CP violation in $B \to \phi K_S$ decay at large $\tan\beta$ in the MSSM

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- $\sin 2\beta$ measurement in the SM
- Decoupling scenario
- $B \to \phi K_S$ in the decoupling scenario
- Numerical results
- Conclusions

$\sin 2\beta$ *measurement in the SM*

• The unique source of CP violation in the SM is the phase (δ) appearing in the CKM quark mixing matrix.

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}, \qquad (1)$$

The unitarity of $V_{\rm CKM}$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad (2)$$

$\Rightarrow$ gives a triangle, "unitarity triangle".

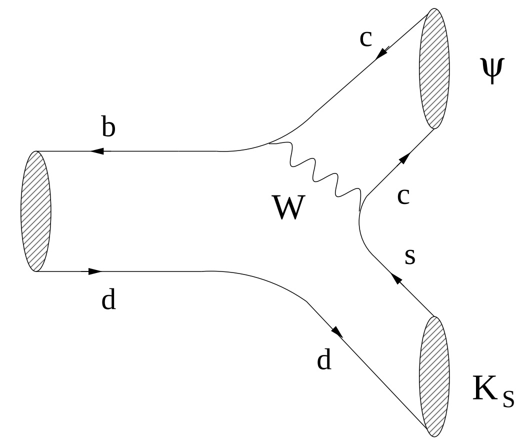
$\Rightarrow$ Not uniquely determined by experiments $\rightarrow \exists$ new physics.

• The angles of the unitarity triangle can be determined by a measurement of time-dependent CP asymmetry.

$$\begin{aligned} a_{CP}(t) &\equiv \frac{\Gamma(\overline{B^0}(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B^0}(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} \\ &= -C_{f_{CP}} \cos(\Delta m t) + S_{f_{CP}} \sin(\Delta m t) \\ C_{f_{CP}} &= -A_{f_{CP}} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}, \quad S_{f_{CP}} = -\frac{2{\rm Im}\lambda_{CP}}{1+|\lambda_{CP}|^2}, \quad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}. \end{aligned}$$

$\sin 2\beta$ *measurement in the SM*

- $B \to J/\psi K_S$
  - $B \to J/\psi K_S$ is dominated by tree-level diagram
  - $\lambda_{J/\psi K_S}$



$$\begin{aligned} \lambda_{J/\psi K_S} &= -\eta_{J/\psi K_S} \left(\frac{q}{p}\right)_B \left(\frac{p}{q}\right)_K \frac{\overline{A}(\overline{B^0} \to J/\psi \overline{K^0})}{A(B^0 \to J/\psi K^0)} \\ &= -\eta_{J/\psi K_S} \frac{V_{td} V_{tb}^*}{V_{td}^* V_{tb}} \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*} \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \\ &= e^{-2i\beta} \end{aligned}$$

- CP asymmetries

$$C_{J/\psi K_S} = 0, \quad S_{J/\psi K_S} = \sin 2\beta.$$

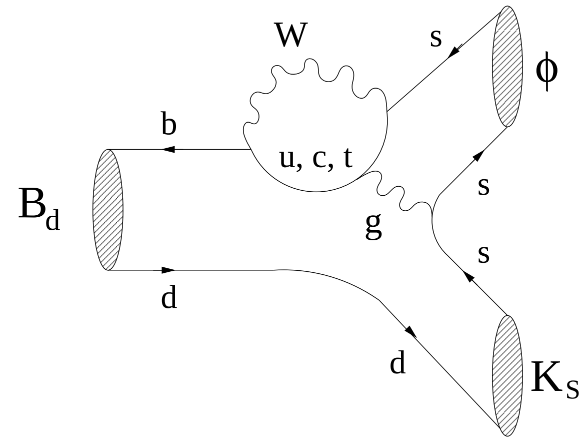
- Experimental results:

$$S_{J/\psi K_S} = 0.736 \pm 0.049(\text{W.A.}) \tag{3}$$

: consistent with other measurements.

