$b \to s\nu\bar{\nu}$ decay in the MSSM at large $\tan\beta$

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Ref. YY, arXiv:0709.1022 (PRD in press)

BNM 2008, Atami, Jan. 25, 2008

- $b \to s\nu\bar{\nu}$ decay

- MSSM contributions at large $\tan\beta$
  - $\tan\beta$ -enhanced contributions from gluino and $H^{\pm}$

- correlation to $b \to s\gamma$
  - gluino loops, chargino loops, $H^{\pm}$ loops

- $B_s \to \mu^+\mu^-$ for $H^{\pm}$ loops

FCNC processes are very important to probe the physics beyond the SM

* No tree-level SM contributions
$\Rightarrow$ sensitive to new physics contributions

FCNC in B physics

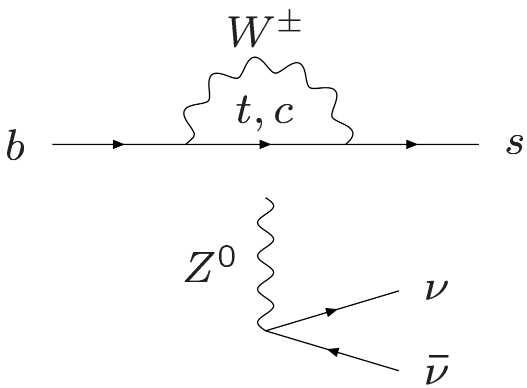
$B_{d,s}$-$\bar{B}_{d,s}$ mixings, $b \to s\gamma$, $b \to sl^+l^-$, $B_{s,d} \to \mu^+\mu^-$, ...

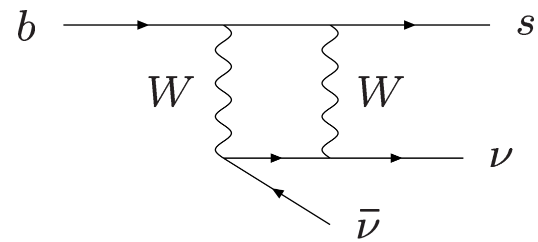
Here we consider the decay $b \to s\nu\bar{\nu}$ in the MSSM, at large $\tan\beta = \langle H_U \rangle / \langle H_D \rangle \gg 1$ and for general flavor mixing of squarks.

$b \to s\nu\bar{\nu}$ $(\bar{B} \to X_s\nu\bar{\nu})$ decay ($B^- \to K^{(*)-}\nu\bar{\nu}$, . . .)

Generated by Z-penguin and box diagrams.

SM contributions $\sim (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_L\gamma_\mu\nu_L)$





* Dominance of short distance contrib. by hard GIM cancellation
* Inclusive branching ratio Br($\bar{B} \to X_s\nu\bar{\nu}$):
  small uncertainty from hadronic/nonpertubative corr.
  $\Rightarrow$ theoretically clean prediction "Golden mode"

Experimental search for $b \to s\nu\bar{\nu}$

Search for $B \to (K, K^*, \cdots) +$ (missing energy):
not observed yet

Upper limits:
Br($\bar{B} \to X_s + E_{miss}$) $< 6.4 \times 10^{-4}$ (ALEPH, 2001)
Br($B^- \to K^- + E_{miss}$) $< 1.4 \times 10^{-5}$ (Belle, 2007) etc.

Still much larger than the SM predictions (sum over $\nu = \nu_{e,\mu,\tau}$)
Br$(\bar{B} \to X_s\nu\bar{\nu})_{SM} = (3.7 \pm 0.2) \times 10^{-5}$ (Bobeth et al, 2005)
Br$(\bar{B} \to K\nu\bar{\nu})_{SM} = (3.8^{+1.2}_{-0.6}) \times 10^{-6}$ (Buchalla et al, 2001)
Br$(\bar{B} \to K^*\nu\bar{\nu})_{SM} = (1.3^{+0.4}_{-0.3}) \times 10^{-5}$ (Buchalla et al, 2001)

A target at Super B factory

expect 20% precision for Br($B^- \to K^-\nu\bar{\nu}$) at 50–100 ab^{-1}

MSSM(minimal supersymmetric standard model)

a very promising extension of the standard model

* All particles in SM have the “superpartners” (SUSY particles), which have the same gauge charges and different spins by 1/2.

