Flavor Violation in SUSY SEESAW models

8th International Workshop on Tau-Lepton Physics

Tau04

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1, Introduction

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

$\Rightarrow$ How large is LFV in charged lepton sector?

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

$\mu \to e\gamma, \mu \to 3e \cdots\cdots$ Muon LFV decays
($\Leftrightarrow$ 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

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

Seesaw model

(Introduction of right-handed neutrinos ν_R)

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

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_N)

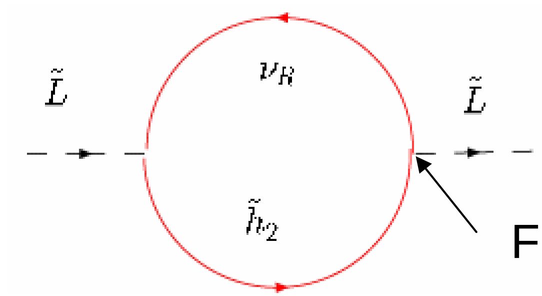
Superheavy M_N: We need Supersymmetry (SUSY)

Charged Lepton-Flavor Violation in SUSY seesaw model

Non-vanishing LFV slepton masses by radiative correction

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

(Borzumati&Masiero)



Flavor-violating Yukawa coupling

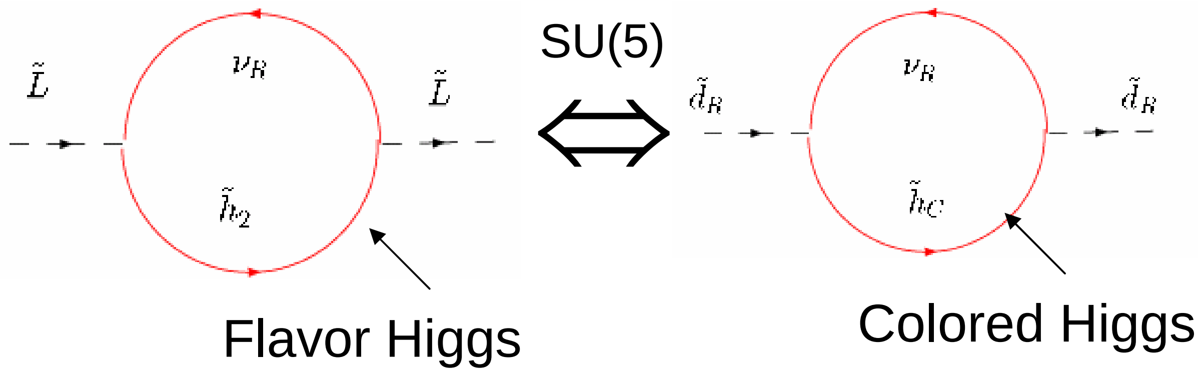
And then, $Br(l_i \to l_j \gamma) \sim 10^{-6}\left(\frac{\left(m^2_{\tilde{L}}\right)_{ij}}{\overline{m^2_{\tilde{L}}}}\right)^2\left(\frac{100GeV}{m_{SUSY}}\right)^4 \tan^2\beta$

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

$$\begin{pmatrix} s_{R1} & s_{R2} & s_{R3} & \mu_L & \nu_{\mu L} \end{pmatrix}$$
$$\begin{pmatrix} b_{R1} & b_{R1} & b_{R3} & \tau_L & \nu_{\tau L} \end{pmatrix}$$



$$\left(m^2_{\tilde{d}_R}\right)^*_{ij} \simeq \left(m^2_{\tilde{L}}\right)_{ij} e^{-i(\phi_i - \phi_j)}$$

(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
- Mixing between 2nd and 3rd generations in SUSY GUT model
- Summary

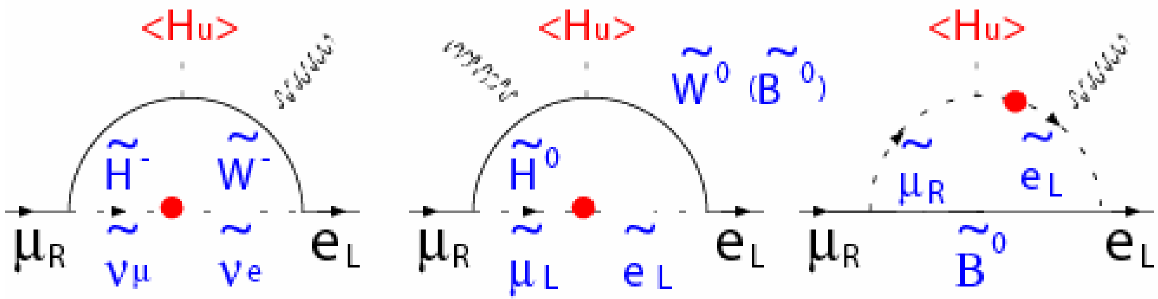
2, Tau LFV in SUSY seesaw model

Non-vanishing LFV slepton masses by radiative correction

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

and $\left(m^2_{\tilde{e}_R}\right)_{ij} \simeq 0$ where $H_{ij} \equiv \left(f_\nu^\dagger \log \frac{M_N}{M_G} f_\nu \right)_{ij}$

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



$\Longrightarrow$ Sizable effect

New bounds and future for tau LFV processes

Bounds on Tau LFV processes are being improved in B factory experiments.

