$B \to \phi K_s$ *versus Electric Dipole Moment of* ^{199}*Hg Atom in Supersymmetric Models with Right-handed Squark Mixing*

J.Hisano, Y.S, hep-ph/0308255 (To appear in PLB)

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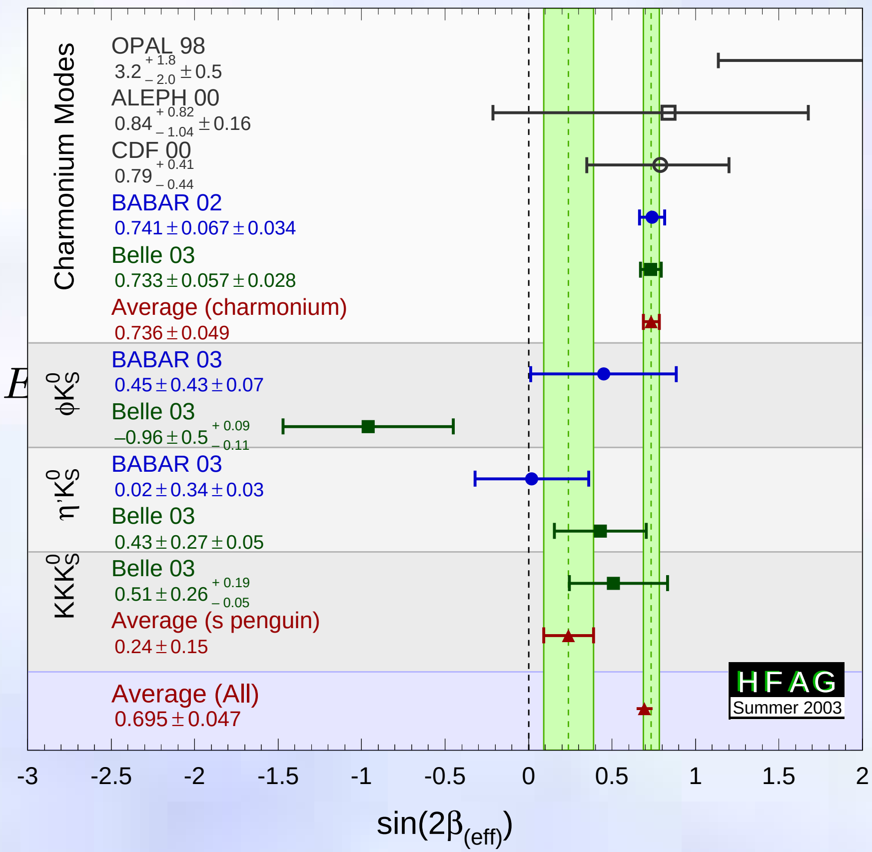
Introduction

CP violation in $B \to \phi K_S$

$$
\begin{aligned}
S_{\phi K} &= \sin(2\phi_1) = 0.734 \pm 0.054\ (SM) \\
&= -0.96 \pm 0.50 + 0.09 - 0.11\ (BELLE \\
&= 0.45 \pm 0.43 \pm 0.07\ (BABAR)
\end{aligned}
$$



Combined: $S_{\phi K} = -0.15 \pm 0.33$ 2.7 σ deviation

Can SUSY explain $B \to \phi K_S$ anomaly?

SUSY contribution to $B \to \phi K_S$

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SU(5) SUSY GUT with right-handed neutrinos

d_{Ri} and L_i are unified in $\bar{\mathbf{5}}$

$$\begin{pmatrix} {d_{R1}}^* \\ {d_{R2}}^* \\ {d_{R3}}^* \\ \nu_e \\ e_L \end{pmatrix} \leftrightarrow \begin{pmatrix} {s_{R1}}^* \\ {s_{R2}}^* \\ {s_{R3}}^* \\ \nu_\mu \\ \mu_L \end{pmatrix} \leftrightarrow \begin{pmatrix} {b_{R1}}^* \\ {b_{R2}}^* \\ {b_{R3}}^* \\ \nu_\tau \\ \tau_L \end{pmatrix},$$

Atmospheric neutrino oscillation: large $\nu_\mu - \nu_\tau$

Atmospheric neutrino makes large $\tilde{s}_R$-$\tilde{b}_R$ mixing in SUSY SU(5) GUT ('00, Moroi)