q_α	$\rightarrow$	squarks $\tilde{q}_{L\alpha}, \tilde{q}_{R\alpha} (\alpha = 1-6)$
l	$\rightarrow$	sleptons $\tilde{l}$
g	$\rightarrow$	gluino $\tilde{g}$
$W^\pm, H^\pm$	$\rightarrow$	charginos $\tilde{\chi}^\pm_{1,2}$
γ, Z, H^0_{1-3}	$\rightarrow$	neutralinos $\tilde{\chi}^0_{1-4}$

Flavor mixing of squarks: not governed by CKM matrix

New sources of FCNC processes

* Having two Higgs doublets

$$H_D = (H_D^0, H_D^-), \quad H_U = (H_U^+, H_U^0),$$

$$\langle H_D^0 \rangle^2 + \langle H_U^0 \rangle^2 = 2m_W^2/g_2^2, \quad \langle H_U^0 \rangle / \langle H_D^0 \rangle \equiv \tan\beta$$

$$\langle H_D \rangle \to m_d, m_l \qquad \langle H_U \rangle \to m_u \qquad \text{(at tree level)}$$

For large $\tan\beta \gg 1$, Yukawa couplings of $b/\tilde{b}$ become large.
Interesting in phenomenology

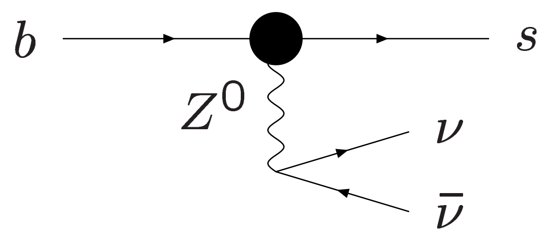
$$Y_b \sim \frac{m_b}{\langle H_D \rangle} \sim \frac{1}{\cos\beta} Y_b(\text{SM})$$

SUSY/Higgs contributions to $b \to s\nu\bar{\nu}$

Bertolini et al; Grossman et al; Goto et al; Buchalla et al; . . .

(1) Z^0 penguin diagrams by 1-loop $Z\bar{s}b$ vertex (quark-Higgs, squark-ino)

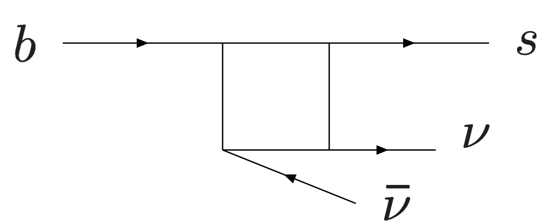
main parts of SUSY/Higgs contributions



Need $3 \to 2$ flavor changing and SU(2) breaking in the loops

(2) Box diagrams

usually small for SUSY loops



Effective Hamiltonian for $b \to s\nu\bar{\nu}$

$$H_{\text{eff}} = -\frac{2G_F}{\sqrt{2}}\frac{\alpha}{\pi}K_{ts}^{*}K_{tb}[C_\nu \mathcal{O}_L + C'_\nu \mathcal{O}_R],$$

$$\mathcal{O}_L = (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_L\gamma_\mu\nu_L), \quad \mathcal{O}_R = (\bar{s}_R\gamma^\mu b_R)(\bar{\nu}_L\gamma_\mu\nu_L)$$

Simple structure

$$C_\nu = C_\nu(\text{SM}) + C_\nu(\text{new}), C_\nu = C'_\nu(\text{new}) \quad (C_\nu(\text{SM}) \simeq -6.8)$$

Branching ratios

$$\sum_\nu \text{Br}(B \to X_s\nu\bar{\nu}) \;\propto\; |C_\nu|^2 + |C'_\nu|^2,$$

$$\sum_\nu \text{Br}(B \to K\nu\bar{\nu}) \;\propto\; |C_\nu - C'_\nu|^2$$

SUSY/Higgs contributions in MSSM

* Chargino-squark loops ($Z\bar{s}b$ vertex $\oplus$ box)

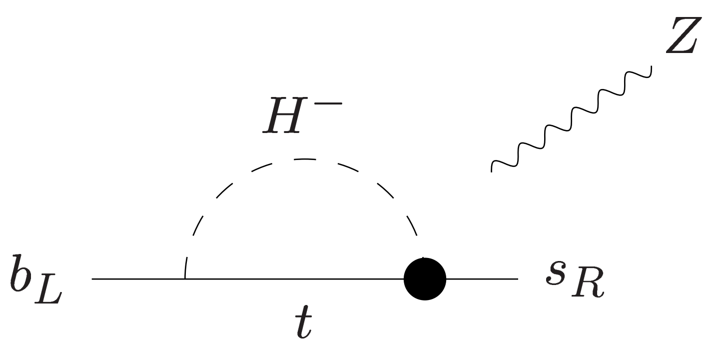
SU(2) breaking by A-term mixings $\tilde{t}_R - \tilde{t}_L$, $\tilde{t}_R - \tilde{c}_L$:
Dominant MSSM contrib. at small/moderate $\tan\beta$
(main target in previous studies)