	$2000\,PDG$	$Belle\ (current)$	$L=100\,fb^{-1}$	$L=3ab^{-1}$
$\tau\to\mu\gamma$	$<1.1\times10^{-6}$	$<3.2\times10^{-7}$	$\sim10^{-7}$	$\sim10^{-8}$
$\tau\to e\gamma$	$<2.7\times10^{-6}$	$<3.6\times10^{-7}$	$\sim10^{-7}$	$\sim10^{-8}$
$\tau\to\mu\eta$	$<9.6\times10^{-6}$	$<4.4\times10^{-7}$	$\sim10^{-7}$	$10^{-8}\sim10^{-9}$
$\tau\to e\eta$	$<8.2\times10^{-6}$	$<6.9\times10^{-7}$	$\sim10^{-7}$	$10^{-8}\sim10^{-9}$
$\tau\to lll$	$<a\ few\times10^{-6}$	$<a\ few\times10^{-7}$	$\sim10^{-7}$	$10^{-8}\sim10^{-9}$

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)

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

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

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

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

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

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

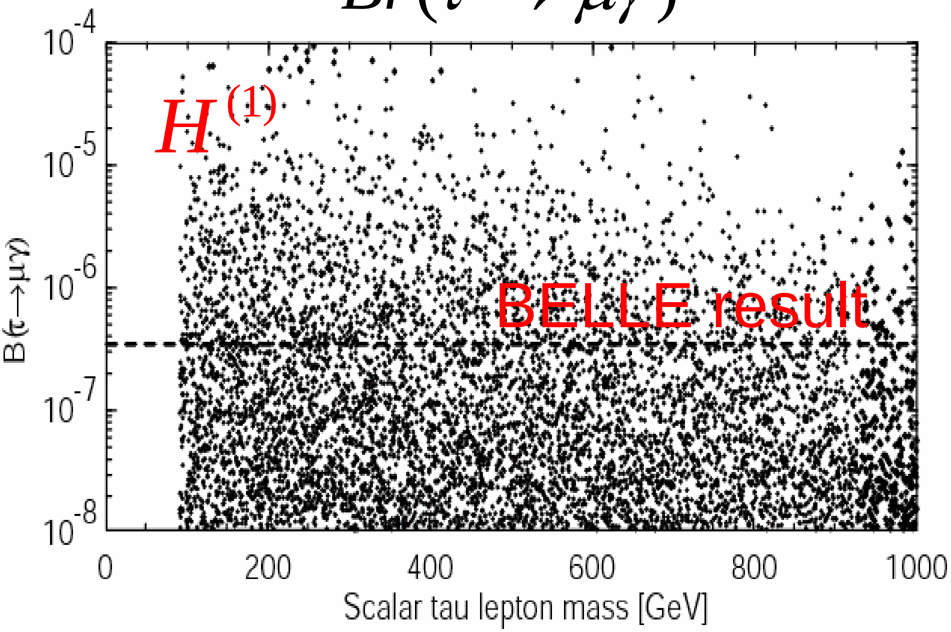
(Observed large mixings of neutrino come from Yukawa coupling in a case of $H^{(1)}$, but Majorana mass in $H^{(2)}$.)

Normal ordering for neutrino mass

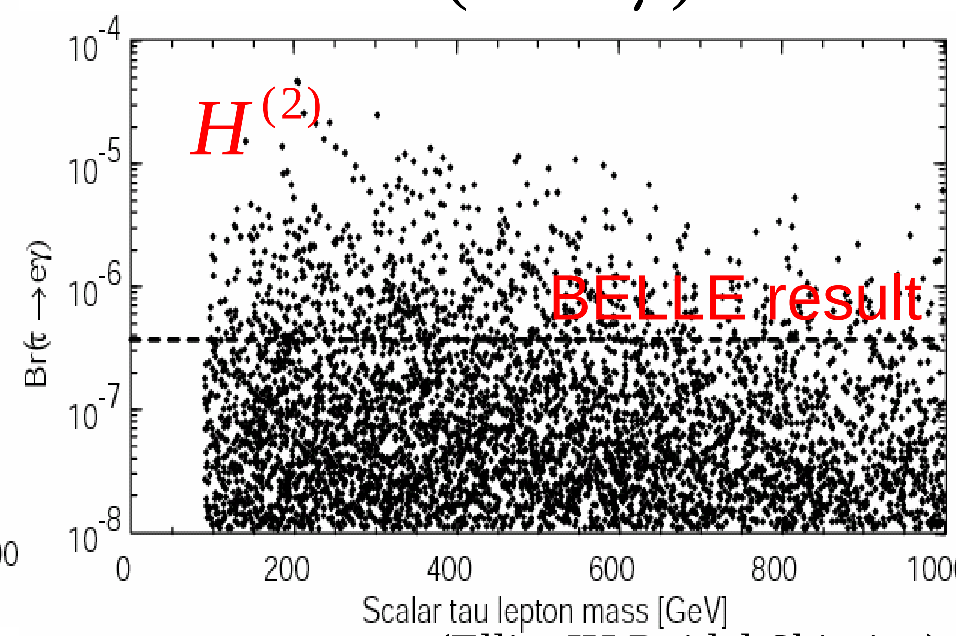
$(m_{\tilde{w}} = 200GeV,\ A_0 = 0GeV,\ \tan\beta = 10\ or\ 30,\ sign(\mu) = +1)$

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

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



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



(Ellis, JH,Raidal,Shimizu)