Squark mixings in SUSY SU(5) GUT with right-handed neutrinos

Right-handed mixing: neutrino mixing

$$(m^2_{\tilde{d}_R})_{23} \simeq \frac{-2}{(4\pi)^2} e^{-i(\varphi_{d_2}-\varphi_{d_3})} U_{32} U^\star_{33} \frac{m_{\nu_\tau} M_N}{\langle H_f \rangle^2} (3m_0^2 + A_0^2) \log \frac{M_P}{M_{GUT}}$$

U: MNS matrix, φ_{d_i}: GUT phases

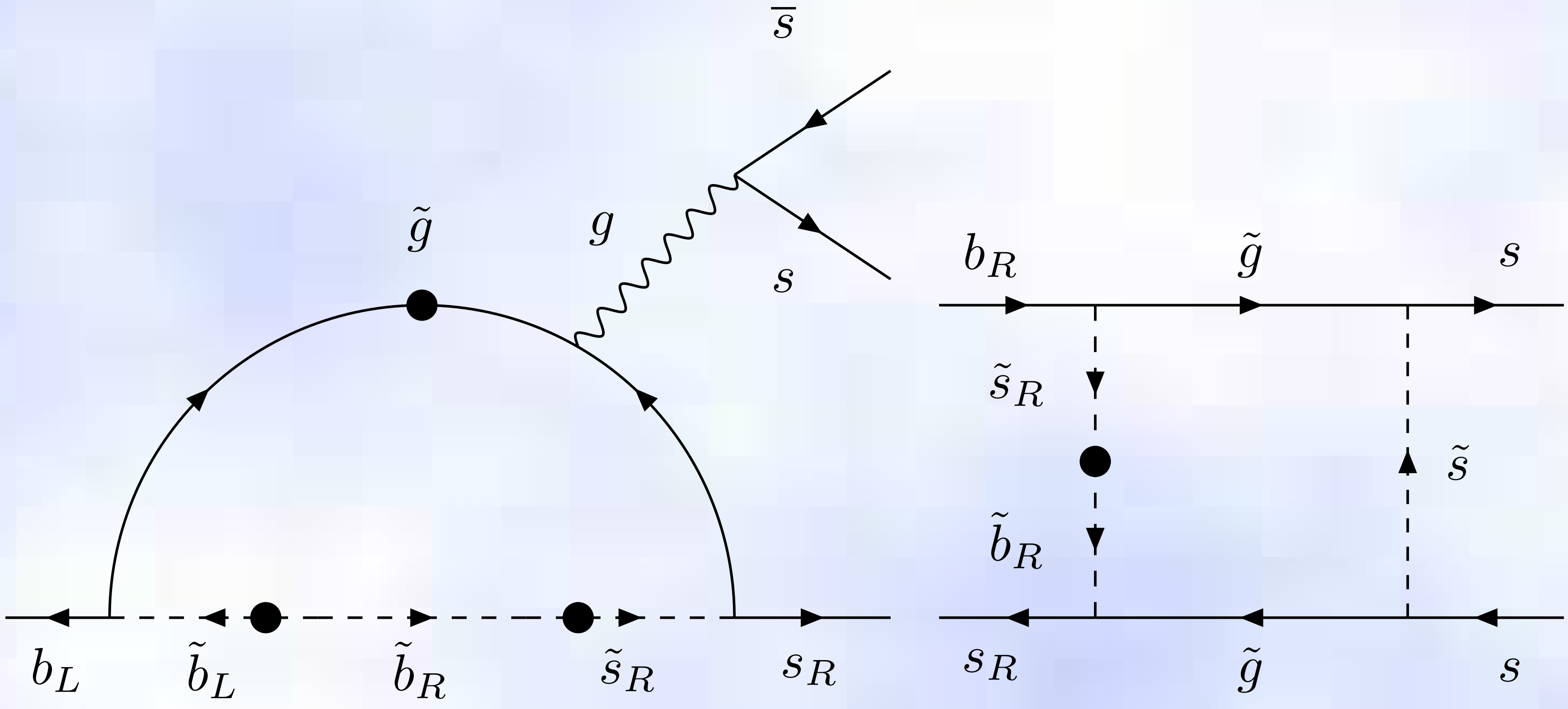
Left-handed mixing: CKM mixing

$$(m^2_{\tilde{Q}})_{23} \simeq \frac{-2}{(4\pi)^2} V^\star_{32} V_{33} f_t^2 (3m_0^2 + A_0^2)(3 \log \frac{M_G}{M_{GUT}} + \log \frac{M_{GUT}}{M_{SUSY}}),$$