* Gluino-squark loops ($Z\bar{s}b$ vertex)

SU(2) breaking by $\tilde{q}_L - \tilde{q}_R$ mixing for $\tilde{q} = (\tilde{b}, \tilde{s}) \propto m_b \mu \tan\beta$
enhanced by $\tan\beta \gg 1$ and $\tilde{b} - \tilde{s}$ flavor mixing

* $(H^{\pm}, t)$ loops ($Z\bar{s}b$ vertex)

ΔC_ν $(b_L \to s_L)$: suppressed by $1/\tan^2\beta$
$\Delta C'_\nu$ $(b_R \to s_R)$: induced by $\tan\beta$-enhanced one-loop effective $\bar{s}_R t_L H^-$ coupling $\sim (\hat{Y}_d)_{23}$, which can be much larger than tree-level $\sim m_s \tan\beta$ (see later)



$C'_\nu(H^+)$ may be relevant at $\tan\beta \gg 1$ and with $\tilde{s}_R - \tilde{b}_R$ mixing

Cf. Similar $\tan\beta$-enhanced $H^{\pm}$ contribution to $K \to \pi\nu\bar{\nu}$: Isidori, Paradisi,

$\tan\beta$-enhanced one-loop quark flavor violation

Hempfling; Hall et al.; Carena et al.; Blazek et al.; Babu, Kolda; Foster et al.; . . .

Effective interactions of $d_{iR} = (d, s, b)_R$ to two Higgs doublets, after squarks are integrated out

$$\mathcal{L}_{\text{int}} = -(\hat{Y}_d)_{ij} \bar{d}_{iR} q_{jL} H_D - (\Delta Y_d)_{ij} \bar{d}_{iR} q_{jL} H_U^c$$

$H_U \sim h^0(\text{SM} - \text{like})$, $H_D \sim (H^0, A^0, H^\pm)$ at $\tan\beta \gg 1$

$\Delta Y_d = 0$ at tree-level by SUSY, but are induced by squark loops with soft SUSY breaking.

* quark mass matrix: set to flavor-diagonal

$$m_d(\text{SM})_{ij} \;\propto\; [\hat{Y}_d v_d + \Delta Y_d v_u]_{ij} \propto [\hat{Y}_d + \tan\beta \Delta Y_d]_{ij}$$

* $(H^0, A^0, H^\pm, \tilde{H}_D)$-couplings to d_{Ri}: determined by $\hat{Y}_d$

Not diagonal in quark mass basis

$\tan\beta$-enhanced effective flavor-changing higgs-(s)quark couplings, not governed by CKM matrix, are generated.
Numerically important at large $\tan\beta$

Constraints on $b \to s\nu\bar{\nu}$ from $b \to s\gamma$

$b \to s\gamma$:
enhanced by the SU(2)×U(1) breakings and 3 → 2 flavor changing in the loops (similar to $b \to s\nu\bar{\nu}$)
⇒ experimental bound on $b \to s\gamma$ should give constraints on the SUSY/Higgs contributions to $b \to s\nu\bar{\nu}$.
especially important at large $\tan\beta$

Very rough estimation of the constraints:
Requiring Wilson coeff. $(\Delta C_7, \Delta C_7')(\mu_W)$ for $b \to s\gamma$ from each SUSY/Higgs sector to be not larger than $C_7(\text{SM}, \mu_W) \sim -0.2$