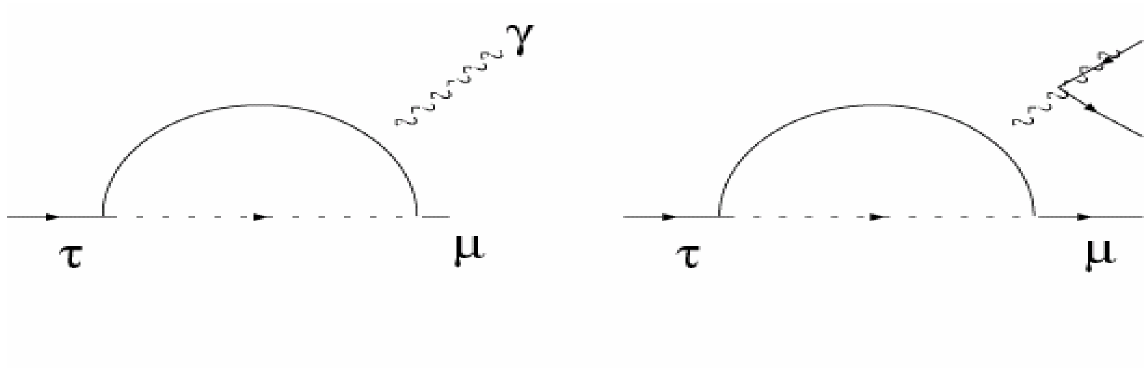
Other tau LFV processes:

Normal case $(m_{\tilde{l}} \approx O(100) GeV)$

One-shell photon contribution is dominant,

since dipole operator contribution is proportional to $\tan^2 \beta$.

Furthermore, 3lepton processes is enhanced by $\log\left(m_\tau / m_l \right)$



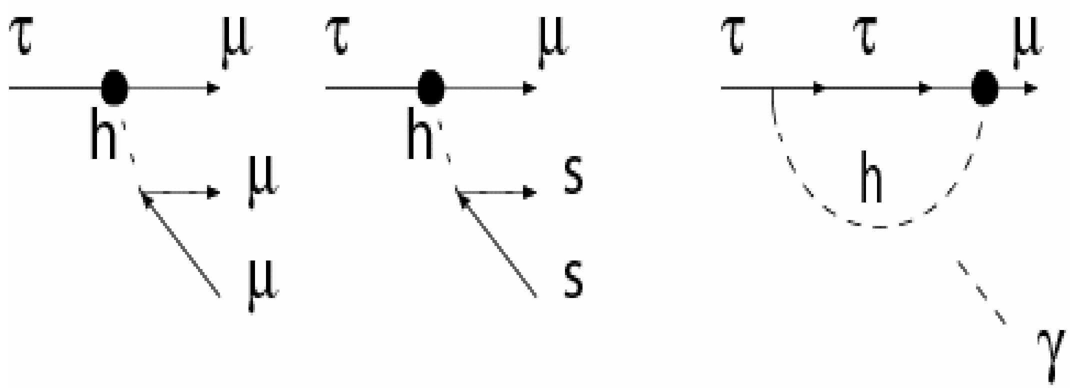
$$Br(\tau \to \mu ee(3e)) / Br(\tau \to \mu(e)\gamma) \simeq 1/94,$$

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

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

Even if the slide: 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.



$$Br(\tau \to 3\mu) \approx (4\times 10^{-7}) \times \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100GeV}{m_A}\right)^4 \left(\frac{\left(m_{\tilde{L}}^2\right)_{32}}{\overline{m_{\tilde{L}}^2}}\right)^2$$

$$Br(\tau \to \mu\eta) : Br(\tau \to 3\mu) : Br(\tau \to \mu\gamma) \approx 5:1:0.5$$

(Babu&Kolda;Shar)

3, Hadron and tau physics in SUSY GUT model

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

$$(m^2_{\tilde{d}_R})_{23} \approx (m^2_{\tilde{l}_L})_{23}\ e^{i(\varphi_2-\varphi_3)}$$

$\Rightarrow$

1) $CP\ asymmetry\ in\ b-s\ penguin\ processes,$

$\quad such\ as\ B^0_d \to \phi K_S.$

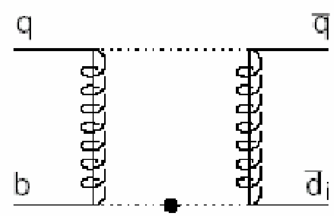
2) $mixing\ induced\ CP\ assymmetry\ in\ B^0_d \to M_s \gamma.$

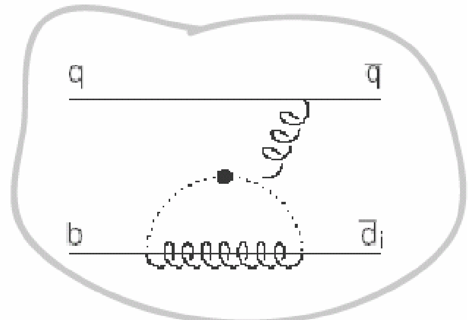
3) $B^0_s - \overline{B}^0_s\ mixing.$

These processes are correlated with $Br(\tau \to \mu\gamma)$ and hadronic EDMs, such as Hg and neutron EDMs, in SUSY GUTs.

