$b \to s\nu\bar{\nu}$ decays in the MSSM with general flavor mixing

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

- SUSY and Higgs contributions
  - $\tan\beta$ -enhanced one-loop flavor violations
  - correlation with $b \to s\gamma$

- each sector
  - gluino-squark loops
  - chargino-squark loops
  - $(H^{\pm}, q)$ loops and other B processes

Introduction

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

* No tree-level SM contributions
$\Rightarrow$ contributions from new physics are relatively enhanced

FCNC in B physics

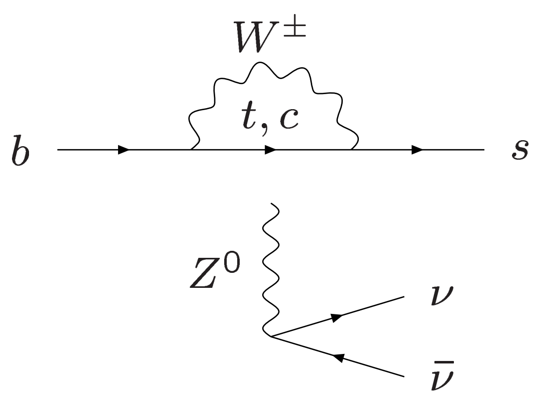
$B_{d,s}$-$\bar{B}_{d,s}$ mixings, $b \to s\gamma$, $b \to sl^+l^-$, $B_{s,d} \to \mu^+\mu^-$, ...

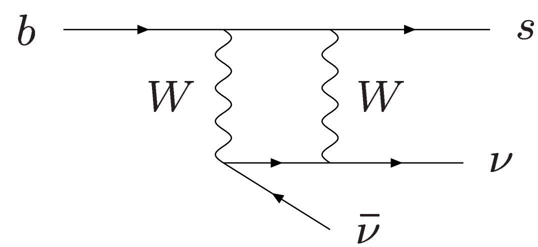
Here we consider the decays $b \to s\nu\bar{\nu}$ in the MSSM (minimal supersymmetric standard model), especially for general squark flavor mixing and at large $\tan\beta = \langle H_U \rangle / \langle H_D \rangle \gg 1$.

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

Generated by Z-penguin and box diagrams.

SM contributions $\sim K_{ts}^* K_{tb} (\bar{s}_L \gamma^\mu b_L)(\bar{\nu}\gamma_\mu \nu)$





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

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

Search for $B \to (K, K^*, \cdots)$ $+E_{\text{missing}}$: not observed yet

Upper limits:
Br$(\bar{B} \to X_s + E_{miss}) < 6.4 \times 10^{-4}$ (ALEPH, 2001)
Br$(B^- \to K^- + E_{miss}) < 3.6 \times 10^{-5}$ (Belle, 2005)

Still much larger than the SM predictions (sum of $\nu = \nu_{e,\mu,\tau}$)
Br$(\bar{B} \to X_s\nu\bar{\nu})_{SM} \sim (3.7 \pm 0.2) \times 10^{-5}$ (Bobeth et al, 2005)
Br$(B^- \to K^-\nu\bar{\nu})_{SM} = (3.8 \pm {}^{1.2}_{0.6}) \times 10^{-6}$ (Buchalla et al, 2001)
A target at Super B factory

Comparison with $s \to d\nu\bar{\nu}$

$$\mathcal{A}(b \to s\nu\bar{\nu}) \propto K_{ts}^* K_{tb} \sim \lambda^2 \gg \mathcal{A}(s \to d\nu\bar{\nu}) \propto K_{td}^* K_{ts} \sim \lambda^5$$

Larger amplitude, but harder to detect

Cf.
$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})_{SM} = (8.0 \pm 1.1) \times 10^{-11}$
$\mathrm{Br}(K_L^0 \to \pi\nu\bar{\nu})_{SM} = (2.8 \pm 0.4) \times 10^{-11}$ (Buras et al, 2006)

$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})_{exp} = (1.5 \pm {}^{1.3}_{0.9}) \times 10^{-10}$ (E949, 2004)
Observed

MSSM (minimal supersymmetric standard model)

A very promising extension of the Standard model

All particles in SM form "supermultiplets" with their SUSY partners(SUSY particles), which have the same gauge charges and different spins by 1/2.