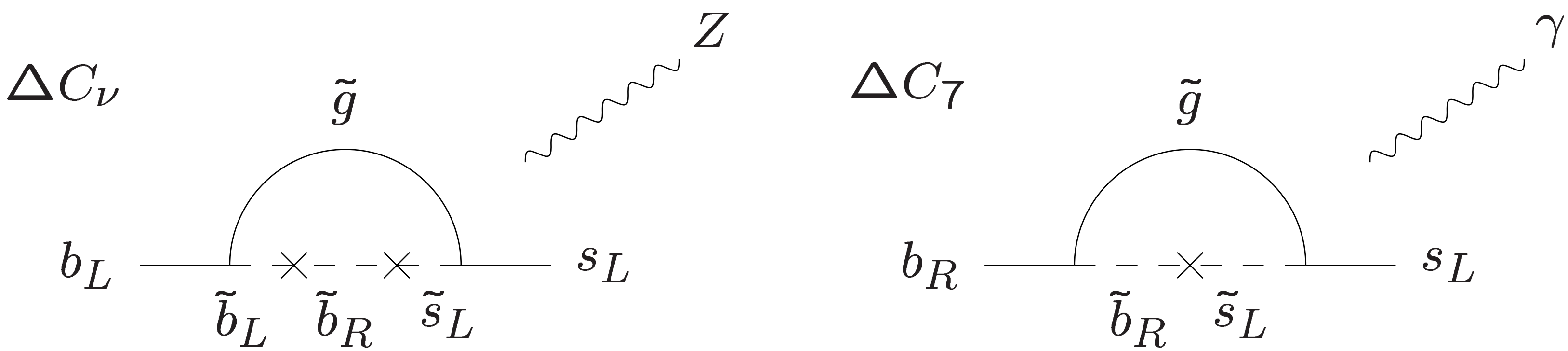
Numerical correlation between $C_\nu^{(\prime)}$ and $C_7^{(\prime)}$

Scan over 2-3 flavor mixing parameters in squark mass matrices ($\delta^q_{LL}, \delta^u_{RR}, \delta^d_{RR}, (A_u)_{33,32}$)

$$
\begin{aligned}
M^2_{\tilde{Q}XX} &= M^2_{\tilde{Q}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & (\delta^q_{XX})_{23} \\ 0 & (\delta^q_{XX})_{23} & 1 \end{pmatrix} + (m_q^{(0)})^2 + D_q I, \\
& \quad (XX = (LL, RR), Q = (U, D)), \\
M^2_{\tilde{U}RL} &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & m_t (A_u)_{32} & m_t (A_u)_{33} - \mu m_t \cot\beta \end{pmatrix}, \\
M^2_{\tilde{D}RL} &= -\mu m_d^{(0)} \tan\beta
\end{aligned}
$$

$m_d^{(0)} \propto \widehat{Y}_d$: "bare" quark mass matrix, not necessarily diagonal.

(1) Gluino-squark contribution to (C_ν, C'_ν)