$\sin 2\beta$ *measurement in the SM*

- $B \to \phi K_S$
  - $B \to \phi K_S$ is dominated by one-loop diagram $\to$ very sensitive to new physics
  - $\lambda_{\phi K_S}$



$$\begin{aligned}
\lambda_{\phi K_S} &= -\eta_{\phi K_S} \left(\frac{q}{p}\right)_B \left(\frac{p}{q}\right)_K \frac{\overline{A}(\overline{B^0} \to \phi \overline{K^0})}{A(B^0 \to \phi K^0)} \\
&= -\eta_{\phi K_S} \frac{V_{td} V_{tb}^*}{V_{td}^* V_{tb}} \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*} \frac{V_{ts}^* V_{tb}}{V_{ts} V_{tb}^*} \\
&= e^{-2i\beta}
\end{aligned}$$

  - CP asymmetries

$$C_{\phi K_S} = 0, \quad S_{\phi K_S} = \sin 2\beta.$$

- Experimental results (**Belle,BaBar(2003)**)

$$\begin{aligned}
S_{\phi K_S} &= -0.96 \pm 0.50^{+0.09}_{-0.11} (\text{Belle}), \\
S_{\phi K_S} &= 0.45 \pm 0.43 \pm 0.07 (\text{BaBar}), \\
S_{\phi K_S}(\text{WA}) &= -0.15 \pm 0.33.
\end{aligned} \tag{4}$$

Decoupling scenario

- MSSM has 124 free parameters including 45 CPV phases
  - SUSY FCNC problem
  - SUSY CP problem
- We considered a scenario with
  - very heavy sfermions of the first two generations ($\gtrsim 10$ TeV)
  - CKM as the only source of flavor violation

which naturally solves the SUSY FCNC/CP problems (e.g. effective SUSY models **(Cohen,Kaplan,Nelson,1996)**).

- In our scenario,
  - flavor mixing comes only from CKM matrix $\Rightarrow$ no gluino-mediated FCNC **(cf. Moroi (2000), Lunghi and Wyler (2001), Khalil, Kou (2002), Kane, Ko, Wang, Kolda, Park, Wang (2002), Harnik, Larson, Murayama, Pierce (2002), Ciuchini, Franco, Masiero, Silvestrini (2002)), Goto, Okada, Shimizu, Shindou, Tanaka (2003), ...)**
  - new sources of CPV from the phases of μ, M_2 and A_t in chagino/stop mass matrix

$$M_C = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

$$U^* M_C V^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^\pm})$$

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_{\tilde{Q}}^2 + m_t^2 + D_L & m_t(A_t^* - \mu \cot\beta) \\ m_t(A_t - \mu^* \cot\beta) & m_{\tilde{t}}^2 + m_t^2 + D_R \end{pmatrix}$$

$$S M_{\tilde{t}}^2 S^\dagger = \mathrm{diag}(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2)$$

- The predictions of this scenario: **Demir, Masiero, Vives(1999), S.B., Ko (1999), Boz, Pak (2002), Demir, Olive (2002), Akeroyd, Recksiegel, Keum (2001),etc**
  - The SUSY constribution $B - \overline{B}$, $K - \overline{K}$ mixing is small.
  - Large direct CP asymmetries in $B \to X_{s(d)}\gamma$ upto $\pm 16(\pm 40)$ % are possible,

$$A_{CP}^{b\to s(d)\gamma} \equiv \frac{\Gamma(\overline{B} \to X_{s(d)} + \gamma) - \Gamma(B \to X_{s(d)} + \gamma)}{\Gamma(\overline{B} \to X_{s(d)} + \gamma) + \Gamma(B \to X_{s(d)} + \gamma)}$$

