DEPENDENT CORRECTION.

Neutrino oscillation data *v.s.* LFV processes

See-Saw mechanism in the minimal supergravity

$$W = \bar{E}_i {Y_e}^i L_i H_d + \bar{N}_i {Y_\nu}^{ij} L_j H_u + \frac{1}{2} \bar{N}_i {M_N}_i \bar{N}_i \qquad (Y_\nu = Z^* Y_\nu^D X^\dagger)$$

Light ν mass matrix: $\mathcal{M}_\nu = Y_\nu^T \frac{1}{M_N} Y_\nu \langle H_u \rangle^2 = U^* m_\nu U^\dagger$ (U:MNS matrix)

slepton mass matrix: $\Delta(m_{\tilde{L}}^2) \simeq -\frac{1}{8\pi^2} (X (Y_\nu^D)^2 X^\dagger)_{ij} \log \frac{\tilde{M}_{pl}}{M_N} (3m_0^2 + A_0^2)$

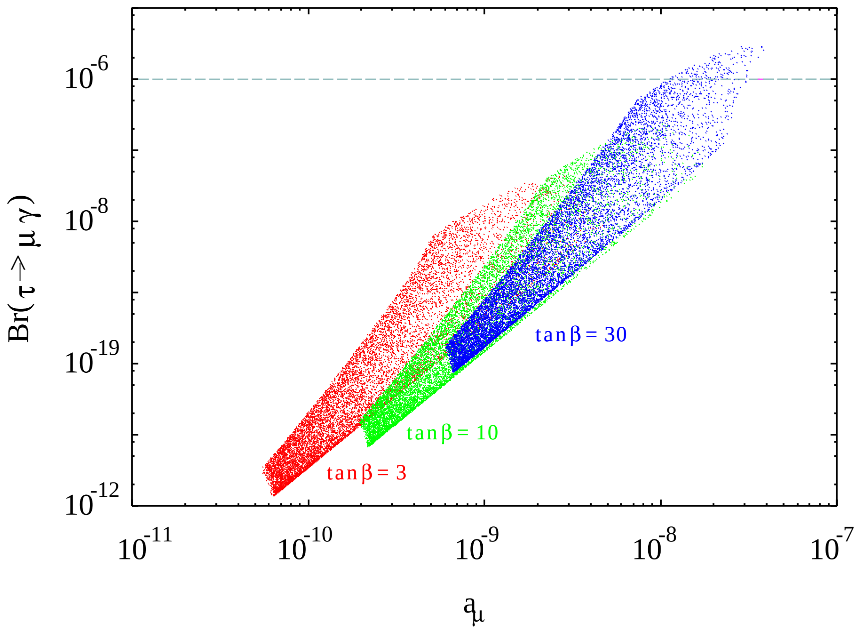
atmospheric neutrino data ($\nu_\mu \to \nu_\tau$)

$$U_{\mu 3} \simeq \frac{1}{\sqrt{2}} \quad \Rightarrow \quad X_{\mu 3} \simeq \frac{1}{\sqrt{2}}$$

$\tau \to \mu\gamma$ Minimal SU(5) SUSY GUT with right-handed neutrinos

$$m_0 < 500\text{GeV}, \quad M_{\tilde{B}} < 500\text{GeV}, \quad A_0 = 0$$

$$m^2_{\nu_\tau} = 2 \times 10^{-3}\text{eV}^2, \quad X_{\mu 3} = 1/\sqrt{2}, \quad Y_{\text{top}} = Y_{\nu_\tau} \text{ at } \tilde{M}_{pl}$$