V: CKM matrix

gluino contribution to $B_d \to \phi K_S$

Large $\tilde{s}_R$-$\tilde{b}_R$ mixing contributes $B_d \to \phi K_S$



$B \to \phi K_S$

The contribution from the penguin diagram is dominant.

$$H = -C_8^R \frac{g_s}{8\pi^2} m_b \overline{s_R} \sigma^{\mu\nu} T^A b_L G^A_{\mu\nu}$$

Mass insertion approximation

$$C_8^R = \frac{\pi\alpha_s}{m_{\tilde{q}}^2} \frac{m_{\tilde{g}}}{m_b} (\delta^{(d)}_{RR})_{23} (\delta^{(d)}_{LR})_{33} (\frac{1}{3} M_1(x) + 3M_2(x))$$

where

$$\begin{aligned} (\delta^{(d)}_{LL})_{23} &= \left(m^2_{\tilde{d}_L}\right)_{23} / m^2_{\tilde{q}}, \quad (\delta^{(d)}_{RR})_{32} = \left(m^2_{\tilde{d}_R}\right)_{32} / m^2_{\tilde{q}}, \\ (\delta^{(d)}_{LL})_{33} &= m_b \, (A_b - \mu \tan\beta) / m^2_{\tilde{q}}, \end{aligned}$$

Double mass insertion $LR + RR$ is dominant

Hadronic uncertainty of $B \to \phi K_S$

The matrix element of C_8 in $B \to \phi K_S$.
Phenomenological calculation: R.Barbieri, A.Strumia, NPB508(1997)3.

$$\langle \phi K_S | \frac{g_s}{8\pi^2} m_b (\bar{s}_i \sigma^{\mu\nu} T^a_{ij} P_R b_j) G^a_{\mu\nu} | \overline{B}_d \rangle = \kappa \frac{4\alpha_s}{9\pi} (\epsilon_\phi p_B) f_\phi m_\phi^2 F_+(m_\phi^2)$$

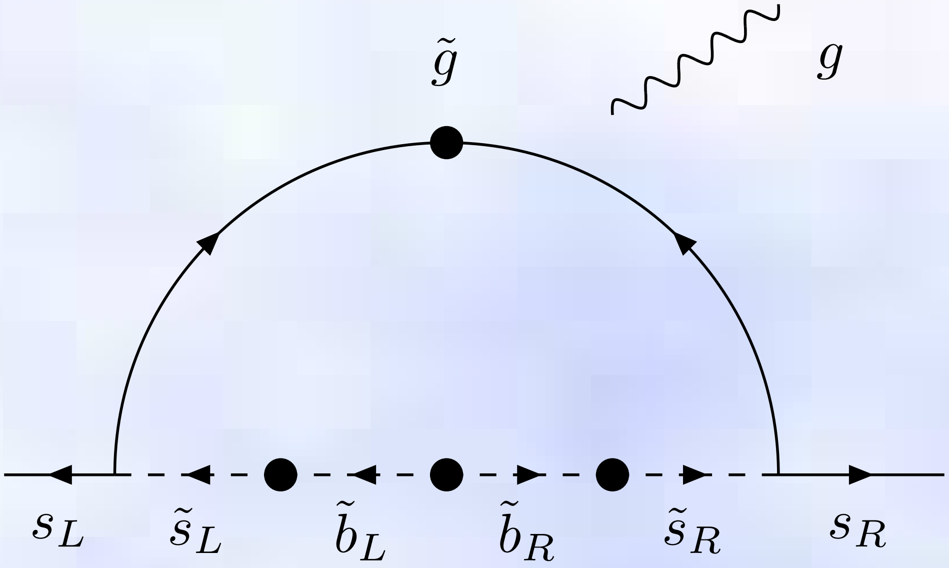
$\kappa = -1.1$: heavy-quark effective theory $\cdots$ large theoretical uncertainty

quark CEDM

The chromo-electric dipole moment (CEDM) for u, d, s

$$H = \sum d_q^C \frac{i}{2} g_s \overline{q} \sigma^{\mu\nu} T^A \gamma_5 q G_{\mu\nu}^A$$