* Having two Higgs doublets

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

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

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

Chiral supermultiplets

fermion ($s = 1/2$)		scalar ($s = 0$)	
$q_L = (u_L, d_L)$ $u_R,\ d_R$ $l_L = (\nu_L, e_L)$ e_R	quarks leptons	$\tilde{q}_L = (\tilde{u}_L, \tilde{d}_L)$ $\tilde{u}_R,\ \tilde{d}_R$ $\tilde{l}_L = (\tilde{\nu}_L, \tilde{e}_L)$ $\tilde{e}_R$	squarks sleptons
$\tilde{H}_D,\ \tilde{H}_U$	higgsino	$H_D,\ H_U$	Higgs bosons

Vector supermultiplets

fermion ($s = 1/2$)		gauge boson ($s = 1$)	
$\tilde{g}$ $\tilde{W}$ $\tilde{B}$	gluino wino bino	g_μ W_μ B_μ	SU(3) boson (gluon SU(2) boson U(1) boson

$(\tilde{W}^\pm, \tilde{H}^\pm) \to \tilde{\chi}^\pm_{1,2}$(charginos), $(\tilde{B}, \tilde{W}^0, \tilde{H}^0_D, \tilde{H}^0_U) \to \tilde{\chi}^0_{1-4}$(neutralinos),

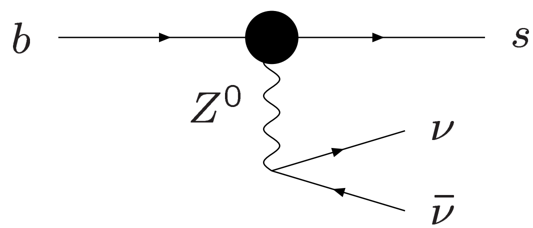
$(\tilde{q}_L, \tilde{q}_R) \to \tilde{q}_{1-6}$

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

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

(1) Z^0-penguin diagrams by effective $(Z_\mu \bar{s}_L \gamma^\mu b_L, Z_\mu \bar{s}_R \gamma^\mu b_R)$ vertex (quark-Higgs, squark-ino)

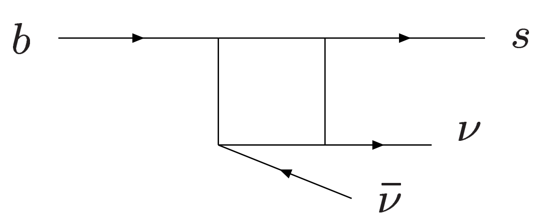
main parts of SUSY/Higgs contributions



Need flavor changing and SU(2) breaking in the loops

(2) Box diagrams

usually small for SUSY loops



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

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

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

$$C_\nu = C_\nu(\mathrm{SM}) + C_\nu(\mathrm{new}), C_\nu = C'_\nu(\mathrm{new}) \quad (C_\nu(\mathrm{SM}) \simeq -6.6)$$

Inclusive branching ratio

$$\sum_\nu \mathrm{Br}(B \to X_s\nu\bar{\nu}) \sim \frac{N_\nu\alpha^2}{4\pi^2}\mathrm{Br}(B \to X_c e\bar{\nu}_e)\frac{|K_{tb}K_{ts}^*|^2}{|K_{cb}|^2}(|C_\nu|^2+|C'_\nu|^2)$$

(+ QCD corr.)

Flavor mixing in squark sector

Squark mass matrix in the "super-CKM" basis $(\tilde{q}_{Li}, \tilde{q}_{Ri})$ $(i = 1-3,\ q = (u, c, t; d, s, b))$

$$
\begin{aligned}
M^2_{\tilde{q}} &= \begin{pmatrix} M^2_{\tilde{q}LL} & (M^2_{\tilde{q}RL})^\dagger \\ M^2_{\tilde{q}RL} & M^2_{\tilde{q}RR} \end{pmatrix}, \\
(M^2_{\tilde{q}LL}) &= m^2_{\tilde{q}LL} + (m_q^{(0)})^\dagger (m_q^{(0)}) + D_{q_L} I, \\
(M^2_{\tilde{q}RR}) &= m^2_{\tilde{q}RR} + (m_q^{(0)})(m_q^{(0)})^\dagger + D_{q_R} I, \\
(M^2_{\tilde{q}RL}) &= (m^2_{\tilde{q}RL}) - (\tan\beta)^{-2I_q} \mu m_q^{(0)}
\end{aligned}
$$

Off-diagonal parts of $M^2_{\tilde{q}LL,RR,RL}$ may generate potentially large FCNC. here assume only $2-3$ mixings

