Neutrino-Inspired Flavor Physics

-induced by mixing between 2nd and 3rd generations-

Fujihara Seminar
NEUTRINO MASS AND SEESAW MECHANISM
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1, Introduction

Lepton-flavor Violation (LFV) in neutrino sector
: Neutrino oscillation experiments

⇒How large is LFV in charged lepton sector?

$\tau \to \mu\gamma, \tau \to 3\mu, \cdots$ **Tau LFV decays**
(⇔ Atmospheric neutrino ?)

$\mu \to e\gamma, \mu \to 3e \cdots\cdots$ **Muon LFV decays**
(⇔ Solar neutrino ?)

However,

$$Br(\mu \to e\gamma) \prec 10^{-48} (m_\nu / 1eV)^4$$

Charged LFV depends on the physics beyond the SM and origin of the neutrino masses.

Neutrino oscillation:
Finite, but small neutrino mass

$$m_\nu \simeq \frac{(f_\nu \langle h_2 \rangle)^2}{M} \to 0 \ \ (M \to \infty)$$

Seesaw model

(Introduction of right-handed neutrinos ν_R)

$$L = f_l \, \overline{e}_R L h_1 + f_\nu \, \overline{\nu}_R L h_2 + M \ \nu_R \nu_R$$

Unification of Matter
in SO(10) GUT:

$$\Psi(16) = \begin{pmatrix} u_L, u_R, d_L, d_R \\ e_L, e_R, \nu_L, \nu_R \end{pmatrix}$$

Baryon in Universe:
Leptogenesis
(B-L violation
by Majorana mass M)

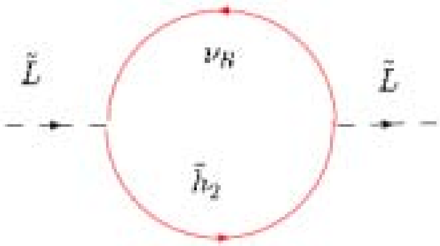
Superheavy M : We need Supersymmetry (SUSY)

Charged Lepton-Flavor Violation in SUSY seesaw model

Non-vanishing LFV slepton masses by radiative correction

$$\left(m^2_{\tilde{L}}\right)_{ij} \square \frac{1}{8\pi^2}(3m_0^2 + A_0^2)\left(f_\nu^\dagger f_\nu\right)_{ij} \log\frac{M}{M_G}$$

(Borzumati&Masiero)



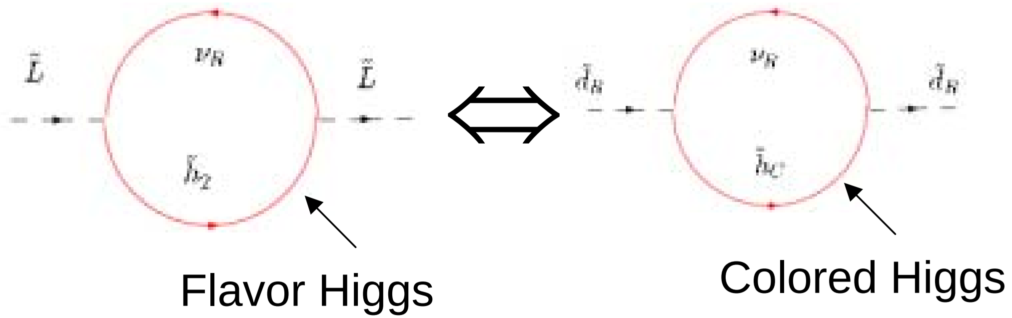
And then, $Br(l_i \to l_j\gamma) \square 10^{-6}\left(\frac{\left(m^2_{\tilde{L}}\right)_{ij}}{\overline{m^2_{\tilde{L}}}}\right)^2\left(\frac{100GeV}{m_{SUSY}}\right)^4 \tan^2\beta$

The charged LFV, $\tau \to \mu\gamma, \mu \to e\gamma \cdots\cdots$, may be observed in near future experiments.