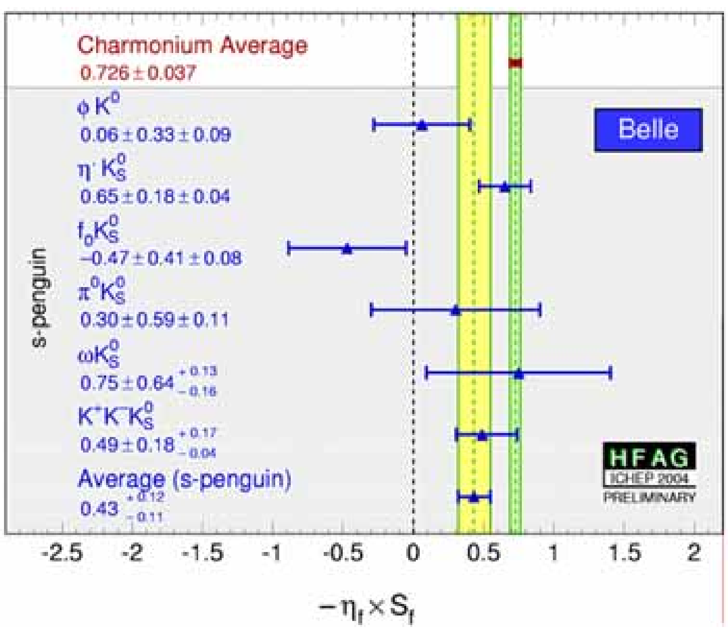
b-s penguin processes in SUSY GUT

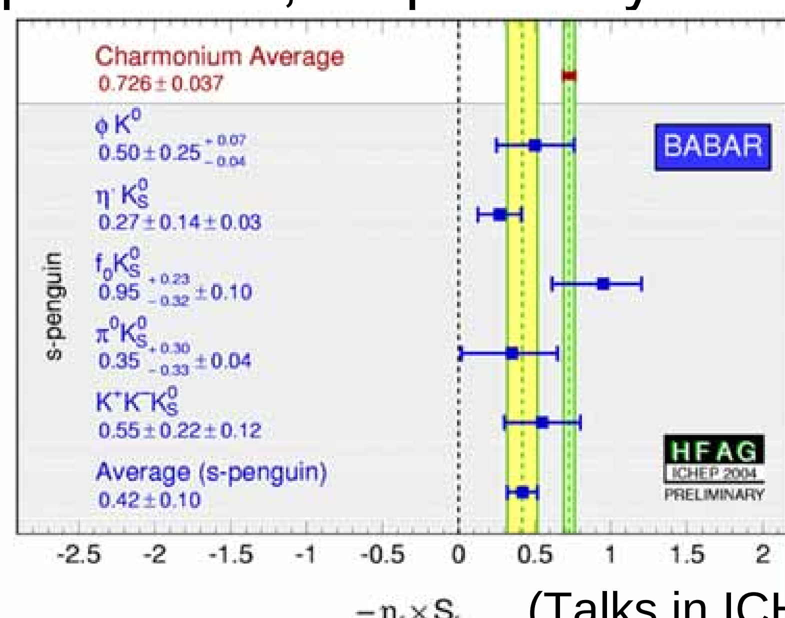
Non-negligible $(m^2_{\tilde{d}_R})_{23}$ may lead to the deviation of CP asymmetry in b-s penguin processes, such as $B^0_d \to \phi K_S$ since $b \to s\bar{s}s$ and $b \to sd\bar{d}$ are radiative processes.





2.4 and 2.7 sigma deviations in the b-s penguin processes are observed in Belle and Babar experiments, respectively.