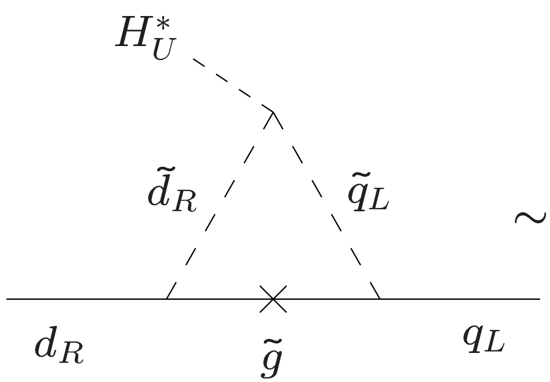
$\tan\beta$-enhanced one-loop quark flavor violation

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

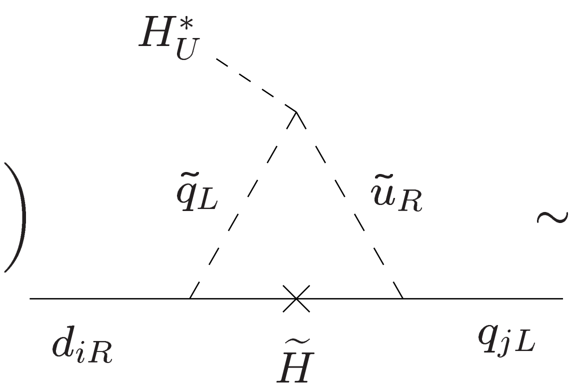
$$\mathcal{L}_{\rm int} = -(Y_1^d)_{ij}\bar{d}_{iR}q_{jL}H_D - (\Delta Y_2^d)_{ij}\bar{d}_{iR}q_{jL}H_U^c$$

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

$\Delta Y_2^d = 0$ at tree-level by SUSY (No FCNC in $H{-}q$ interaction), but induced by SUSY loops with soft SUSY breaking.



$$\sim O\left(\alpha_s Y_d \frac{\mu m_{\tilde{g}}}{M^2_{\rm SUSY}}\right)$$



$$\sim O\left(h_t^2 Y_d \frac{\mu A_t}{M^2_{\rm SUSY}}\right)$$

$O(\tan\beta)$ corrections to $H - q$ couplings

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

$$m_d(\mathrm{SM})_{ij} \;=\; \frac{\bar{v}}{\sqrt{2}}\cos\beta[Y_1^d + \tan\beta\,\Delta Y_2^d]_{ij} \quad \text{diagonal (superCKM basis)}$$

$$\Updownarrow$$

$$(\text{bare mass})(m_d^{(0)})_{ij} \;=\; \frac{\bar{v}}{\sqrt{2}}\cos\beta(Y_1^d)_{ij} \ \text{ in } M_{\tilde{d}RL}\text{: nondiagonal}$$

$$g(H^0\bar{d}_{iR}d_{jL}, \tilde{H}_D^0\tilde{d}_{iR}^*d_{jL})^{\mathrm{eff}} \;\simeq\; (Y_1^d)_{ij} \quad \text{nondiagonal}$$

$$g(H^-\bar{d}_{iR}u_{jL}, \tilde{H}_D^-\tilde{d}_{iR}^*u_{jL})^{\mathrm{eff}} \;\simeq\; (Y_1^d)_{il}K_{jl}^*, \quad \text{not prop. to } K_{ji}^*$$

$\tan\beta$-enhanced one-loop flavor-changing couplings of $(H,\ \tilde{H})$ to (s)quarks, not governed by CKM matrix, are generated.

New source for FCNC

SUSY/Higgs contributions in MSSM

(1) Gluino-squark loops

generated by $\tilde{b} - \tilde{s}$ and $\tilde{q}_L - \tilde{q}_R$ mixings in the loops enhanced by $\tan\beta \gg 1$ and squark flavor mixings

(2) Chargino-squark loops

Important for small/moderate $\tan\beta$:
Main subject in previous studies

(3) $(H^\pm, t)$ loops

ΔC_ν $(b_L \to s_L)$: $O(m_t^2/\tan^2\beta)$, only relevant for $\tan\beta \sim 1$
$\Delta C'_\nu$ $(b_R \to s_R)$: $O(m_b m_s \tan^2\beta)$ in "minimal flavor violation" relevant for $\tan\beta \gg 1$ and with flavor mixing of $\tilde{s}_R$