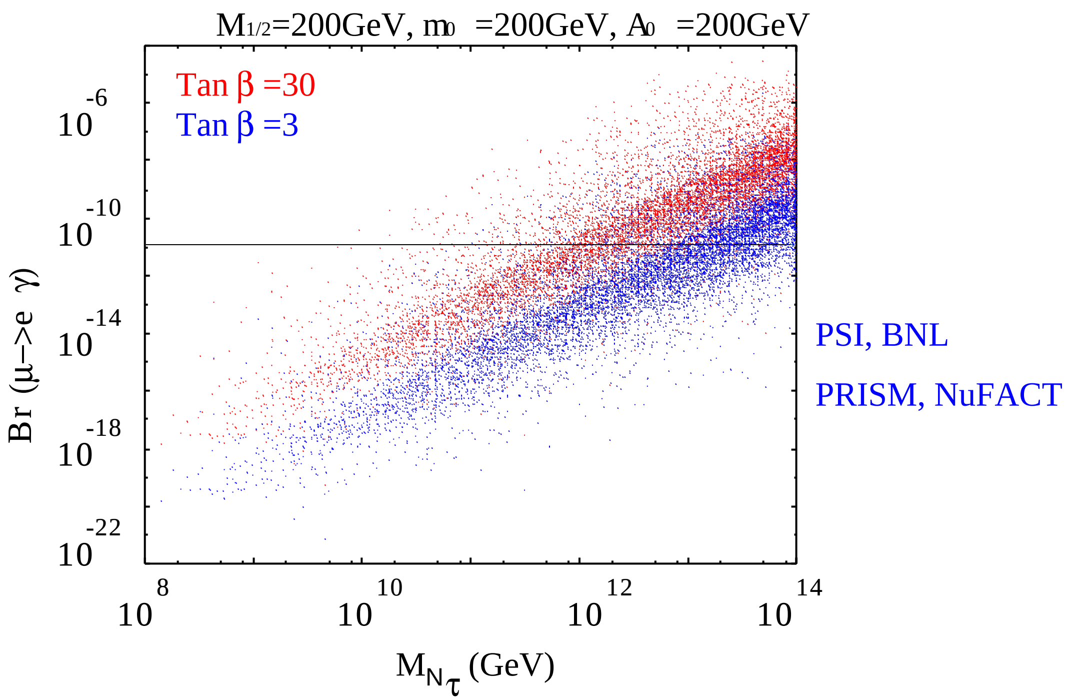


$\mu \to e\gamma$ See-saw model, assuming the LMA solution

$$m^2_{\nu_\tau} = 2 \times 10^{-3}\mathrm{eV}^2, \quad U_{\mu 3} = 1/\sqrt{2}$$

$$m^2_{\nu_\mu} = 7.5 \times 10^{-5}\mathrm{eV}^2, \quad U_{e2} = 1/\sqrt{2}, \quad m_{\nu_e} = 0$$

$$10^8\mathrm{GeV} \leq M_{N_e} \leq M_{N_\mu} \leq M_{N_\tau} \leq 10^{14}\mathrm{GeV}$$

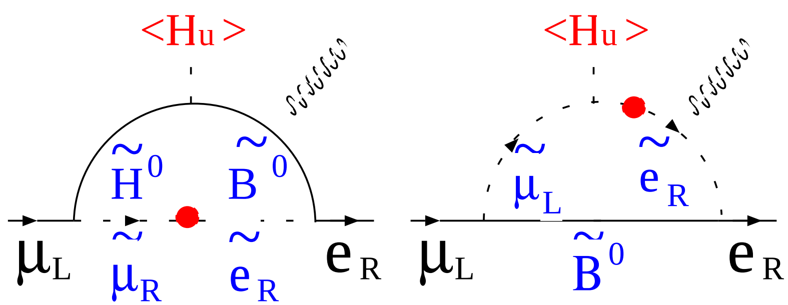


Related topics(1)

LFV in SUSY GUTs

The minimal SU(5) SUSY GUT: right-handed sleptons get LFV mass terms.

⇒ LFV processes rates are reduced by cancellation among diagrams.

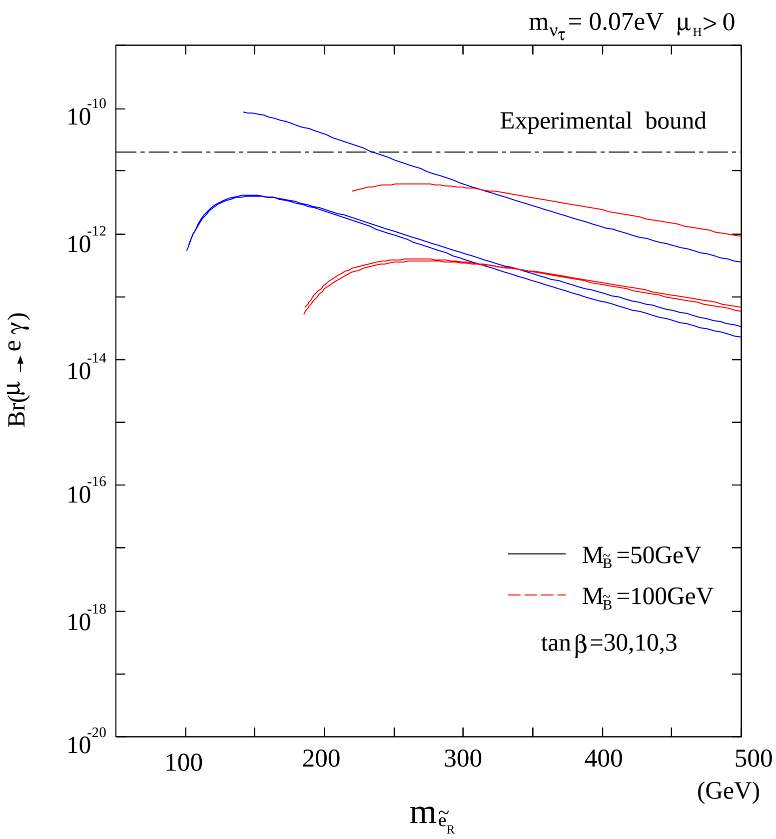


The extensions of the model { introduction of right-handed neutrinos; modification of Yukawa sector }