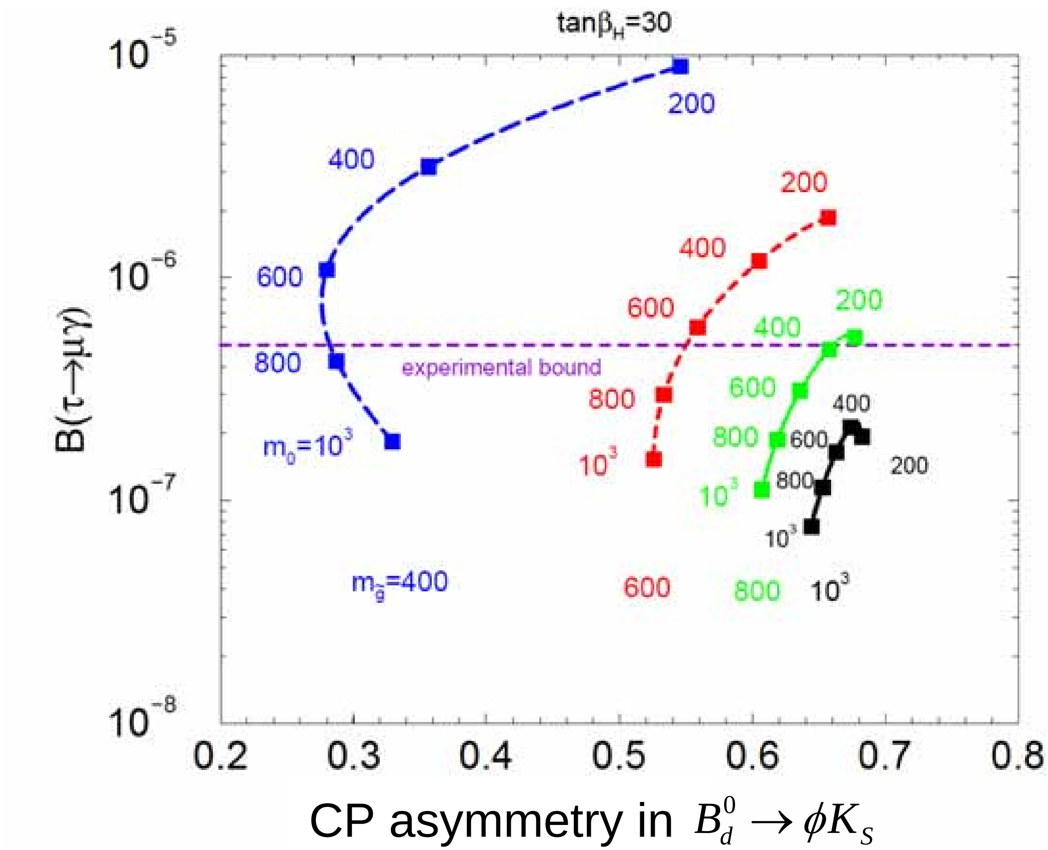


(Talks in ICHEP04)

b-s penguin v.s. $\tau \to \mu\gamma$

GUT relation: $(m^2_{\tilde{d}_R})_{23} \approx (m^2_{\tilde{l}_L})_{23}\ e^{i(\varphi_1 - \varphi_2)}$

Thus, b-s penguin processes and $\tau \to \mu\gamma$ are correlated in the SUSY GUTs.



$m_{\nu_\tau} = 5\times10^{-2}eV,$

$U_{\mu 3} = 1/\sqrt{2},$

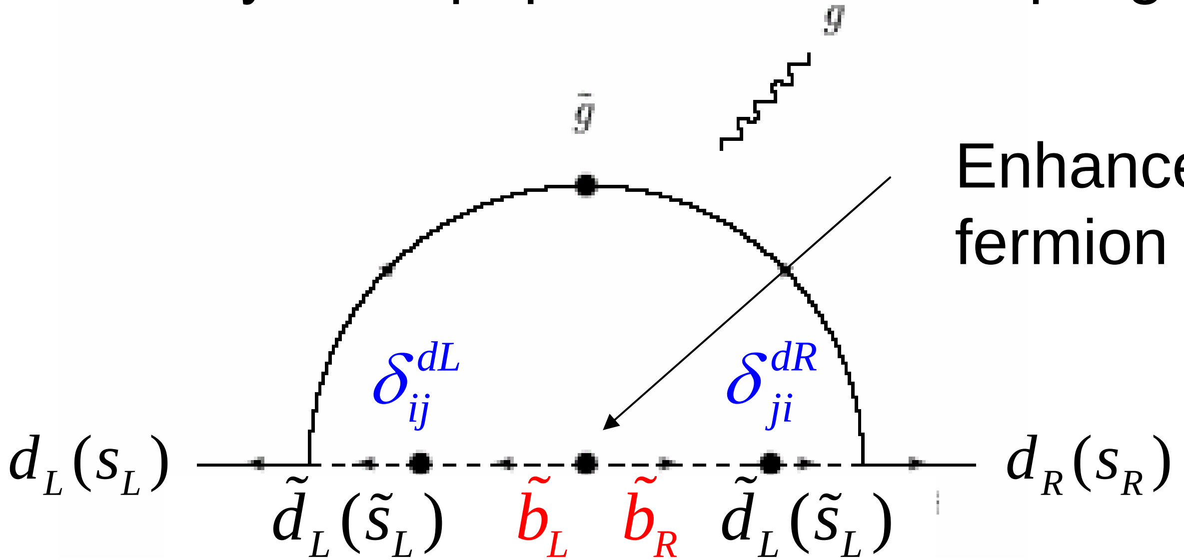
$M_{N_\tau} = 5\times10^{14}GeV,$

$\tan\beta = 30$

This is non-trivial test for the SUSY GUTs.

Hadronic EDM induced by $(m^2_{\tilde{d}_R})$ in SUSY GUT

If the off-diagonal term in $(m^2_{\tilde{d}_R})$ has a CP phase, it contributes to choromoelectric dipole moments (CEDM) for quarks in the cooperation with the left-handed squark. The off-diagonal terms are induced by the top quark Yukawa coupling with CKM.



In typical models, the left-handed squark mixings are induced by top quark as

$$\delta^{dL}_{23} \sim \lambda^2, \quad \delta^{dL}_{13} \sim \lambda^3, \quad \delta^{dL}_{13} \sim \lambda^5 \quad (\lambda \sim 0.2)$$

Here, $\delta^{dR}_{ij} = (m^2_{\tilde{d}_R})_{ij} / \overline{m}^2_{\tilde{d}_R} \quad \delta^{dL}_{ij} = (m^2_{\tilde{d}_L})_{ij} / \overline{m}^2_{\tilde{d}_L}$

Hadronic EDMs

Current bounds on Mercury and neutron EDMs constrain the SUSY models.

$$|d_{Hg}| < 2.1\times 10^{-28}\, e\, cm, \qquad |d_n| < 6.3\times 10^{-26}\, e\, cm.$$

Choromoelectric dipole moments (CEDM) generate CP violating hadronic interaction, which leads to EDMs of Mercury and neutron.

$$L_{CP} = \sum_q i\frac{d_q^C}{2}\bar{q} g_s (G_{\mu\nu}\sigma^{\mu\nu})\gamma_5 q$$

Strange quark component in necleon is not negligible. From baryon mass and sigma term in chiral perturbation theory,