Correlations to $b \to s\gamma$

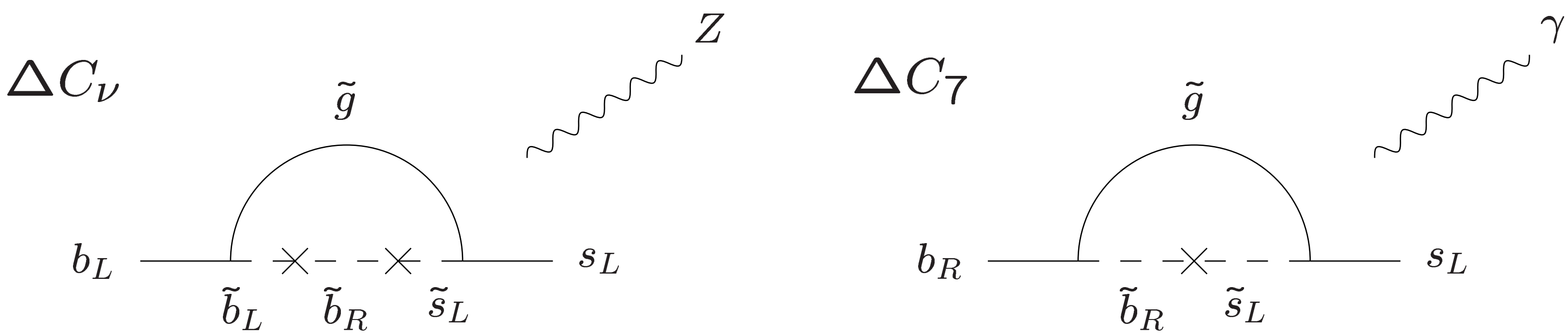
$b \to s\gamma$:

enhanced by the SU(2)×U(1) breakings and 3 → 2 flavor changing in the loops (same as $b \to s\nu\bar{\nu}$)

⇒ experimental bound on $b \to s\gamma$ might give constraints on the SUSY/Higgs contributions to $b \to s\nu\bar{\nu}$.

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 $C_7(\text{SM}, \mu_W) \sim -0.2$

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



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

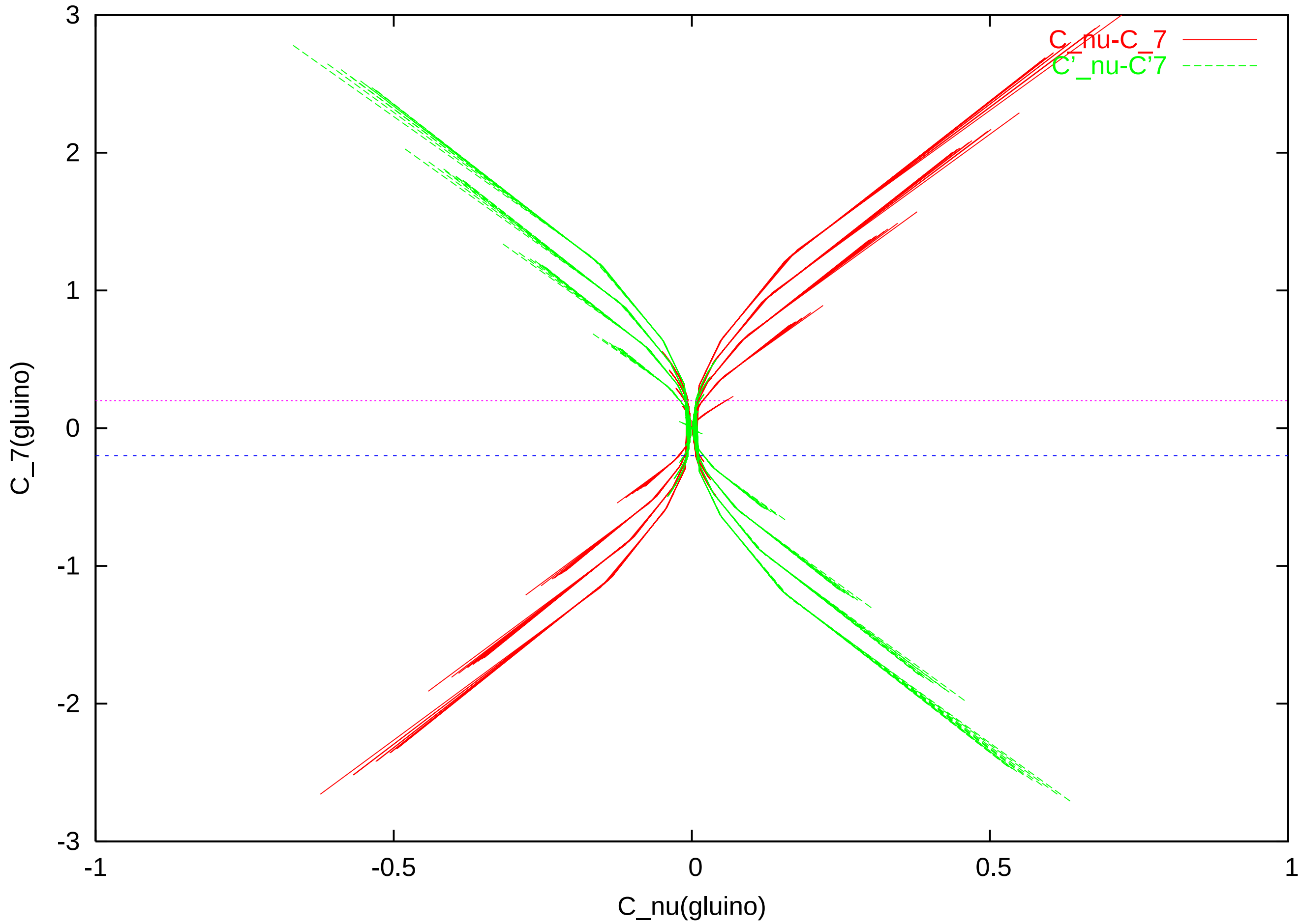
(loop-induced or multi-insertion)