⇒ Both left-handed and right-handed sleptons get LFV masses, and the cancellation disappears.

Minimal SU(5) SUSY GUT with right-handed neutrinos
(JH, Nomura, and Yanagida)

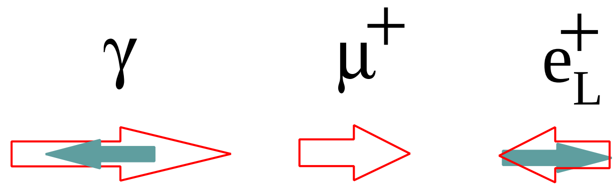
$$m_{\nu_\tau} = 0.07\mathrm{eV}^2, \quad X_{\mu 3} = 1/\sqrt{2}, \quad Y_{\rm top} = Y_{\nu_\tau} \text{ at } \tilde{M}_{pl}$$



Related topics(2)

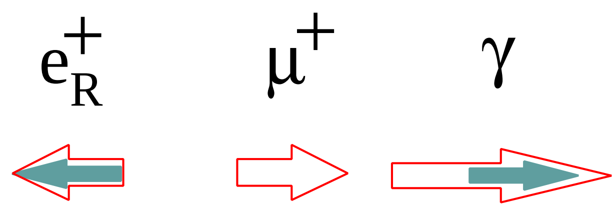
P-odd asymmetry of $\mu \to e\gamma$ by polarized muon

right-handed slepton
(ex, Minimal SU(5) SUSY GUT)



(1-cos θ_γ)

left-handed slepton
(ex, see-saw)



(1+cos θ_γ)

We can distinguish the origin of the LFV by P-odd asymmetry.

EDM of lepton

Experimental status

	Current	Present Activities	Future
d_e	$1.5 \times 10^{-27} e$ cm		$10^{-33} e$ cm(?) (nucl-ex/0109014)
d_μ	$(3.7 \pm 3.4) \times 10^{-19} e$ cm	$2 \times 10^{-24} e$ cm (BNL)	$10^{-26} e$ cm (?) (PRISM, NuFACT)

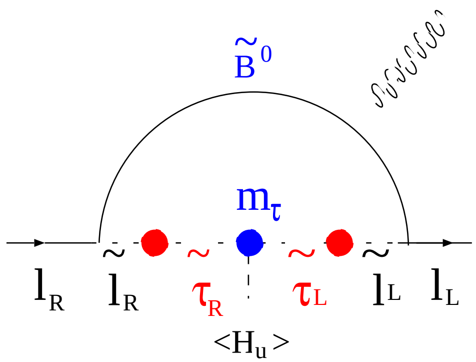
The prediction in the SM

$$
\begin{aligned}
d_e &< 10^{-40} e \text{ cm} \\
d_\mu &< 10^{-38} e \text{ cm}
\end{aligned}
$$

EDM is sensitive to physics beyond the SM.

EDM in SUSY GUTs

Relative phases of left-handed and right-handed slepton mixing



Sizable EDMs in
- SO(10) SUSY GUT
- SU(5) SUSY GUT with right-handed neutrinos
- non-minimal SUSY SU(5) GUT

EDMs of lepton are sensitive to SUSY GUTs' models.

Correlation between $\mu \to e\gamma$ and EDMs of leptons.