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

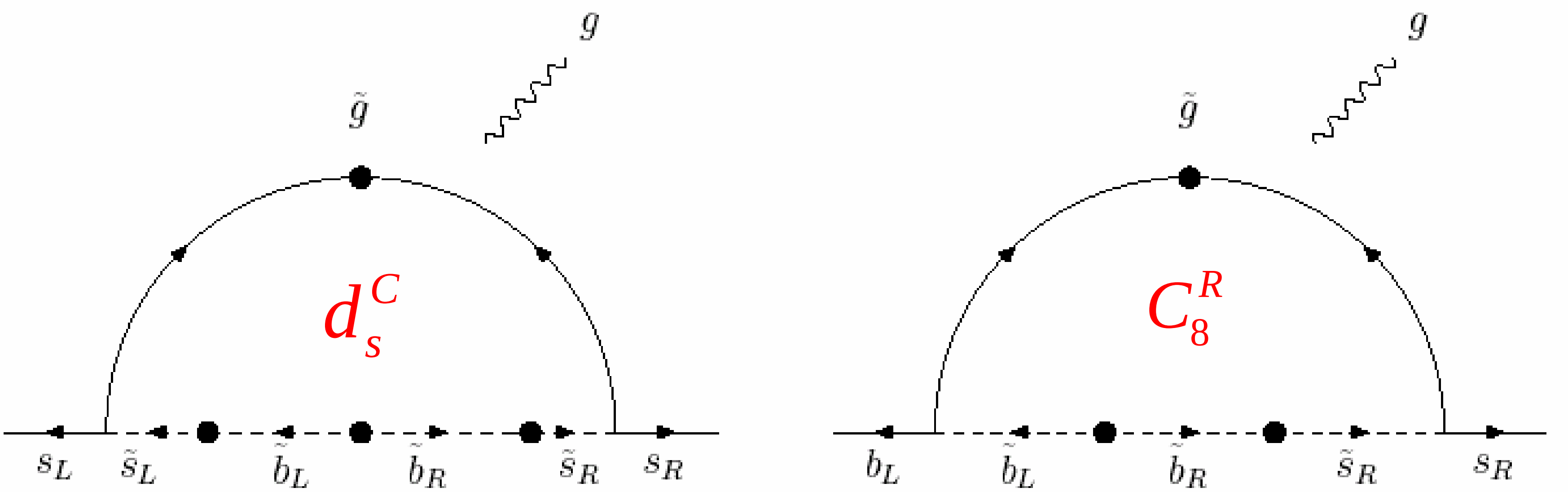
Thus, hadronic EDMs depend on the strange quark CEDM via K or eta meson interaction, in addition to up and down CEDMs. Using the QCD sum rule, ex,

$$g_{pp\eta}^{CP} \approx -\frac{2}{3\sqrt{3} f_\pi}\langle p|\bar{s}s|p\rangle m_0^2\, d_s^C, \qquad (m_0^2 \approx 0.8 GeV^2).$$ (Falk et al)

b-s penguin v.s. strange quark CEDM

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

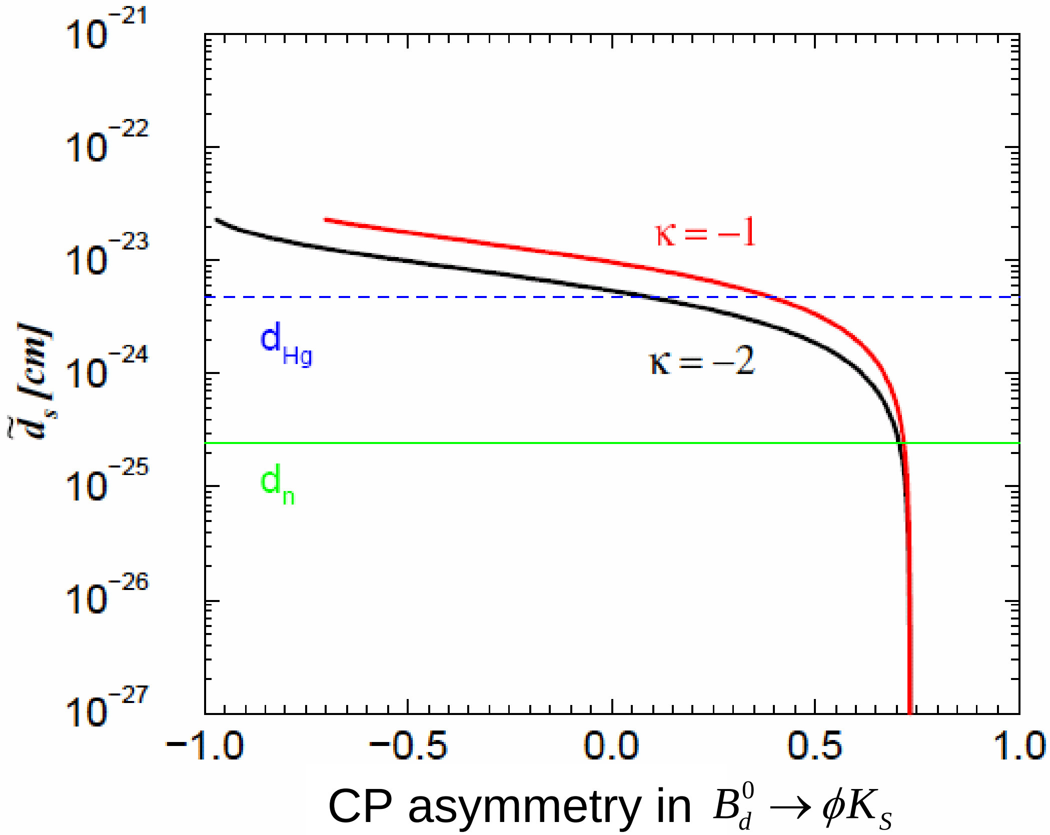
$$H = C_8^R \frac{g_s}{8\pi^2} m_b \overline{s}(\sigma G) P_L b$$



$$\Rightarrow \ d_s^C = -\frac{m_b}{12\pi^2}(1 \sim 3)\,\mathrm{Im}\left[\delta_{23}^{dL} C_8^R\right]$$

CP asymmetry in b-s penguin processes and strange quark CEDM are strongly correlated.