Requiring $|\Delta C_7(\tilde{g})| < |C_7(\text{SM}, \mu_W)| \sim 0.2$ constrains $\Delta C_\nu(\tilde{g})$ much smaller than $C_\nu(\text{SM}) = -6.6$.

Gluino contributions cannot be large, even at $\tan\beta \gg 1$

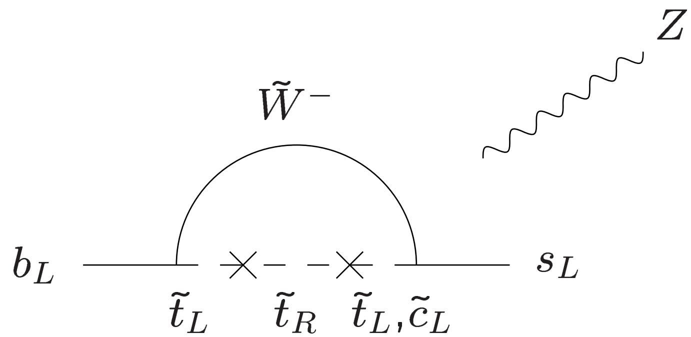
$\Delta C_\nu - \Delta C_7$ corr. (gluino-squark loops)

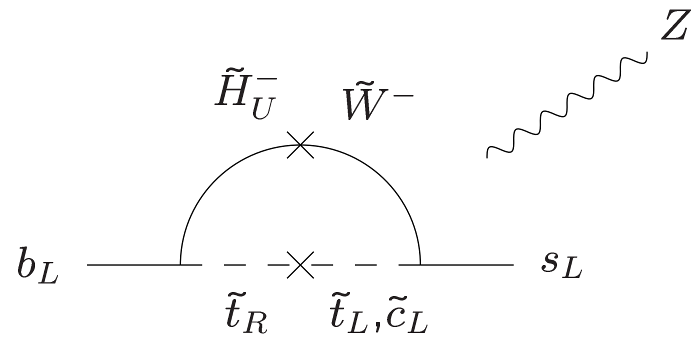
tan $\beta = 50$, $M_{\tilde{q}} = 500$ GeV, $m_{\tilde{g}} = 600$ GeV, $\mu = [-500, 500]$ GeV, $(\delta^d_{LL,RR})_{23} = [-0.2, 0.2]$