Feynman diagram is similar to that of $B \to \phi K_S$



CP violating N-N-Meson coupling

CEDMs $\longrightarrow$ CP violating N-N-meson coupling. ('88 Khatsimovsky et al)
From the current algebra,

$$\begin{aligned}
\bar{g}_{\pi pp} &= \frac{\tilde{d}_u + \tilde{d}_d}{4 f_\pi} \left(\langle p | \bar{u} g_s (G\sigma) u - \bar{d} g_s (G\sigma) d | p \rangle \right) \\
&+ \frac{\tilde{d}_u - \tilde{d}_d}{4 f_\pi} \left(\langle p | \bar{u} g_s (G\sigma) u + \bar{d} g_s (G\sigma) d | p \rangle - m^2 \langle p | \bar{u} u + \bar{d} d | p \rangle \right) \\
\bar{g}_{\eta pp} &= -\frac{\tilde{d}_s}{\sqrt{3} f_\pi} \left(\langle p | \bar{s} g_s (G\sigma) s | p \rangle - m^2 \langle p | \bar{s} s | p \rangle \right)
\end{aligned}$$

where $G\sigma = G^a_{\mu\nu} T^a \sigma^{\mu\nu}$ and

$$m^2 = \frac{\langle 0 | g \bar{q} (G\sigma) q | 0 \rangle}{\langle 0 | \bar{q} q | 0 \rangle} \simeq 0.8 \text{GeV}^2.$$

We need to evaluate the matrix elements.

QCD sum rule

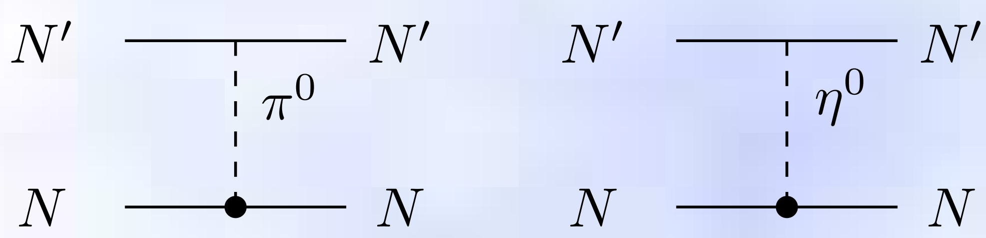
Using the QCD sum rule, ('97 Zhitnitsky)

$$\langle p|\bar{q}g_s(G\sigma)q|p\rangle \simeq \frac{5}{3}m^2\langle p|\bar{q}q|p\rangle.$$

where

$$\langle p|\bar{u}u|p\rangle \simeq 4.8; \qquad \langle p|\bar{d}d|p\rangle \simeq 4.1; \quad \langle p|\bar{s}s|p\rangle \simeq 2.8$$

for $m_u = 4.5$ MeV, $m_d = 9.5$ MeV and $m_s = 175$ MeV.
The CP violating N-N-Meson coupling $\longrightarrow \bar{N}N\bar{N}'i\gamma_5 N'$



Hg EDM

^{199}Hg atom:

- closed electronic shell (J=0)
- nucleus spin (I=1/2)

Hg EDM is sensitive to the nucleus EDM.($\bar{N}N\bar{N}' i\gamma_5 N'$)

$$d_{Hg} = S \cdot 3.2 \cdot 10^{-18} \text{fm}^{-2}$$

S: Schiff moment ($V_{eff} = -eS(I\nabla)\delta(r)$)

$$S = -1.8 \cdot 10^{-7} G_F^{-1} \frac{3 g_{\pi pp} m_0^2}{f_\pi m_\pi^2} (\tilde{d}_d - \tilde{d}_u - 0.012 \tilde{d}_s) e \cdot \text{fm}^3.$$

'99: Falk et al The experimental bound on Hg EDM

$$e|d_d^C - d_u^C - 0.012 d_s^C| < 7 \times 10^{-27} ecm \quad \rightarrow e|d_s^C| < 5.8 \times 10^{-25} ecm$$