SUSY GUT with right-handed neutrinos

Matter unification: GUT relation in flavor physics

$$\begin{array}{c} (\; s_{R1} \;\; s_{R2} \;\; s_{R3} \;\; \mu_L \;\; \nu_{\mu L} \;) \\ (\; b_{R1} \;\; b_{R1} \;\; b_{R3} \;\; \tau_L \;\; \nu_{\tau L} \;) \end{array}$$



$$\left(m^2_{\tilde d_R}\right)_{ij} / \left(m^2_{\tilde L}\right)_{ij} \simeq e^{-i(\phi_i-\phi_j)} \left(\log\frac{M_{GUT}}{M_G} / \log\frac{M}{M_G}\right)$$

(ϕ_i :generic CP phase in GUT)

(moroi)

Flavor-violating right-handed current might predict deviation of $B_d^0 \to \phi K_s$ and so on.

Contents of my talk

- **Introduction**
- **Tau LFV in SUSY seesaw model**
- **EDMs induced by** mixing between 2nd and 3rd generations **and** $B_d^0 \to \phi K_S$ **in SUSY GUT model**
- **Summary**

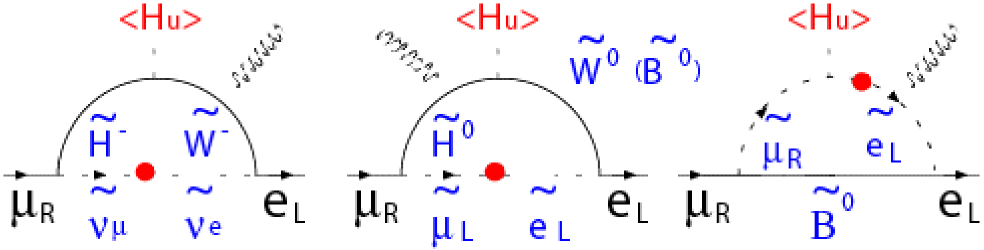
2, Tau LFV in SUSY seesaw model

Non-vanishing LFV slepton masses by radiative correction

$$\left(m^2_{\tilde L}\right)_{ij} \square \frac{1}{8\pi^2}(3m_0^2 + A_0^2)H_{ij} \qquad \left(A_e\right)_{ij} \square \frac{1}{8\pi^2} f_e A_0 H_{ij}$$

and $\left(m^{2}_{\tilde e_R}\right)_{ij} \square\ 0$ where $H_{ij} \equiv \left(f_\nu^\dagger \log\frac{M}{M_G} f_\nu\right)_{ij}$

Radiative decay processes: $l \to l'\gamma,\ l \to l'l''l''$



$\Longrightarrow$ Sizable effect

Belle’s new bounds and future

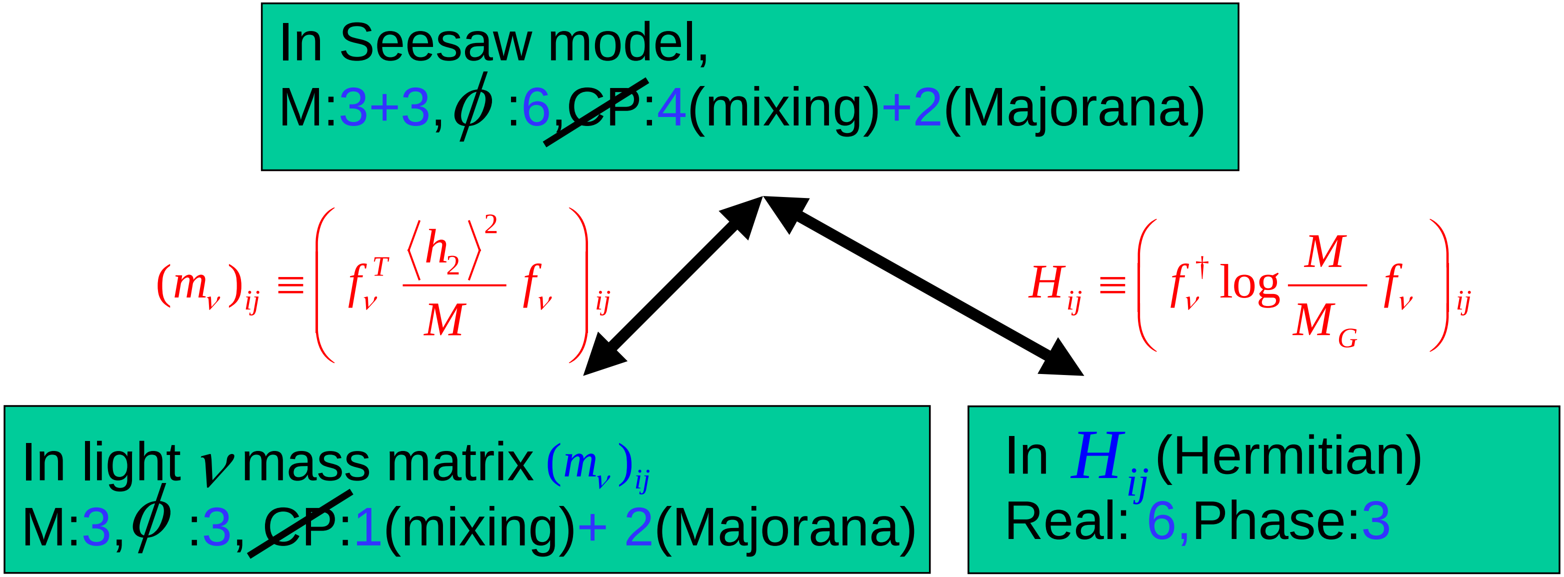
Belle experiment is improving the bounds on Tau LFV processes significantly.