(2) Chargino-squark contributions

main parts



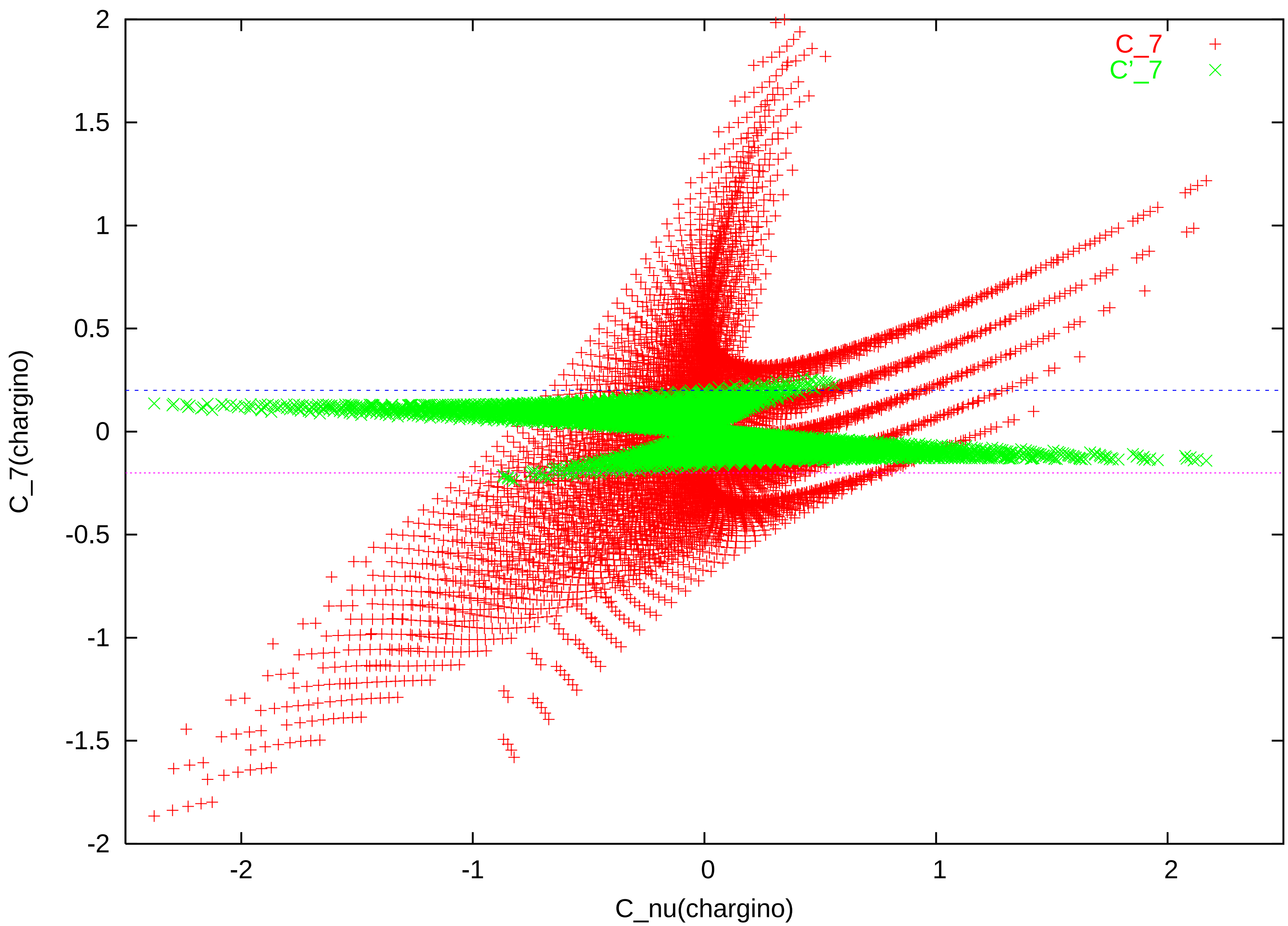


ΔC_ν increases with $(A_u)_{33}$ $(\tilde{t}_R - \tilde{t}_L)$ and $(A_u)_{32}$ $(\tilde{t}_R - \tilde{c}_L)$ mixings

$(m_{\tilde{u}RL})_{33,32} \equiv m_t (A_u)_{33,32}$

$\Delta C_7(\tilde{\chi}^\pm)$ also increases with $(A_u)_{33,32}$ as well as with $\tan\beta$, but Possible to have sizable $\Delta C_\nu(\tilde{\chi}^\pm)$ while $\Delta C_7(\tilde{\chi}^\pm) \sim 0$ due to their different dependences on $((A_u)_{33}, (A_u)_{32})$