$B \to \phi K_S$ *in the decoupling scenario*

- $\Delta B = 1$ effective Hamiltonian

$$\mathcal{H}_{\rm eff}(\Delta B=1) = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \Big[C_1(\mu_b) Q_1^p + C_2(\mu_b) Q_2^p + \sum_{i=3}^{10} C_i(\mu_b) Q_i + C_{7\gamma}(\mu_b) Q_{7\gamma} + C_{8g}(\mu_b) Q_{8g} \Big]$$

where

$$\lambda_q = V_{qs}^* V_{qb}$$

and

$$\begin{aligned}
Q_1^q &= (\overline{q}_\alpha b_\beta)_{V-A} (\overline{b}_\beta q_\alpha)_{V-A}, \\
Q_2^q &= (\overline{q} b)_{V-A} (\overline{b} q)_{V-A} \\
Q_3 &= (\overline{s} b)_{V-A} \sum_{q=u,d,s,c,b} (\overline{q} q)_{V-A}, \\
Q_4 &= (\overline{s}_\alpha b_\beta)_{V-A} \sum_{q=u,d,s,c,b} (\overline{q}_\beta q_\alpha)_{V-A}
\end{aligned}$$

$$\begin{aligned}
Q_5 &= (\overline{s} b)_{V-A} \sum_{q=u,d,s,c,b} (\overline{q} q)_{V+A}, \\
Q_6 &= (\overline{s}_\alpha b_\beta)_{V-A} \sum_{q=u,d,s,c,b} (\overline{q}_\beta q_\alpha)_{V+A} \\
Q_{7\gamma} &= \frac{e}{8\pi^2} m_b \overline{s} \sigma^{\mu\nu} (1+\gamma_5) b F_{\mu\nu}, \\
Q_{8g} &= \frac{g_s}{8\pi^2} m_b \overline{s} \sigma^{\mu\nu} (1+\gamma_5) T^a b G^a_{\mu\nu}.
\end{aligned}$$

$B \to \phi K_S$ *in the decoupling scenario*

- The Wilson coefficients
  - The chargino contributions

$$
\begin{aligned}
C_3^{\tilde{\chi}^\pm} &= C_5^{\tilde{\chi}^\pm} = -\frac{\alpha_s}{12\pi}\sum_{I,k=1}^{2}\frac{m_W^2}{m_{\tilde{\chi}_I^\pm}^2}(\chi_I^L)_{k2}^*(\chi_I^L)_{k3}P_2(x_{Ik}),\\
C_4^{\tilde{\chi}^\pm} &= C_6^{\tilde{\chi}^\pm} = -3C_3^{\tilde{\chi}^\pm}\\
C_{7\gamma}^{\tilde{\chi}^\pm} &= \sum_{I=1}^{2}\sum_{k=1}^{2}\frac{m_W^2}{m_{\tilde{t}_k}^2}\Bigg\{\left(\chi_I^{d_L}\right)_{k2}^*\left(\chi_I^{d_L}\right)_{k3}\left(I_1(x_{Ik})+\frac{2}{3}J_1(x_{Ik})\right)\\
&\quad+\left(\chi_I^{d_L}\right)_{k2}^*\left(\chi_I^{d_R}\right)_{k3}\frac{m_{\tilde{\chi}_I^-}}{m_b}\left(I_2(x_{Ik})+\frac{2}{3}J_2(x_{Ik})\right)\Bigg\},\\
C_{8g}^{\tilde{\chi}^\pm} &= \sum_{I=1}^{2}\sum_{k=1}^{2}\frac{m_W^2}{m_{\tilde{t}_k}^2}\Bigg\{\left(\chi_I^{d_L}\right)_{k2}^*\left(\chi_I^{d_L}\right)_{k3}J_1(x_{Ik})+\left(\chi_I^{d_L}\right)_{k2}^*\left(\chi_I^{d_R}\right)_{k3}\frac{m_{\tilde{\chi}_I^-}}{m_b}J_2(x_{Ik})\Bigg\},
\end{aligned}
$$