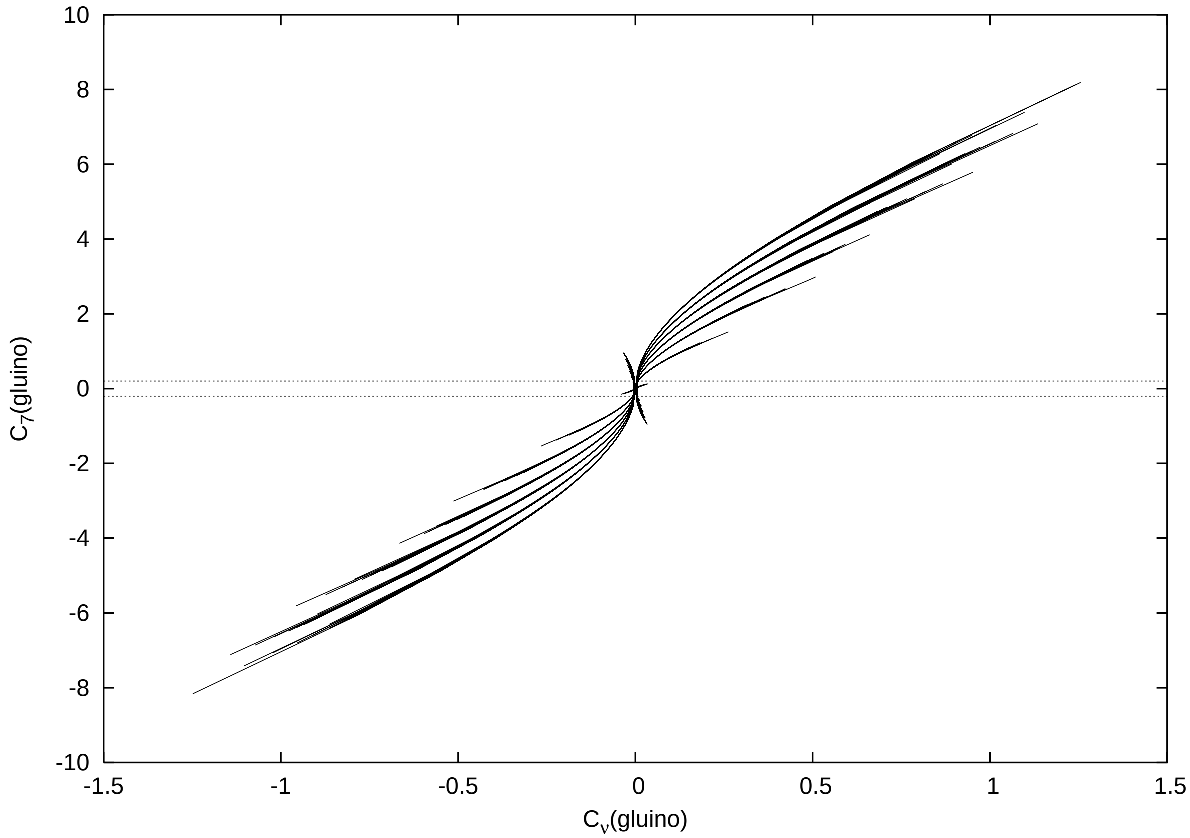


Both scale with $\tilde{b}_R - \tilde{s}_L$ mixing $\propto m_b \mu \tan\beta$

Requiring $|\Delta C_7(\tilde{g})| < |C_7(\mathrm{SM}, \mu_W)| \sim 0.2$ constrains $\Delta C_\nu(\tilde{g})$ much smaller than $C_\nu(\mathrm{SM}) \sim -6.8$.

$\Delta C_\nu - \Delta C_7$ corr. (gluino-squark loops)

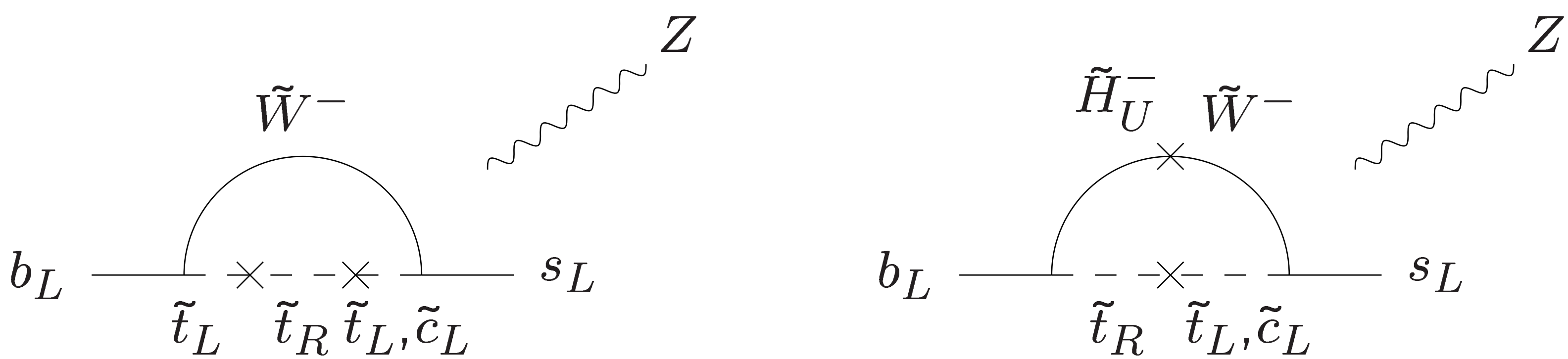
[$\tan\beta = 50$, $M_{\tilde{q}} = 500\,\mathrm{GeV}$, $m_{\tilde{g}} = 500\,\mathrm{GeV}$, $\mu = [-550, 550]\,\mathrm{GeV}$, $(\delta^d_{LL,RR})_{23} = [-0.3, 0.3]$]



Gluino contributions cannot be large, even at $\tan\beta \gg 1$ and with large $\tilde{b} - \tilde{s}$ mixing