	$2000 PDG$	$Belle\ (current)$	$L=100 fb^{-1}$	$L=3ab^{-1}$
$\tau \to \mu\gamma$	$<1.1\times 10^{-6}$	$<3.2\times 10^{-7}$	$\square 10^{-7}$	$\square 10^{-8}$
$\tau \to e\gamma$	$<2.7\times 10^{-6}$	$<3.6\times 10^{-7}$	$\square 10^{-7}$	$\square 10^{-8}$
$\tau \to \mu\eta$	$<9.6\times 10^{-6}$	$<4.4\times 10^{-7}$	$\square 10^{-7}$	$10^{-8} \square 10^{-9}$
$\tau \to e\eta$	$<8.2\times 10^{-6}$	$<6.9\times 10^{-7}$	$\square 10^{-7}$	$10^{-8} \square 10^{-9}$
$\tau \to lll$	$<a\ few\times 10^{-6}$	$<a\ few\times 10^{-7}$	$\square 10^{-7}$	$10^{-8} \square 10^{-9}$

Further improvements of one or two orders may be expected in super B factory.

Bottom-up approach to seesaw model

Degrees of freedom of physical observables



In Seesaw model,
M:3+3, ϕ :6, ~~CP~~:4(mixing)+2(Majorana)

$$(m_\nu)_{ij} \equiv \left(f_\nu^T \frac{\langle h_2 \rangle^2}{M} f_\nu \right)_{ij}$$

$$H_{ij} \equiv \left(f_\nu^\dagger \log \frac{M}{M_G} f_\nu \right)_{ij}$$

In light ν mass matrix $(m_\nu)_{ij}$
M:3, ϕ :3, ~~CP~~:1(mixing)+ 2(Majorana)

In H_{ij} (Hermitian)
Real: 6,Phase:3

We can take $(m_\nu)_{ij}$ and H_{ij} for parameterization of seesaw model, and neutrino and charged lepton experiments give independent information of seesaw model.

$Br(\tau \to \mu\gamma)$ comes from H_{23}, and $Br(\tau \to e\gamma)$ from H_{13} .

Question: How large they can be?

$\mu \to e\gamma$ is generated if $H_{12,} \, and \, / \, or \, .H_{13} H_{32} \neq 0$.

We assume $H^{(1)} = \begin{pmatrix} * & 0 & 0 \\ 0 & * & * \\ 0 & * & * \end{pmatrix}$ $H^{(2)} = \begin{pmatrix} * & 0 & * \\ 0 & * & 0 \\ * & 0 & * \end{pmatrix}$

$Br(\tau \to \mu\gamma)$ $Br(\tau \to e\gamma)$

Model-building may favor with $H^{(1)}$, not $H^{(2)}$.