Assuming $d_s^C = -\frac{m_b}{4\pi^2}\frac{11}{21}\mathrm{Im}\left[\delta_{23}^{dL} C_8^R\right]$ and $\delta_{23}^{dL} = \lambda^2 = 0.04$



(JH, Shimizu)

The neutron EDM bound is one order of magnitude stronger for a sizable deviation in b-s penguin processes.

The discrepancy might come from QCD uncertainties. New technique for deuteron EDM may reach to $d_s^C \sim 10^{-26}\, cm$.

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.

In the SUSY GUTs, tau LFV is related with other hadronic processes, such b-s penguin processes and hadronic EDMs. It is important to check the correlation. The recent result for b-s penguin processes suggest large Br(tau->mu gamma) in the SUSY GUTs.

EDMs are also a good probe in the SUSY GUTs since non-vanishing mixings for both left-handed right-handed sfermions are predicted in this model. We show constraints from hadronic EDMs induced by strange qaurk CEDM. Since the QCD uncertainties are big, the further experimental and theoretical improvements are very important.

Slepton oscillation

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

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

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)

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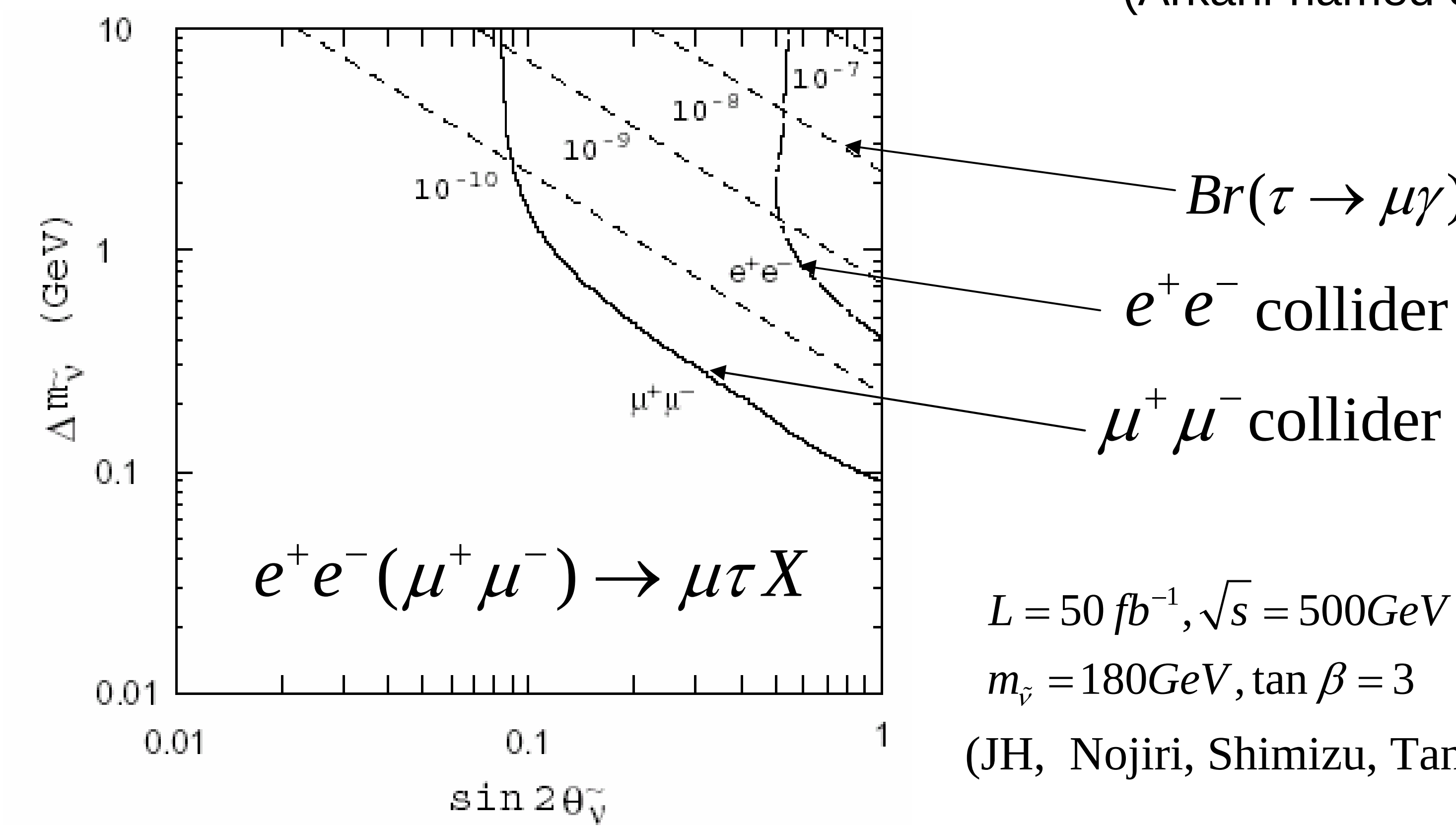