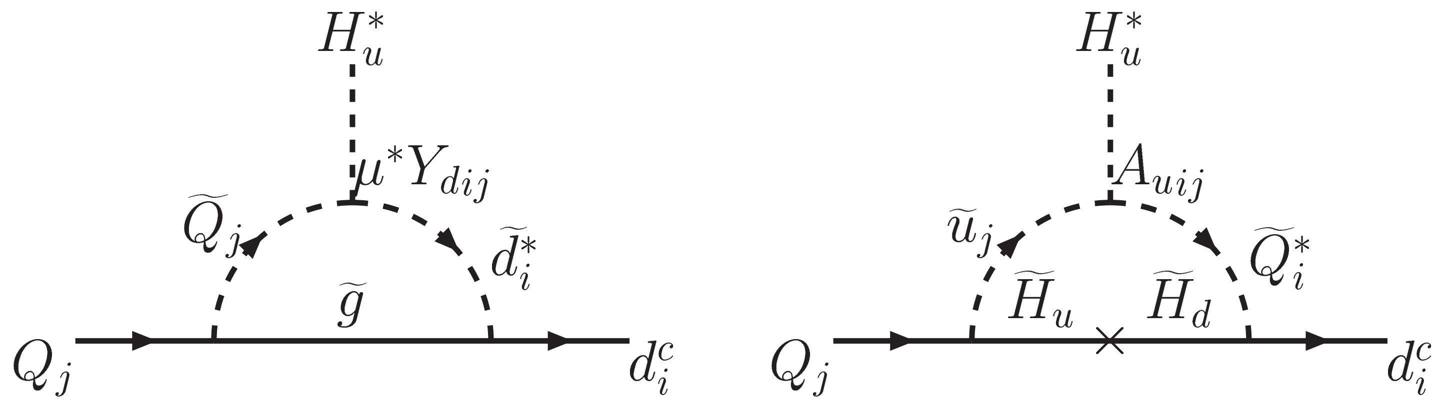
where $x_{tH} = m_t^2/m_{H^\pm}^2$, $x_{Ik} = m_{\tilde{\chi}_I^\pm}^2/m_{\tilde{t}_k}^2$ and

$$
\begin{aligned}
(\chi_I^L)_{kq} &= -V_{I1}^*S_{\tilde{t}_k\tilde{t}_L}+V_{I2}^*S_{\tilde{t}_k\tilde{t}_R}\frac{m_t}{\sqrt{2}m_W\sin\beta},\\
(\chi_I^R)_{kq} &= U_{I2}S_{\tilde{t}_k\tilde{t}_L}\frac{m_q}{\sqrt{2}m_W\cos\beta}.
\end{aligned}
$$

- We have decoupled the charged Higgs contributions ($m_{H^\pm} = 1$ TeV) to evade the EDM constraints from Barr-Zee type two-loop diagrams which become important at large $\tan\beta$ **Chang,Keung,Piliaftsis (1999)**
- $C_{3,4,5,6}^{\widetilde{\chi}^\pm} \ll C_{3,4,5,6}^{\rm SM}$
- The contribution of the chirality-flipped operators are suppressed by m_s/m_b
- C_{8g} can be enhanced by the chargino contributions. $\rightarrow$ Large phase in the ratio of decay amplitudes, $\overline{A}/A$.

$B \to \phi K_S$ *in the decoupling scenario*

- SUSY QCD/EW corrections become very important at large $\tan\beta$ **Hall, Rattazzi, Sarid (1994), Blazek, Raby, Pokorski (1995)**



$$m_b = \frac{\overline{m}_b}{1+\widetilde{\epsilon}_3 \tan\beta}, \qquad V_{JI} = V_{JI}^{\rm eff}\left[\frac{1+\widetilde{\epsilon}_3\tan\beta}{1+\epsilon_0\tan\beta}\right]$$

where $\widetilde{\epsilon}_3 \approx \epsilon_0 + \epsilon_Y y_t^2$ and $(JI) = (13)(23)(31)(32)$. $\overline{m}_b$, $V_{JI}^{\rm eff}$ are b-quark mass and CKM elements measured at experiments, respectively.