(2) Chargino-squark contributions

main parts

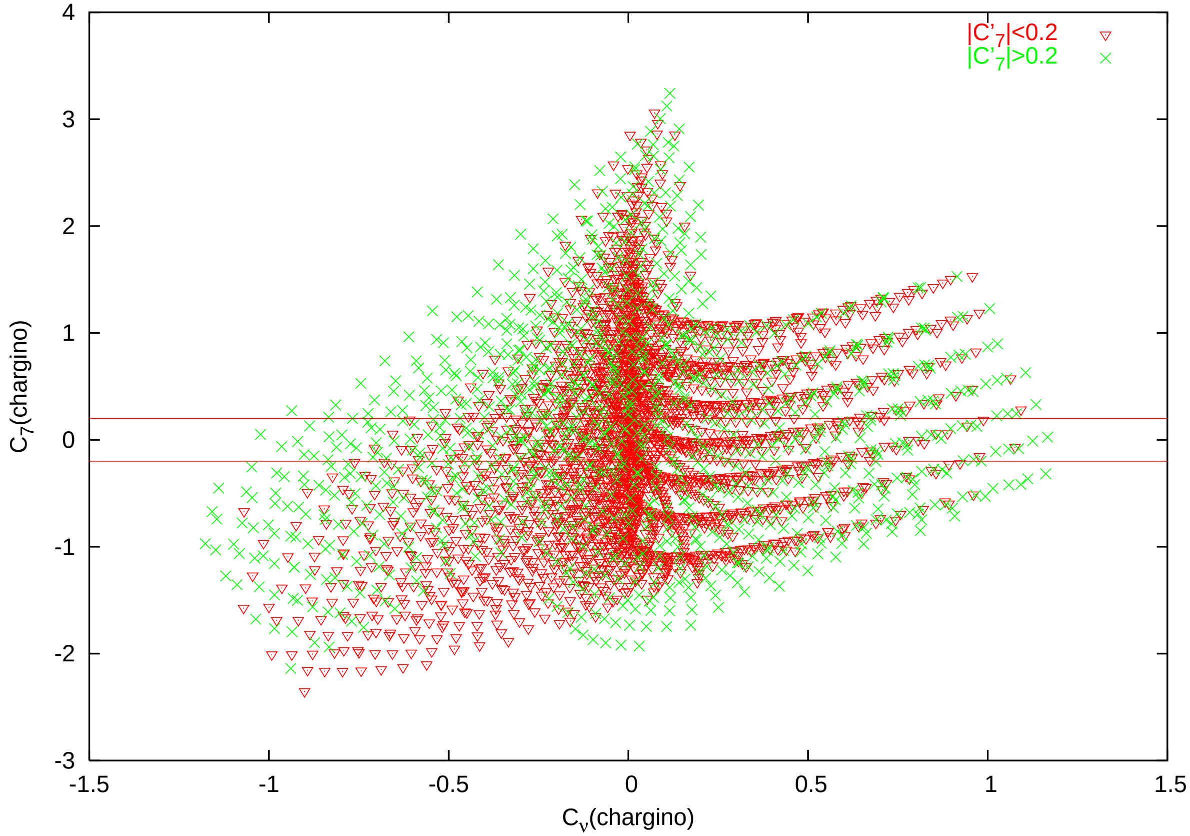


ΔC_ν increases with $(A_u)_{33}$ $(\tilde{t}_R - \tilde{t}_L)$ and $(A_u)_{32}$ $(\tilde{t}_R - \tilde{c}_L)$ mixings

$\Delta C_7(\tilde{\chi}^\pm)$ also increases with $(A_u)_{33,32}$ as well as with $\tan\beta$, but $\Delta C_\nu - \Delta C_7$ correlation is not so strong due to their different dependences on $((A_u)_{33}, (A_u)_{32})$

$\Delta C_\nu - \Delta C_7$ corr. (chargino-squark loops)

[$\tan\beta = 50$, $M_{\tilde{q}} = 500$ GeV, $M_2 = 300$ GeV, $\mu = 500$ GeV, $m_{\tilde{l}^\pm} = 400$ GeV, $(\delta^u_{LL})_{23} = [-0.3, 0.3]$, $(\delta^u_{RR})_{23} = 0$, $(A_u)_{33,32} = [-1500, 1500]$ GeV]