Strange CEDM

Mass insertion approximation

$$d_s^C = c\frac{\alpha_s}{4\pi}\frac{m_{\tilde g}}{m_{\tilde q}^2}\left(\frac{1}{3}N_1(x)+3N_2(x)\right)\mathrm{Im}\left[(\delta_{LL}^{(d)})_{23}\,(\delta_{LR}^{(d)})_{33}\,(\delta_{RR}^{(d)})_{32}\right]$$

$$= -4.0\times 10^{-23}\sin\theta\, e\,\mathrm{cm}$$

$$\times\left(\frac{m_{\tilde q}}{500\mathrm{GeV}}\right)^{-1}\left(\frac{(\delta_{LL}^{(d)})_{23}}{0.04}\right)\left(\frac{(\delta_{RR}^{(d)})_{32}}{0.04}\right)\left(\frac{\mu\tan\beta}{5000\mathrm{GeV}}\right)$$

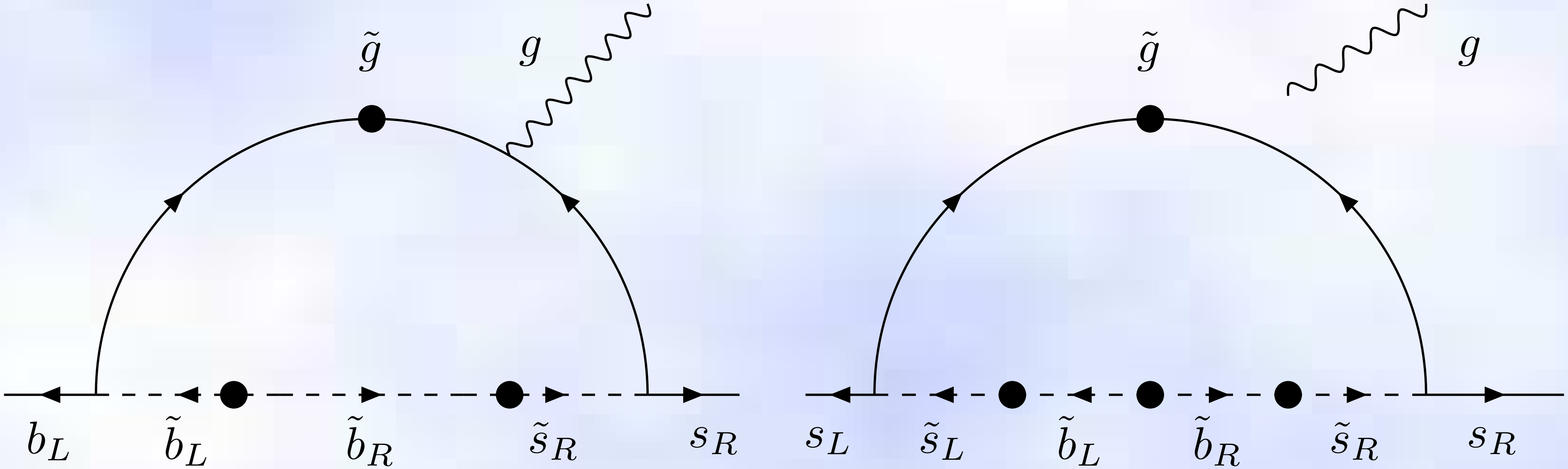
$\theta = \arg[(\delta_{LL}^{(d)})_{23}\,(\delta_{LR}^{(d)})_{33}\,(\delta_{RR}^{(d)})_{32}]$

Naively, the strange CEDM becomes too large.