$$\begin{aligned}
\epsilon_0 &= \frac{2\alpha_s}{3\pi}{\rm Re}\left(\frac{\mu^*}{m_{\widetilde{g}}}\right) j(y_{\widetilde{b}\widetilde{g}}, y_{\widetilde{Q}\widetilde{g}}), \\
\epsilon_Y &= \frac{1}{16\pi^2}{\rm Re}\left(\frac{A_t}{\mu}\right) j(y_{\widetilde{Q}\mu}, y_{\widetilde{t}\mu}),
\end{aligned}$$

with $j(x) = x\log x/(x-1)$.

Numerical results

- The hadronic matrix elements were calculated in the QCD factorization **Beneke, Buchalla, Neubert, Sachrajda (2001)**

$$\overline{A} \propto \sum_{p=u,c} V_{ps}^* V_{pb}(a_3 + a_4^p + a_5) \approx -3.9 \times 10^{-4}(3.7e^{0.21i} + 4.5C_{8g}).$$

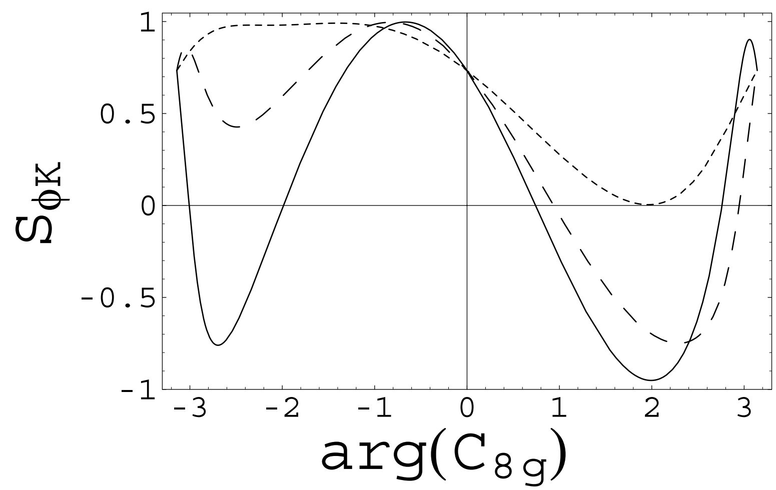


Figure 1: $S_{\phi K}$ as a function of $\arg(C_{8g})$ for $|C_{8g}|$ =0.33 (short dashed line), 0.65 (long dashed line) and 1.0 (solid line). ($C_{8g}^{\rm SM}(m_b) = -0.147$)

- Constraints:

$$2 \times 10^{-4} < B(B \to X_s\gamma) < 4.5 \times 10^{-4}$$

$m_h > 114.3$GeV, at 95% CL

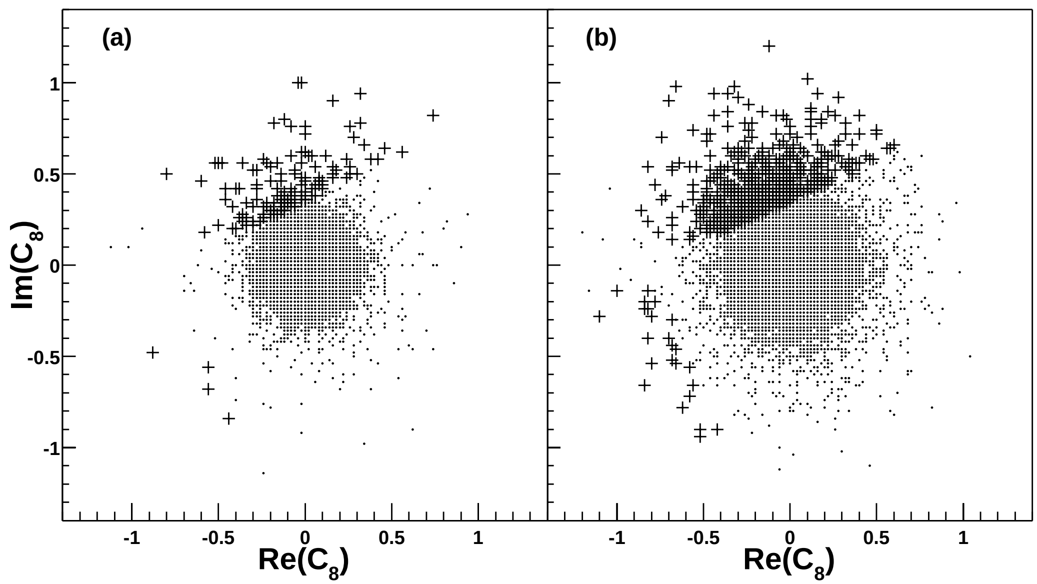
$m_{\tilde{\chi}_1^\pm}, m_{\tilde{t}_1} \gtrsim 100$GeV

Numerical results

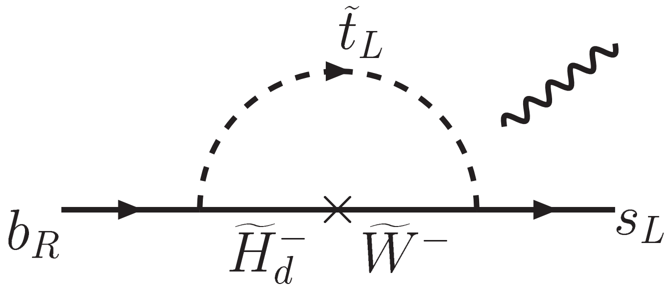
- We scanned in the range

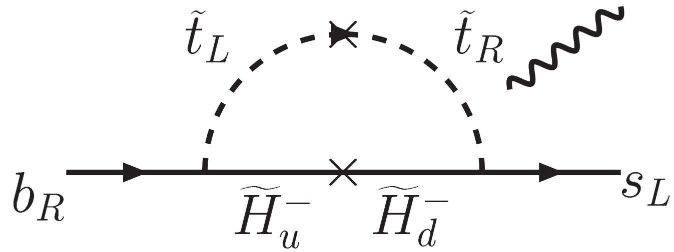
$$0 < m_{\tilde{t}} < 1 \text{ TeV}, \quad 0 < |\mu| < 1 \text{ TeV},$$
$$0 < |A_t| < 2 \text{ TeV}, \quad 0 < |M_2| < 1 \text{ TeV},$$
$$-\pi < \arg(\mu), \arg(A_t), \arg(M_2) < \pi,$$

while we fixed $\delta_{\rm CKM} = \pi/3$, $\tan\beta = 35(60)$, $m_{H^\pm} = 1$ TeV, $m_{\tilde{Q}} = 0.5$ TeV, $m_{\tilde{g}} = 1$ TeV, and $m_{\tilde{b}_R} = 0.5$ TeV.