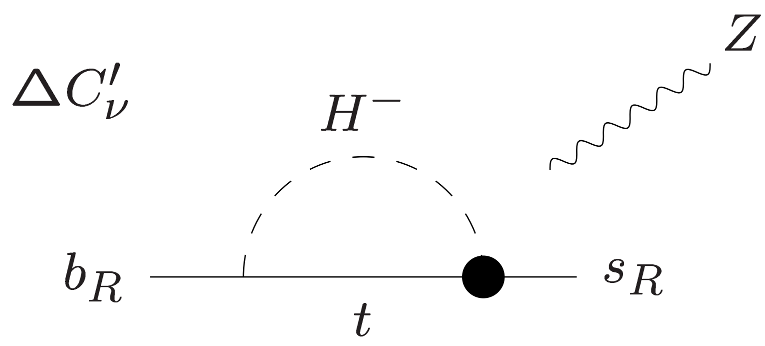


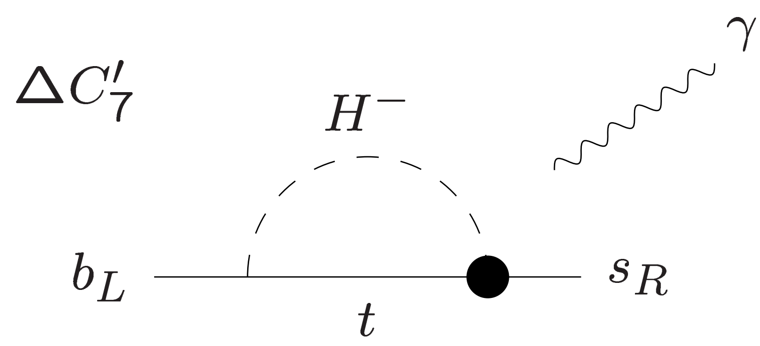
$\Delta C_\nu \sim \pm 1$ possible while $|\Delta C_7^{(\prime)}| < 0.2$

$\sim 30\%$ deviation from SM?

(3) $H^{\pm}$ contributions for $\tan\beta \gg 1$

(by loop-generated effective $H^{-}\bar{s}_R t_L$ couplings)

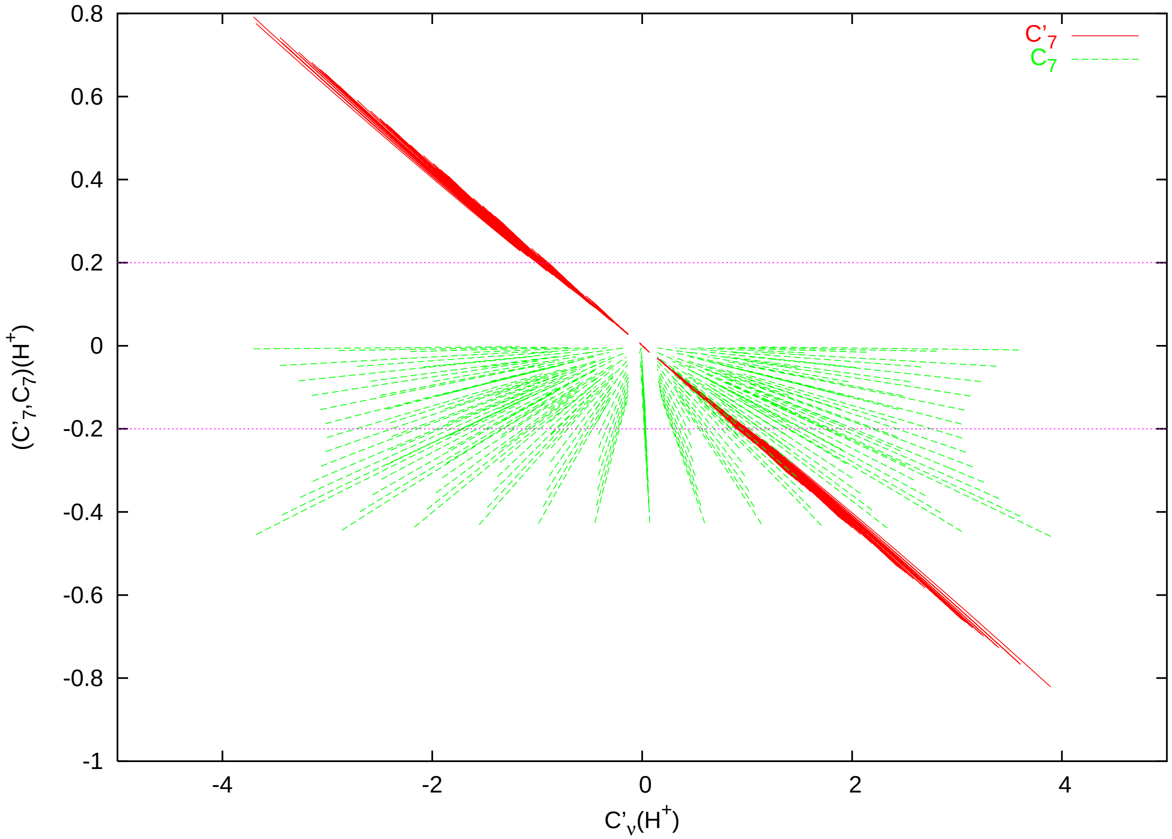




Constraints from $\Delta C_7^{(\prime)}(H^+)$ are not so strong as $\Delta C_7^{(\prime)}(\tilde{g})$, since $\Delta C_7^{(\prime)}(H^+)$ are not $\tan\beta$-enhanced.