In SU(5) SUSY GUT with right-handed neutrinos

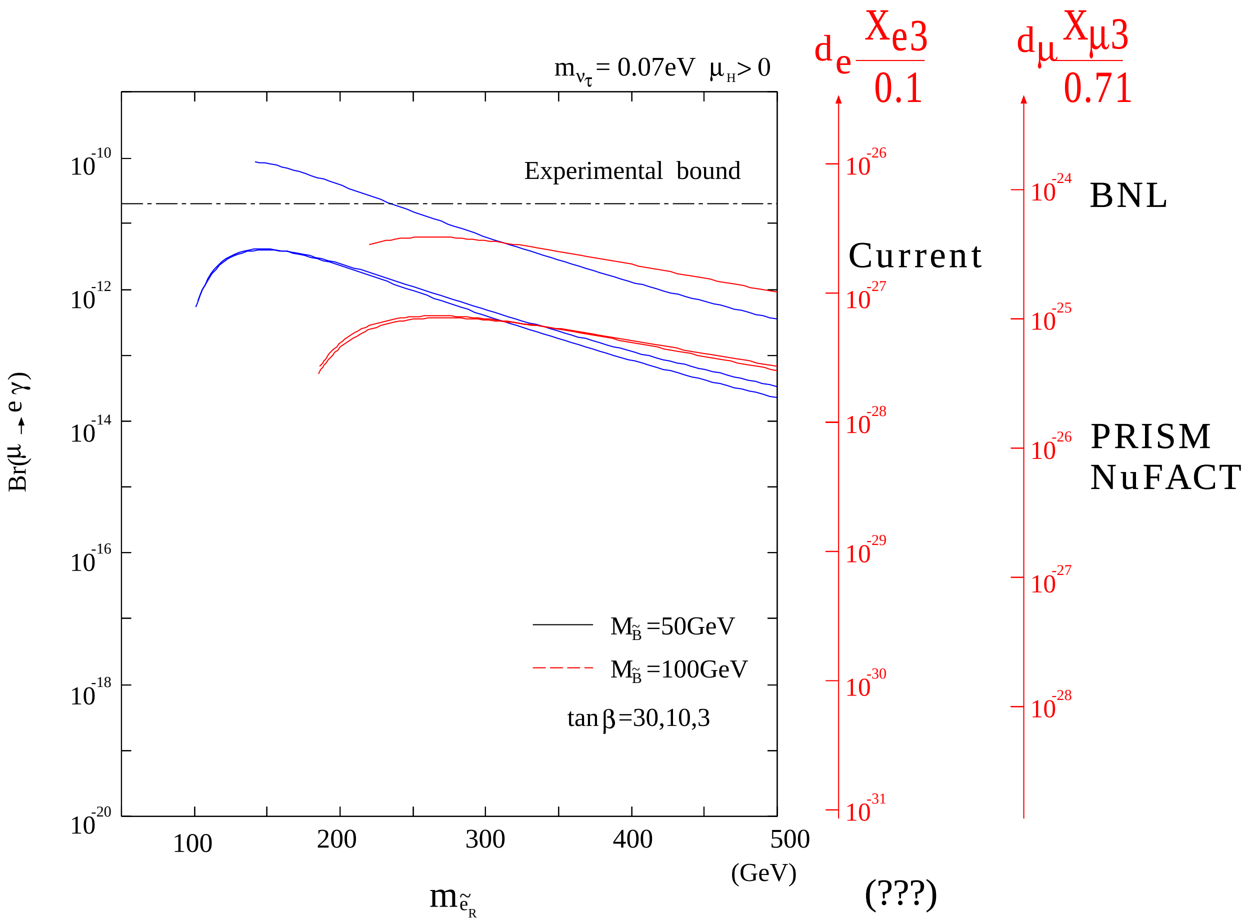
(Here, we assume that $Y_{\nu_\tau} \gg Y_{\nu_\mu} \gg Y_{\nu_e}$)

$$\left(m^2_{\tilde{L}}\right)_{ij} \approx X_{i3}X^\star_{j3}$$
$$\left(m^2_{\tilde{E}}\right)_{ij} \approx V^{\rm KM}_{3i}V^{\rm KM\star}_{3j}$$

Then,

$$d_{l_i} = 1.7 \times 10^{-26}\ \text{cm} \times \frac{\sqrt{2}\,\text{Im}[V^{\rm KM}_{3i}X_{i3}]}{|V^{\rm KM}_{31}X_{32}|^2 + |V^{\rm KM}_{32}X_{31}|^2}\left(\frac{Br(\mu \to e\gamma)}{1.2 \times 10^{-11}}\right)$$

Assuming maximal CP violating phase;



Summary

For **Muon $g-2$**, wait for the update by '00 BNL data. $a_\mu^{\rm SUSY} \sim 10^{-9}$ is expected in the MSSM. Study of **Charged LFV processes** is encouraged ν-oscillation results. If scale of SUSY breaking mediation to the MSSM is so higher than right-handed neutrino scale, the charged LFV processes may be observable in exciting future experiments, PSI, BNL, PRISM, NuFACT. Furthermore, if $a_\mu^{\rm SUSY} \sim 10^{-9}$ is observed, it gives normalization of the processes. **EDMs** of lepton are sensitive to the SUSY GUTs. This may be observable in the future experiments.