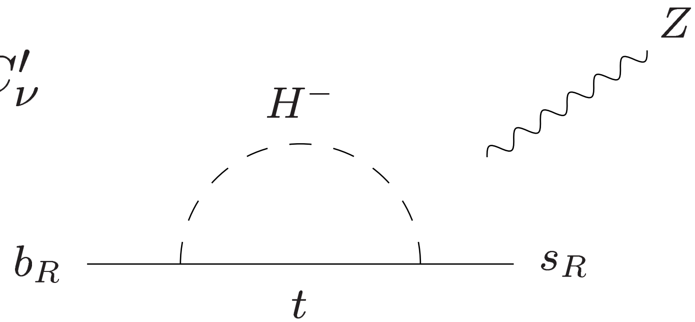
$[\tan\beta = 50,\ M_{\tilde{q}} = 500\,\mathrm{GeV},\ M_2 = 300\,\mathrm{GeV},\ \mu = 550\,\mathrm{GeV},\ m_{\tilde{l}} = 400\,\mathrm{GeV},$
$(\delta^u_{LL})_{23} = [-0.2, 0.2],\ (\delta^u_{RR})_{23} = 0\ ]$ cf. $C_\nu(SM) = -6.6$



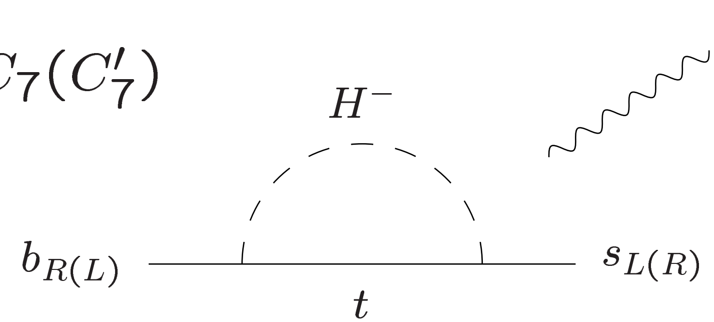
$H^{\pm}$ contributions for $\tan\beta \gg 1$

(by loop-generated effective $H - s_R$ couplings)

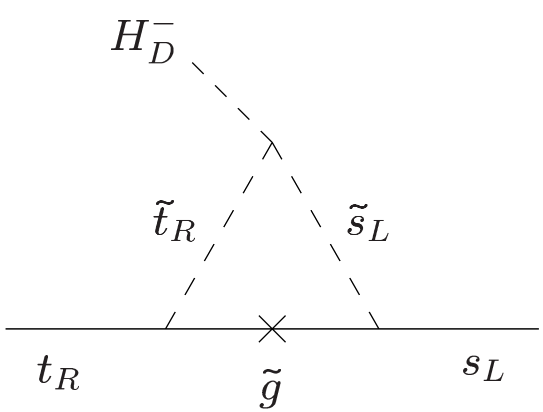
C'_ν



$C_7(C'_7)$



Correlation between $C'_\nu(H^{\pm})$ and $C_7(H^{\pm})$: severely affected by $O(\tan\beta)$ vertex corrections to the $t_R - s_L - H^{\pm}$ coupling in $C_7(H^{\pm})$.