$\Delta C'_\nu - \Delta C_7^{(\prime)}$ corr. ($H^\pm - t$ loops)

[$\tan\beta = 50$, $M_{\tilde{q}} = 500$ GeV, $M_3 = 500$ GeV, $\mu = -500$ GeV, $(A_u) = 0$, $\delta^d_{LL,RR} = [-0.3, 0.3]$, $m_{H^\pm} = [400, 1000]$ GeV]

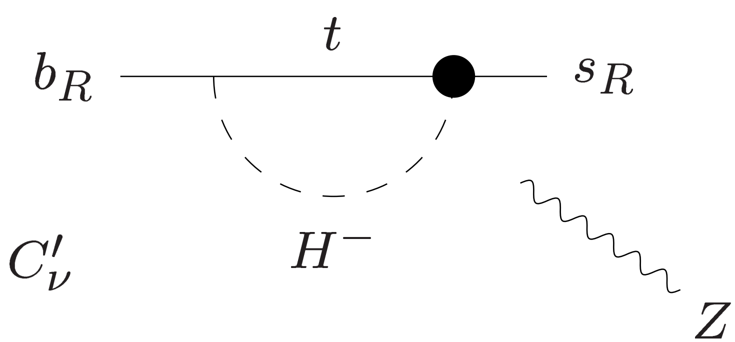


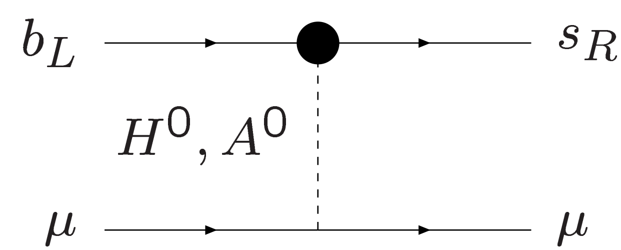
$\Delta C'_\nu \sim \pm 1$ possible

$B_s \to \mu^+\mu^-$ constraint on $C'_\nu(H^\pm)$

Effective $H^+\bar{s}_R t_L$ coupling for $C'_\nu(H^\pm)$ is associated with $(H^0, A^0)\bar{s}_R b_L$, by SU(2) symmetry.

Large "tree-level" contributions to $B_s \to \mu^+\mu^-$ are induced by Higgs penguin.





$\mathrm{Br}(B_s \to \mu^+\mu^-) < 10^{-7}$ (Tevatron, 2007) (cf. 4×10^{-9} in SM)
$\to |(\hat{Y}_d)_{32}|^2 + |(\hat{Y}_d)_{23}|^2 < 0.2 \cos^2\beta (m_A/500\,\mathrm{GeV})^4$

$\Rightarrow$ $C'_\nu(H^+) < 0.15\times$(corr. to $H^+\bar{t}_L b_R$) for $\tan\beta = 50$, $m_A <$ 1 TeV
negligible compared to $C_\nu(\mathrm{SM}) \sim -6.8$

Conclusions

* In the MSSM at large $\tan\beta$ and with general flavor mixings for squarks, the $b \to s\nu\bar{\nu}$ decay may receive potentially sizable, $O(10)$% contributions from the gluino and $H^{\pm}$ loops, in addition to the chargino contribution, through the Z penguin diagrams.

* However, their magnitudes are strongly constrained by other FCNC processes of the b mesons, $b \to s\gamma$, $B_s \to \mu^+\mu^-$, . . .

* Requiring ΔC_7(SUSY) $<$ C_7(SM) for $b \to s\gamma$ and [Higgs penguin] $<$ [Experimental upper limit] for $B_s \to \mu^+\mu^-$ give strong suppression $\Delta C_\nu^{(\prime)}(\tilde{g}, H^+) \ll C_\nu$(SM).

Things to do

* Estimation of SUSY contributions to $b \to s\nu\bar{\nu}$ with wider parameter scan and imposing other constraints (B_s–$\bar{B}_s$ mixing, $\Delta\rho$, etc.):
now in progress

* Comparison with related FCNC processes:
$b \to s l^+ l^-$, $K \to \pi\nu\bar{\nu}$