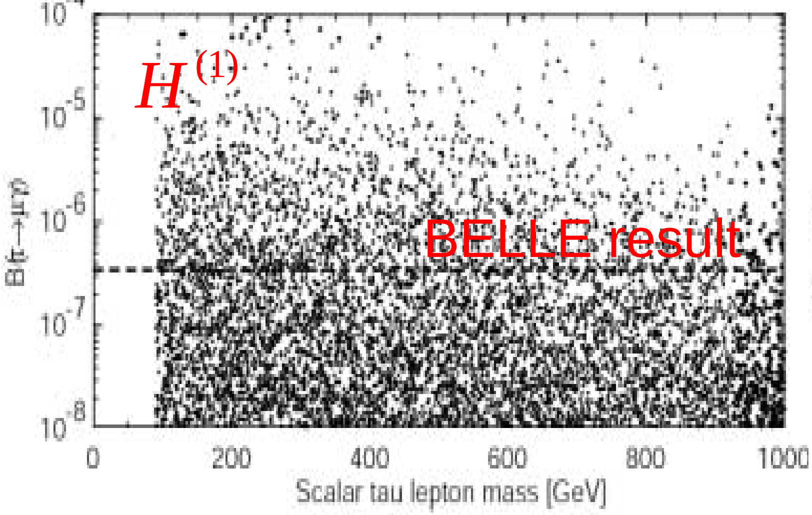
(Observed large mixings of neutrino come from Yukawa coupling in a case of $H^{(1)}$, but Majorana mass in $H^{(2)}$.)

Normal ordering for neutrino mass

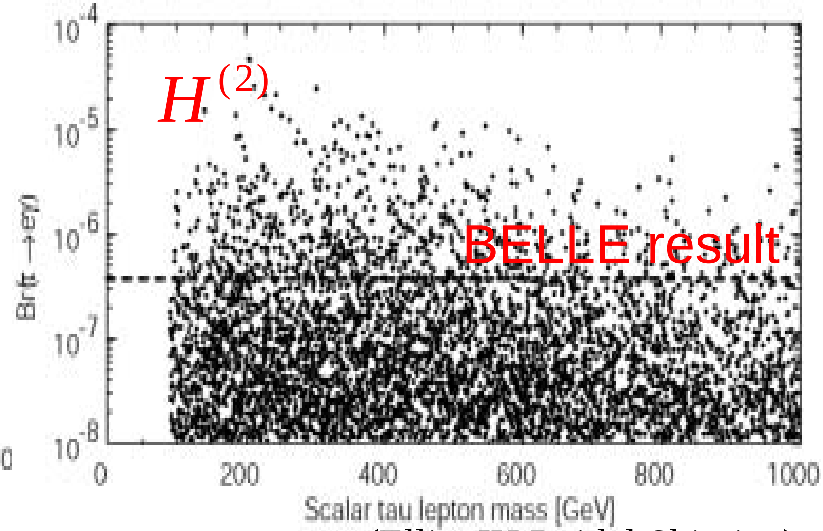
$(m_{\tilde{w}} = 200 GeV,\ A_0 = 0 GeV,\ \tan\beta = 10\ or\ 30,\ sign(\mu) = +1)$

Maximum prediction is fixed by only validity of perturbation, and it Is larger than the experimental bound. These observations give independent information about seesaw model of neutrino oscillation. Even inverted ordering cases give similar results.

$Br(\tau \to \mu\gamma)$



$Br(\tau \to e\gamma)$

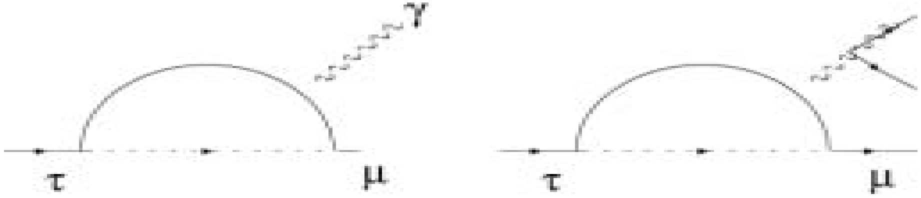


(Ellis, JH,Raidal,Shimizu)

Other tau LFV processes:

- Normal case

One-shell photon contribution is dominant,
since dipole operator contribution is proportional to $\tan^2\beta$.
Furthermore, 3lepton processes is enhanced by $\log\left({}^{m_\tau}\!/_{m_l}\right)$