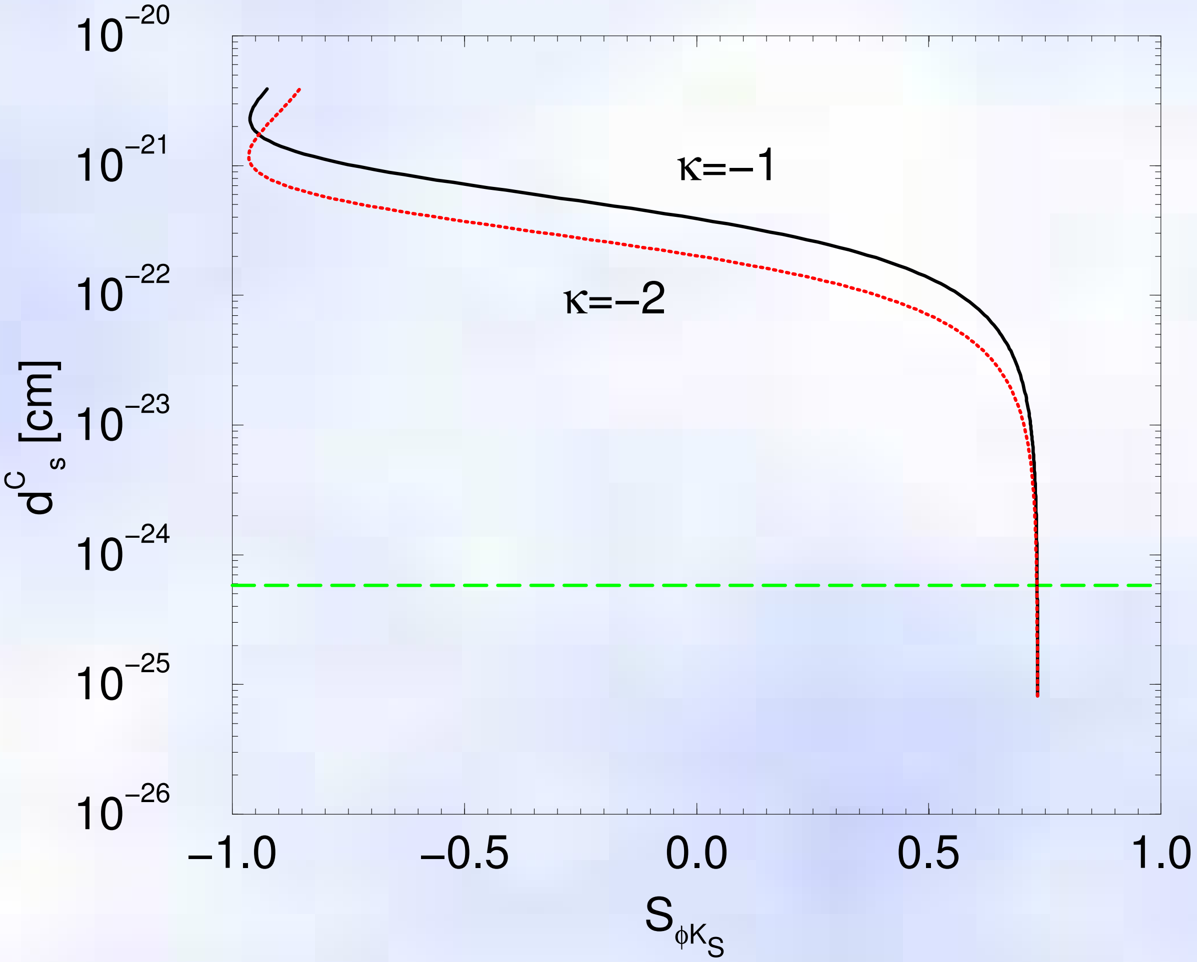
Hg EDM vs $S_{\phi K_s}$

There is strong correlation between d_s^C and C_8^R

$$d_s^C = -\frac{m_b}{4\pi^2}\frac{11}{7}\mathrm{Im}\left[(\delta^{(d)}_{LL})_{23}C_8^R\right] \quad (m_{\tilde g} = m_{\tilde q})$$



Hg EDM vs $S_{\phi K_s}$(II)



Constraints from $B \to X_s\gamma$

Gluino contribution to $B \to X_s\gamma$.

$$Br(B \to X_s\gamma) \quad = \quad 7.0 \times 10^{-6} \left(\frac{\mu \tan\beta}{5000GeV}\right)^2 \left(\frac{m_{\tilde{q}}}{500GeV}\right)^{-4} \left(\frac{|(\delta^{(d)}_{RR})_{23}|}{0.04}\right)^2$$

From the experimental value, $Br(B \to X_s\gamma) = (3.3 \pm 0.4) \times 10^{-4}$,