$L = 50\, fb^{-1}, \sqrt{s} = 500 GeV$

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

(JH, Nojiri, Shimizu, Tanaka)

Constraints on the flavor violation in squark mass term

From neutron (Hg atom) EDM

$$|\mathrm{Im}(\delta_{32}^{dR})| < 4.8(98)\times 10^{-3}$$

$$|\mathrm{Im}(\delta_{31}^{dR})| < 4.7(2.5)\times 10^{-3}$$

$$|\mathrm{Im}(\delta_{21}^{dR})| < 4.5(2.4)$$

for $\tan\beta = 10,\ m_{SUSY} = 500GeV$

Here, $\delta_{23}^{dL} \sim \lambda^2,\ \ \delta_{13}^{dL} \sim \lambda^3,\ \ \delta_{13}^{dL} \sim \lambda^5 \quad (\lambda \sim 0.2)$ are assumed.

Constraints on (1-3) and (2-3) mixing for the right-handed squark mixings are stringent. (1-2) mixing is constrained by ε_K.

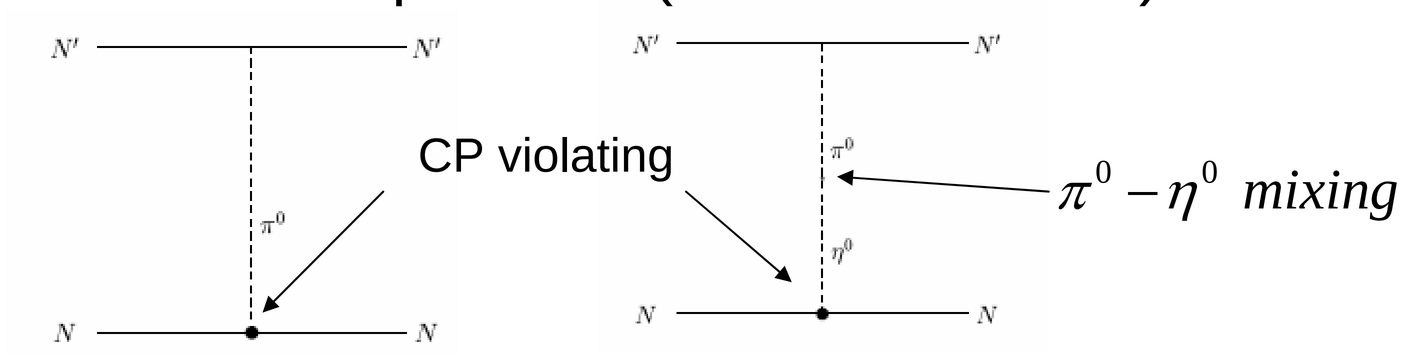
$$|\mathrm{Im}(\delta_{21}^{dR})| < 2\times 10^{-4}, \qquad (\varepsilon_K)$$

$$|\delta_{31}^{dR}| < 1\times 10^{-1}, \qquad (\Delta M_{Bd})$$

$$|\delta_{32}^{dR}| < 0.6, \qquad (b\to s\gamma)$$

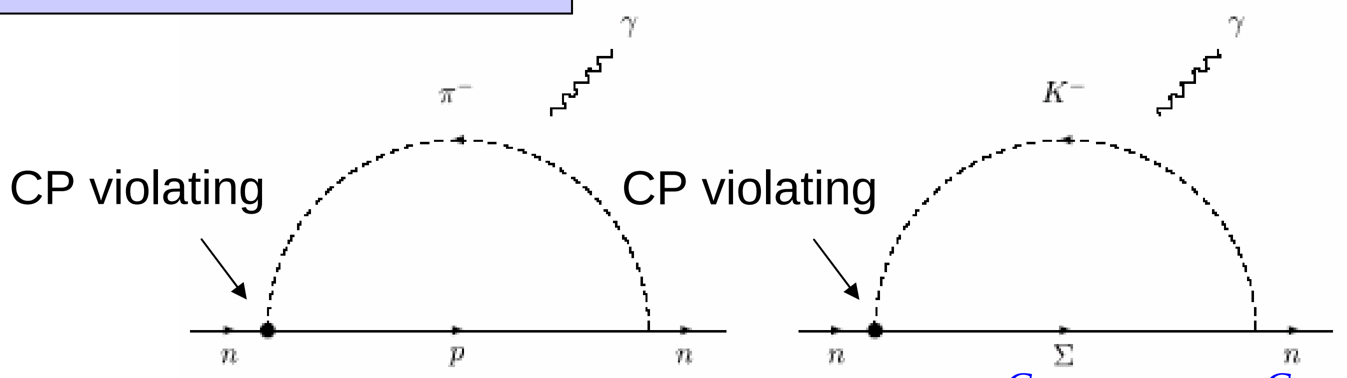
Hg atom EDM

^{199}Hg is a diamagnetic atom, and the EDM is sensitive to CP-violating nuclear force induced by pion and eta exchange, which generates T-odd EM potential (Shiff momentum).



$$d_{Hg} = -8.7 \times 10^{-3} e\, (d_u^C - d_d^C - 0.005 d_s^C)$$

Neutron EDM



$$d_n = -1.6 e\, (d_u^C + 0.81 d_d^C + 0.16 d_s^C)$$