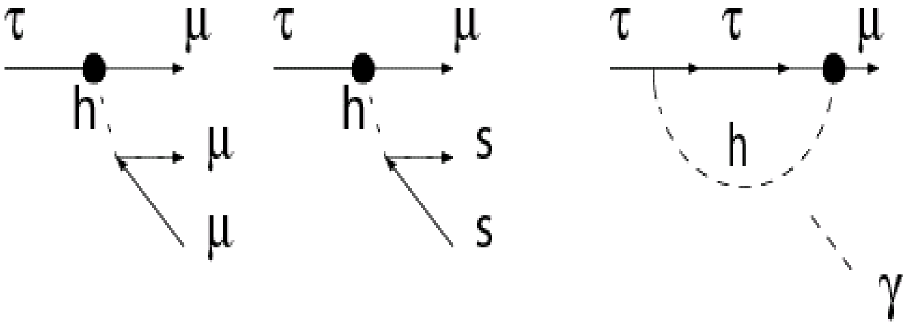
$$Br(\tau \to \mu ee(3e))/Br(\tau \to \mu(e)\gamma) \square 1/94,$$

$$Br(\tau \to 3\mu(e2\mu))/Br(\tau \to \mu(e)\gamma) \square 1/440$$

If we find the LFV, we can examine non-trivial tests!

Even if the slepton is so heavy $(m_{\tilde{l}} > TeV)$,

the anomalous LFV Yukawa coupling for Higgs boson may be generated radiatively and not be suppressed by the SUSY scale. In this case, the tau LFV processes may be generated by Higgs mediation, and 3mu, mu eta, mu gamma are comparable.



$$Br(\tau \to \mu\eta) \approx (8\times 10^{-7}) \times \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100GeV}{m_A}\right)^4$$

$$Br(\tau \to \mu\eta) : Br(\tau \to 3\mu) : Br(\tau \to \mu\gamma) = 8:1:1.5$$

(Babu&Kolda;Shar;JH&Shimizu)

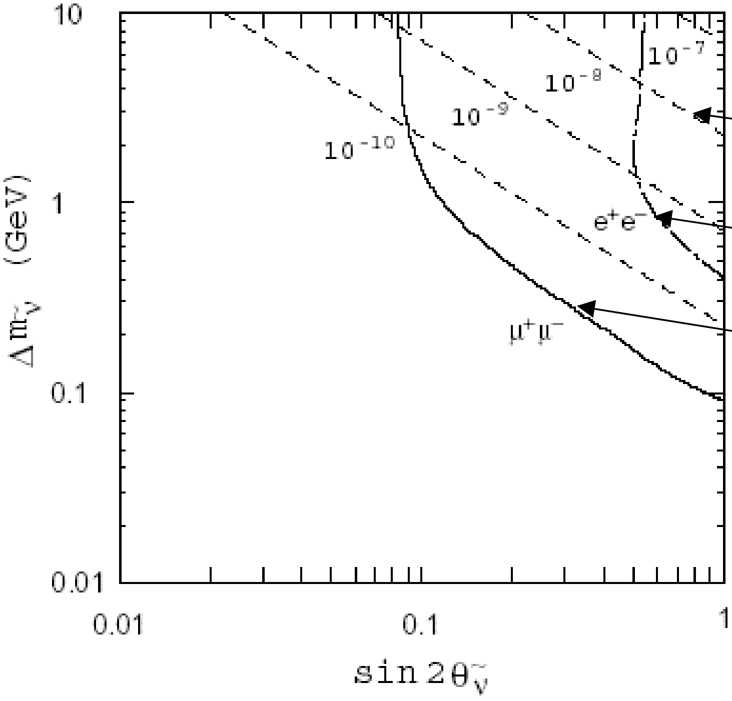
Slepton oscillation

If sleptons are produced in future collider experiments, LFV slepton mass leads to slepton oscillation, and then

$$e^+e^-(\mu^+\mu^-)\to\tilde{l}\tilde{l}\to\mu(e)\tau\cdots$$

The cross section behaves as $\sigma\propto\left((m_{\tilde{\nu}_\mu}-m_{\tilde{\nu}_\tau})/\Gamma_{\tilde{\nu}}\right)^2\sin^2 2\vartheta_{\tilde{\nu}_\tau\tilde{\nu}_\mu}$

(Arkani-hamed et al)



$Br(\tau\to\mu\gamma)$

e^+e^- collider

$\mu^+\mu^-$ collider

$L=50\,fb^{-1},\sqrt{s}=500GeV$

$m_{\tilde{\nu}}=180GeV,\tan\beta=3$

(JH, Nojiri, Shimizu, Tanaka)

3, Hadron physics in SUSY GUT model

In SUSY SU(5) GUT, the neutrino Yukawa induces the **flavor violating right-handed currents.**

$$(m^2_{\tilde{d}_R})_{23} = (m^2_{\tilde{l}_L})_{23}\ e^{i(\varphi_1-\varphi_2)}\ (\log\frac{M_G}{M_{GUT}})/(\log\frac{M_G}{M_{M_3}})$$

$\Rightarrow$

1) $CP\ asymmetry\ in\ B_d^0 \to \phi K_S\ \ (\mathrm{Im}((m^2_{\tilde{d}_R})_{23}) \neq 0)$

(2.7 sigma deviation observed in Belle experiments.)