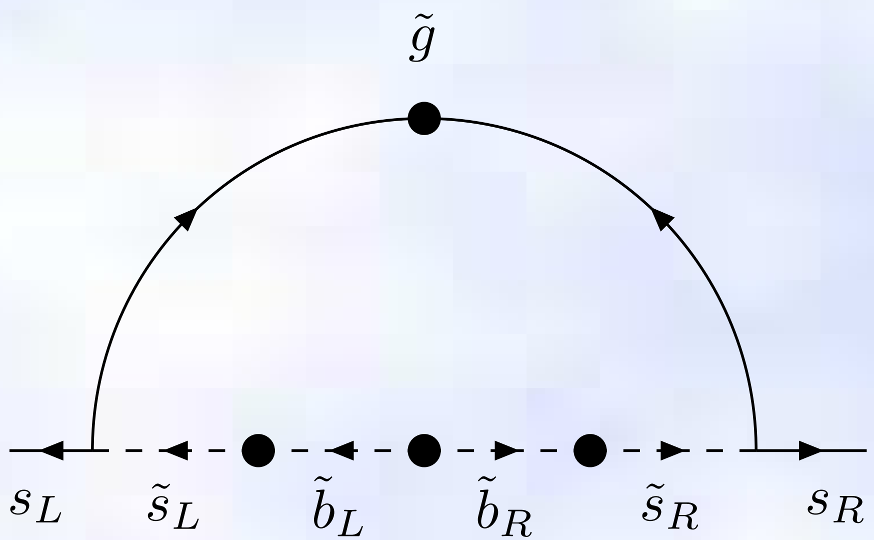
$$\left|(\delta^{(d)}_{RR})_{23}\right| \lesssim 0.27 \left(\frac{\mu \tan\beta}{5000GeV}\right)^{-1} \left(\frac{m_{\tilde{q}}}{500GeV}\right)^2,$$

This constraint is weaker than the one from Hg EDM.

1-loop correction to m_s

If 1-loop correction to m_s is large, the quark mass matrix must be re-diagonalized. The rotation of the right-handed strange quark can remove the contributions to $S_{\phi K_s}$.

$$\delta m_s \simeq 3\,\mathrm{Me}V \left(\frac{(\delta^{(d)}_{LL})_{23}}{0.04}\right)\left(\frac{(\delta^{(d)}_{RR})_{32}}{0.04}\right)\left(\frac{\mu m_{\tilde{g}}}{m^2_{\tilde{d}}}\right)\left(\frac{\tan\beta}{50}\right)\left(\frac{m_b}{5\,\mathrm{GeV}}\right)$$



The one-loop correction to m_s is small due to the $Br(B \to X_s\gamma)$ constraint.

Constraints on the GUT phases

$\tilde{s}_R$-$\tilde{b}_R$ mixing phase induce Hg EDM.

$$(m^2_{\tilde{d}_R})_{32} \simeq -\frac{2}{(4\pi)^2} \mathrm{e}^{i(\varphi_{d_2}-\varphi_{d_3})} U_{33} U^\star_{23} \frac{m_{\nu_\tau} M_{\nu_\tau}}{\langle H_2 \rangle^2} (3m_0^2 + A_0^2) \log \frac{M_G}{M_{GUT}}$$

Hg EDM puts strong constraint on the GUT phases

$$(\delta^{(d)}_{RR})_{32} \simeq -1 \times 10^{-3} \times \mathrm{e}^{i(\varphi_{d_2}-\varphi_{d_3})} \times \left(\frac{m_{\nu_\tau}}{5\times 10^{-2}\mathrm{eV}}\right) \left(\frac{M_{\nu_\tau}}{10^{13}\mathrm{GeV}}\right) \left(\frac{U_{33}U^\star_{23}}{1/2}\right) \left(\frac{3m_0^2 + A_0^2}{3m^2_{\tilde{q}}}\right)$$