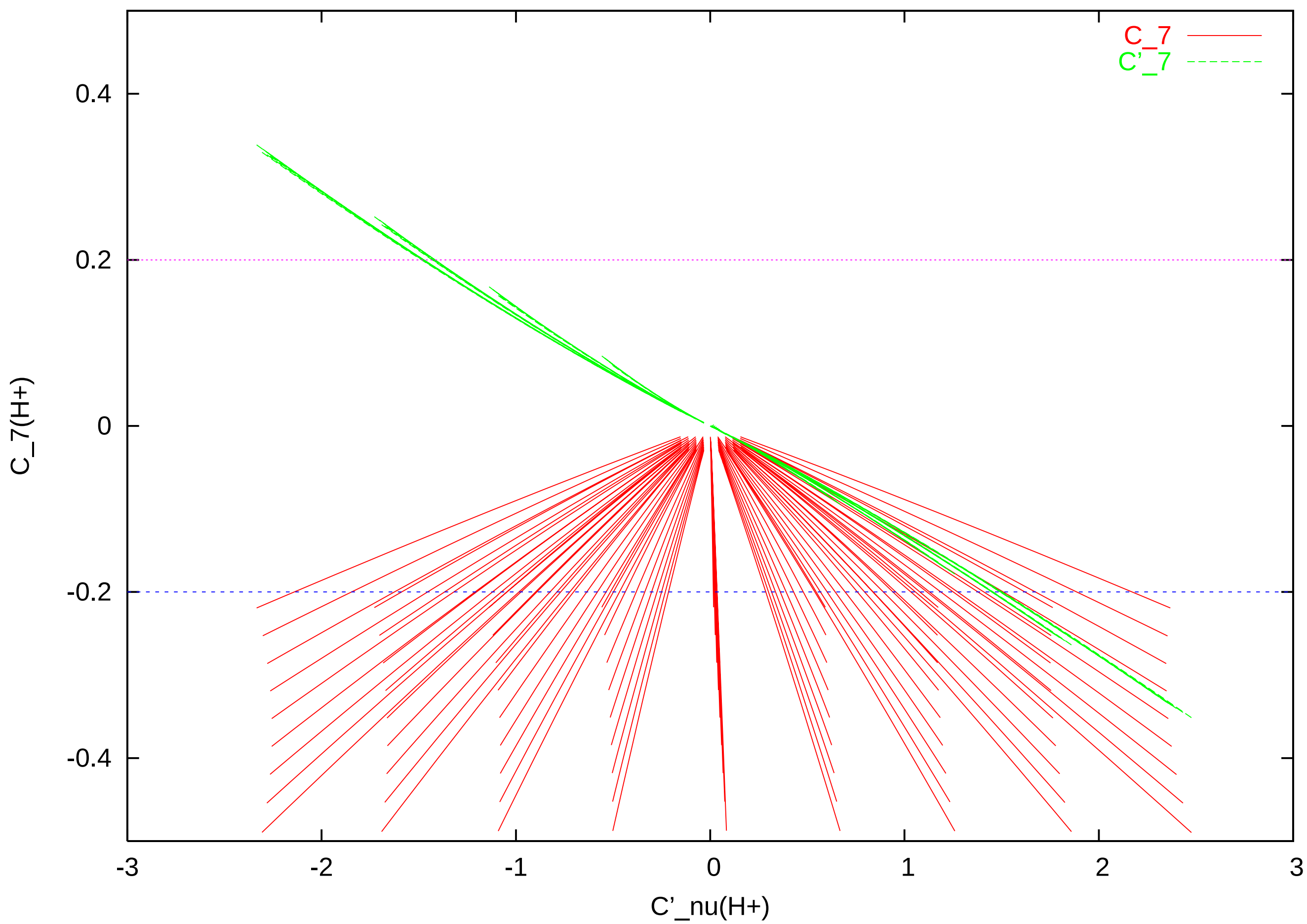


$$= h_t \Delta_t \sim O\left(\alpha_s h_t \frac{\mu m_{\tilde{g}}}{M^2_{\text{SUSY}}}\right)$$

Remove $\cot\beta$ and K_{ts} suppression of tree-level coupl. $\sim K_{ts}\frac{\sqrt{2}}{\bar{v}} m_t \cot\beta$

[$\tan\beta = 50,\ M_{\tilde{q}} = 1000\,\text{GeV},\ M_3 = 1200\,\text{GeV},\ \mu = -500\,\text{GeV},\ (A_u)_{33} = 500\,\text{GeV},\ \delta^d_{LL,RR} = [-0.2, 0.2],\ m_{H^\pm} = [200, 2000]\,\text{GeV}$]

cf. $C_\nu(SM) = -6.6$



Other FCNC constraints on $C'_\nu(H^\pm)$

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

Large "tree-level" contrributions to $B_s - \bar{B}_s$ mixing and $B_s \to \mu^+\mu^-$ are induced by Higgs penguin.

$\Delta M_{B_s}(H^+) < \Delta M_{B_s}(SM) \to |(Y_1^d)_{32}(Y_1^d)^*_{23}| < 8\times10^{-6}(m_A/500\text{ GeV})^2$

$\text{Br}(B_s \to \mu^+\mu^-) < 8\times10^{-8}$ (CDF, 2006)
$\to |(Y_1^d)_{32} - (Y_d^1)^*_{23}| < 0.4\cos\beta(m_A/500\text{ GeV})^2$

$\Rightarrow \quad |C'_\nu(H^+)| < 0.1$ for $\tan\beta = 50$, $m_A < 500$ GeV

Conclusions

* In the MSSM with large $\tan\beta$ and general flavor mixings for squarks, the gluino and $H^{\pm}$ loops may give potentially sizable contributions, similar to the chargino contribution, through the $b \to s\nu\bar{\nu}$ decays by bsZ penguin.

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

* Requiring ΔC_7(gluino) $<$ C_7(SM) and (Higgs penguin) $<$ (Experimental deviation from SM) for $B_s - \bar{B}_s$ mixing and $B_s \to \mu^+\mu^-$ give strong constraints $\Delta C_\nu^{(\prime)}(\tilde{g}, H^+) \ll C_\nu$(SM).