2) $CP\ assymmetry\ in\ B_d^0 \to M_s\gamma$

3) $B_s^0 - \overline{B}_s^0\ mixing$

However, if $\mathrm{Im}(m^2_{\tilde{d}_R})_{23} \neq 0$ and $(m^2_{\tilde{d}_L})_{23} \neq 0$,
Hg EDM gives stringent constraints on these processes.

Strange quark contribution to atomic EDM

Strange quark in necleon: (Chiral perturbation + sigma term (N-pi scattering))

$$(m_u+m_d)\langle p|\bar{u}u+\bar{d}d|p\rangle \simeq 45MeV,$$

$$\langle p|\bar{u}u-\bar{d}d|p\rangle=(m_\Xi-m_\Sigma)/m_s,\quad \langle p|\bar{u}u+\bar{d}d-2\bar{s}s|p\rangle=3(m_\Xi-m_\Lambda)/m_s$$

$$\Rightarrow \langle p|\bar{u}u|p\rangle \simeq 4.8,\ \langle p|\bar{d}d|p\rangle \simeq 4.1,\ \langle p|\bar{s}s|p\rangle \simeq 2.8$$

CEDM (chromoelectric dipole moment) of strange quark (d_s^C)
induces CP violating nuclear force via eta meson exchange.

$$g_{\eta pp}^{CP}=-\frac{d_s^C}{\sqrt{3}f_\pi}(\langle p|\bar{s}g_s(G\sigma)s|p\rangle-m^2\langle p|\bar{s}s|p\rangle)$$

$$\xrightarrow{\substack{QCD\\ sum\,rule}}-\frac{2d_s^C}{3\sqrt{3}f_\pi}m^2\langle p|\bar{s}s|p\rangle$$ **(Pospelov et al)**

⇒ **Nuclei EDM**

Stringent constraint comes from Hg EDM

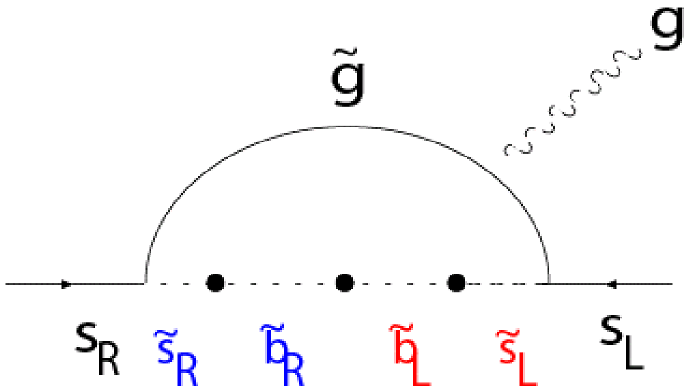
$$e|d_s^C|<5.8\times10^{-25}ecm$$

assuming up and down quark CEDMs are negligible

Hg EDM constraint on $(m^2_{\tilde{d}_R})_{23}$ in SUSY GUT

If $(m^2_{\tilde{d}_R})_{23}$ has a CP phase, it contributes to the CEDM of the strange quark in the cooperation with the left-handed squark mixing $(m^2_{\tilde{Q}})_{32}$.

$(m^2_{\tilde{Q}})_{32}$ is induced by the top quark Yukawa coupling with CKM.



(JH&Shimizu)

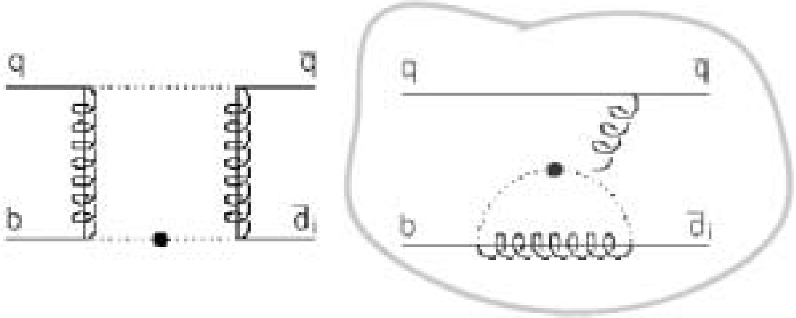
$$|\,\mathrm{Im}(\delta^{RR}_{32})\,| < 5.8\times10^{-4}\left(\frac{10}{\tan\beta}\right)\left(\frac{m_{SUSY}}{500GeV}\right)^{2}\left(\frac{\delta^{LL}_{32}}{0.04}\right)^{-1}$$