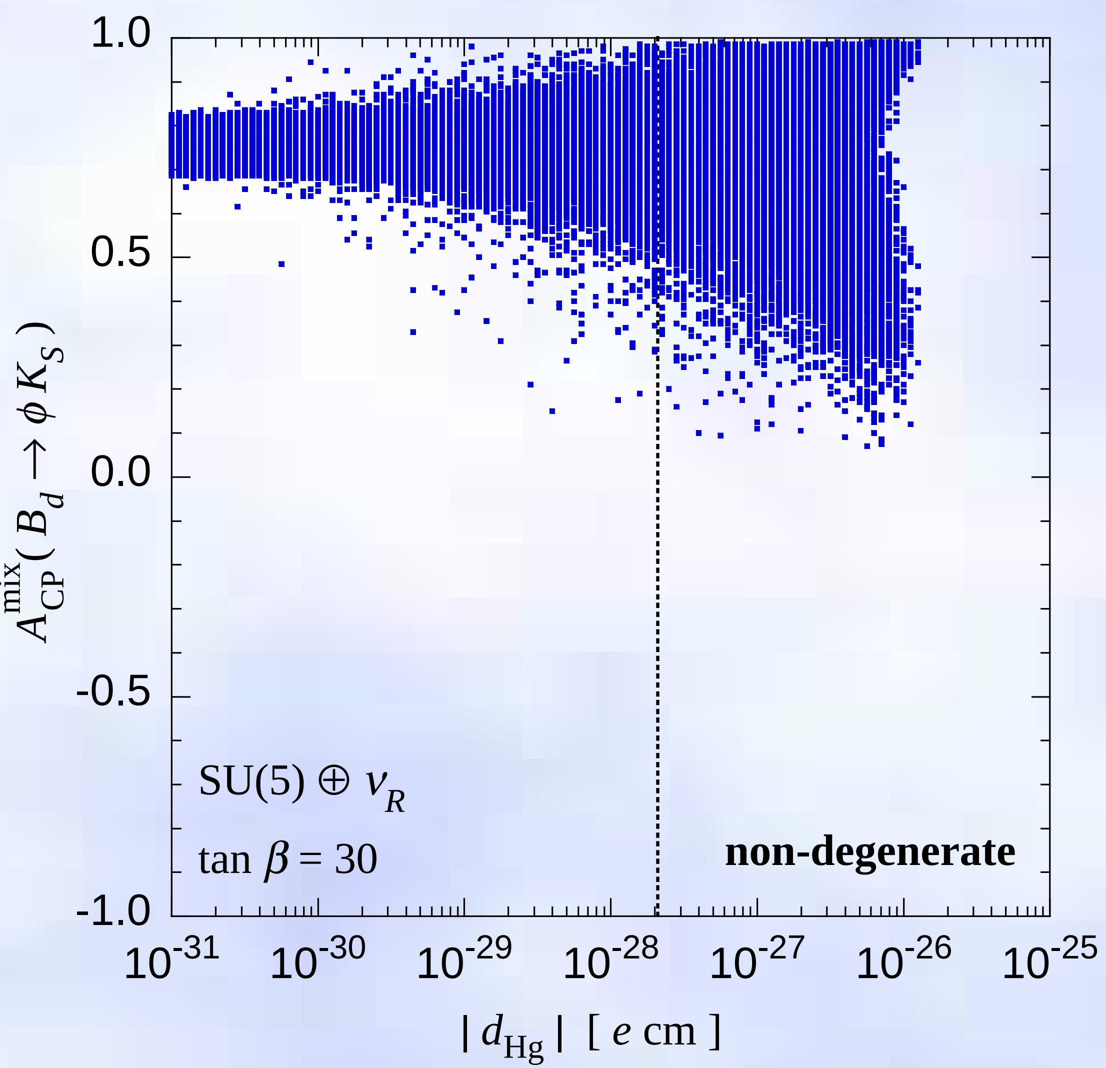
Loopholes

- $(\delta^{(d)}_{LL})_{23} < 10^{-4}$
- $\tilde{s}_L$ is very heavy while other SUSY particles are O(100) GeV
- strong cancellation among d^C_q: $d_{Hg} \propto d^C_d - d^C_u - 0.012 d^C_s$
- Large hadronic uncertainty in d_{Hg} and $B \to \phi K_S$ (κ)
- strong cancellation among various SUSY contributions (chargino, neutralino, higgs, gluino diagram)

Hg EDM

Cancellation between d_d^C and d_s^C.

hep-ph/0306093v2 (T.Goto, Y.Okada, Y.S, T.Shindou, M.Tanaka)



Summary

- Atmospheric neutrino makes large $\tilde{s}_R$-$\tilde{b}_R$ mixing in SUSY SU(5) GUT.
- Large $\tilde{s}_R$-$\tilde{b}_R$ can contribute various B decays, $B \to \phi K_s$,$B \to X_s \gamma$.
- When $\tilde{s}_L$-$\tilde{b}_L$ mixing exists, large strange CEDM is induced. strange CEDM is strongly constrained by Hg EDM.
- $S_{\phi K_s}$ and Hg EDM have a strong correlation.
- Hg EDM should be suppressed by $O(10^{-2})$ in order to get negative $S_{\phi K_S}$.
- There is sizable theoretical uncertainty of Hg EDM. Lattice calculations can help reduce the uncertainty.