Here, $\delta^{RR}_{32} = \dfrac{(m^2_{\tilde{d}_R})_{32}}{\overline{m^2_{\tilde{d}_R}}}$, $\delta^{LL}_{32} = \dfrac{(m^2_{\tilde{Q}})_{32}}{\overline{m^2_{\tilde{Q}}}}$

$B_d^0 \to \phi K_S$ in SUSY GUT

Non-negligible $(m^2_{\tilde{d}_R})_{23}$ may lead to the deviation of CP asymmetry $B_d^0 \to \phi K_S$ since $b \to s\bar{s}s$ is a radiative processes.

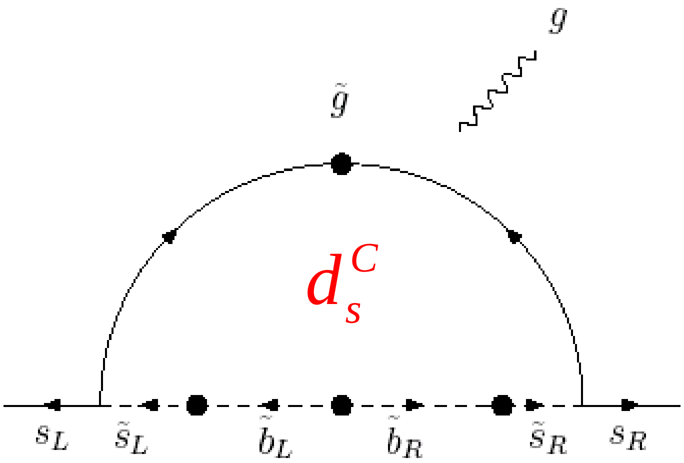
The dominant contribution comes from the gluon penguin diagram in the broad parameter space.

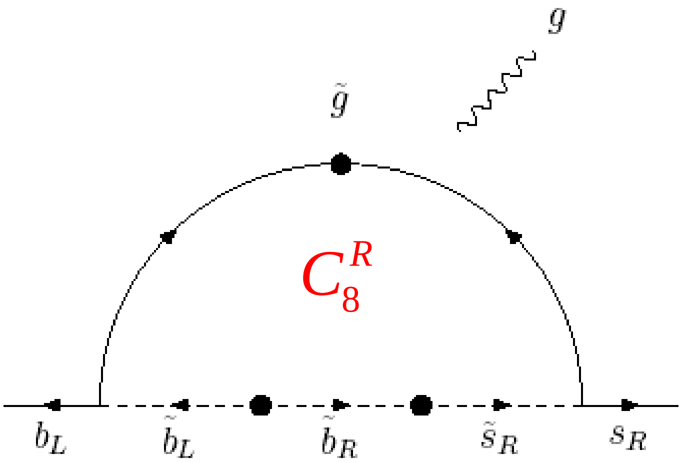


The effective operator for $b \to sg$ induced by $(m^2_{\tilde{d}_R})_{23}$:

$$H = C_8^R \frac{g_s}{8\pi^2} m_b \bar{s}(\sigma G) P_L b$$

CP asymmetry in $B_d^0 \to \phi K_S$ v.s. Strange quark CEDM

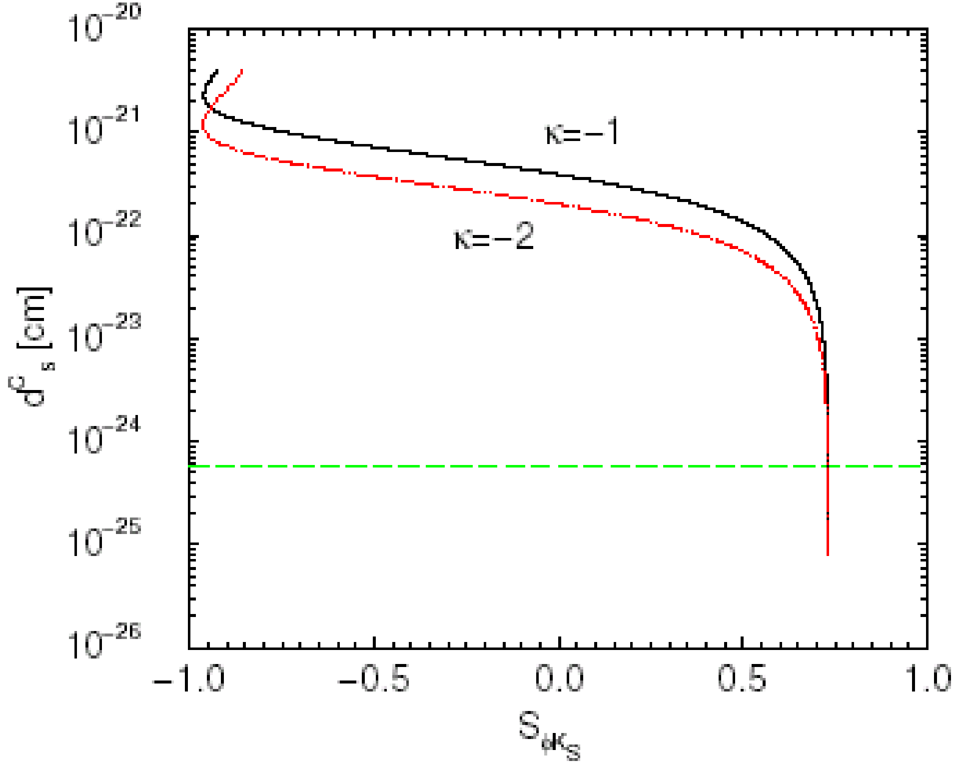




$$\Rightarrow \ d_s^C = -\frac{m_b}{4\pi^2}(1 \square 3)\,\mathrm{Im}\left[\delta_{23}^{LL} C_8^R\right]$$

CP asymmetry in $B_d^0 \to \phi K_S$ and strange quark CEDM are strongly correlated.

Assuming $d_s^C = -\frac{m_b}{4\pi^2}\,\mathrm{Im}\left[\delta_{23}^{LL} C_8^R\right],$



Exp. bound

The Hg EDM bound is O(10^(2-3)) stronger for a sizable deviation in $B_d^0 \to \phi K_S$.

Neutron and Nuclei EDMs and Peccei-Quinn symmetry

CP violating operators for dim =<5 in QCD.

$$L_{CP} = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu} + \sum_q i \frac{d_q^C}{2} \bar{q} g_s (G_{\mu\nu}\sigma^{\mu\nu})\gamma_5 q$$

Axion suppresses the ~~CP~~ nuclear force by CEDM. Effective θ is induced by CEDM,

$$\theta_{eff} = \sum_q \frac{d_s^C}{2m_q} m^2 \qquad \left(m^2 \approx 0.8 GeV^2\right).$$

(Bigi and Ural'tsev)

and contribution of strange CEDM to ~~CP~~ pion-proton (neutron) coupling is decoupled.

$$g^{CP}_{\pi pp}|_{strange} = -\frac{1}{f_\pi}\frac{m_u m_d}{m_u+m_d}\left(\theta - \frac{d_s^C}{2m_s}m^2\right)\left(\langle p|\bar{u}u|p\rangle - \langle p|\bar{d}d|p\rangle\right) \to 0$$

However, ~~CP~~ eta and K meson couplings still suffer from strange CEDM, and loop diagram of K- meson leads to neutron EDM.

But, Pospelov and Ritz argue by using QCD sum rule that Axion suppresses strange CEDM contribution to neutron EDM ....

Summary

After discovering neutrino oscillation, flavor violation induced by neutrino Yukawa coupling gives new interesting phenomena, charged LFV and CP violating hadron phenomena.

Now B factory starts to access interesting region for tau->mu(e) gamma. It may give new information about structure of seesaw mechanism. Even if it is not discovered in B factory, unfortunately, discovery of slepton may lead to new probe of the seesaw model.

We show new constraint from Hg EDM, which has a contribution of strange quark EDM. Strange quark EDM is induced by 3rd generation flavor violation. It gives a stringent constraint to SUSY GUT including seesaw model.

Sensitivity to CP violating nuclear force may be improved furthermore by two orders in measurement of Deuterium EDM. It may be a big impact on SUSY GUT.