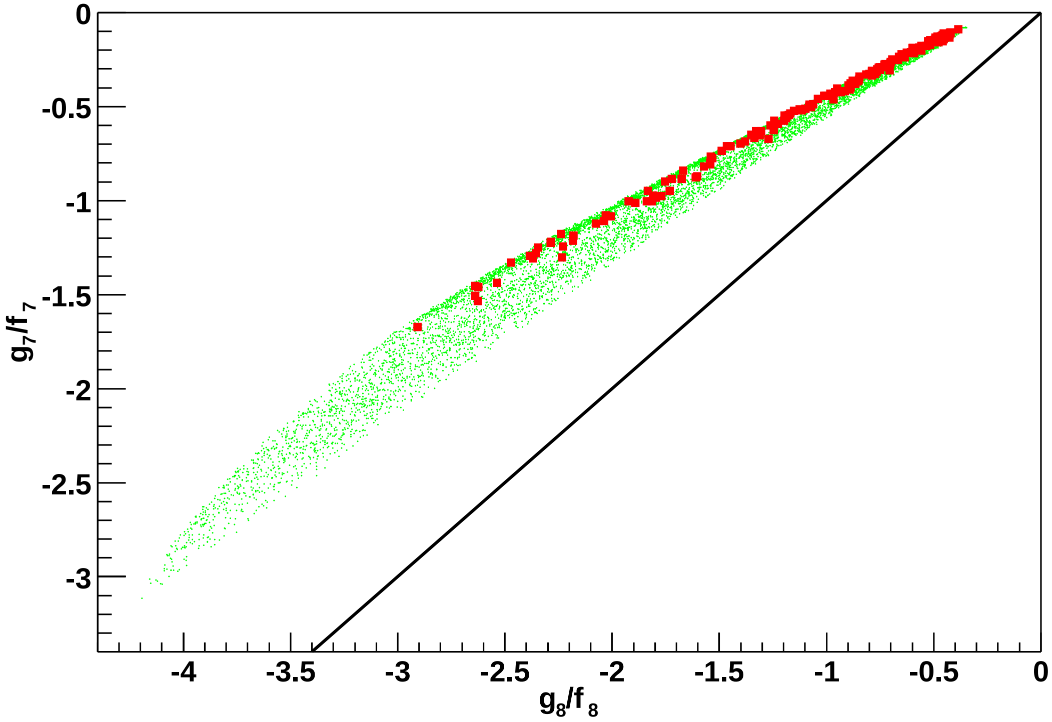
Numerical results



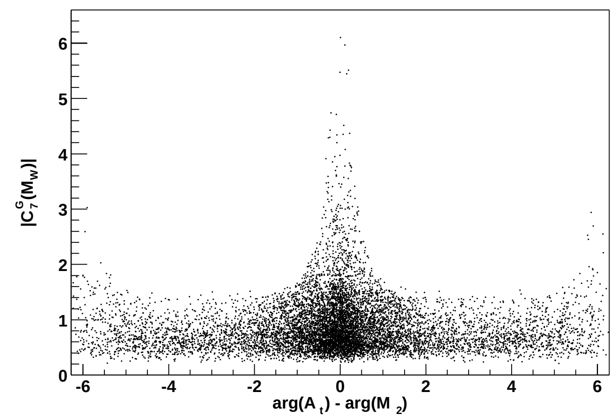


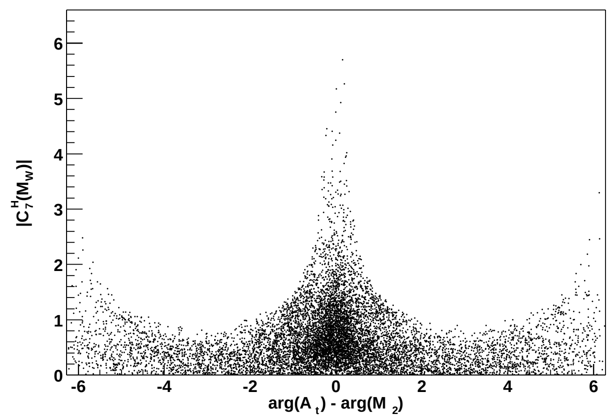
$$C^G_{7\gamma,8g} = -\frac{m_W^2 M_2 \mu \tan\beta}{m^4_{\tilde{t}_L}(1+\widetilde{\epsilon}_3 \tan\beta)} f_{7,8}\left(\frac{|M_2|^2}{m^2_{\tilde{t}_L}}, \frac{|\mu|^2}{m^2_{\tilde{t}_L}}\right) \tag{5}$$

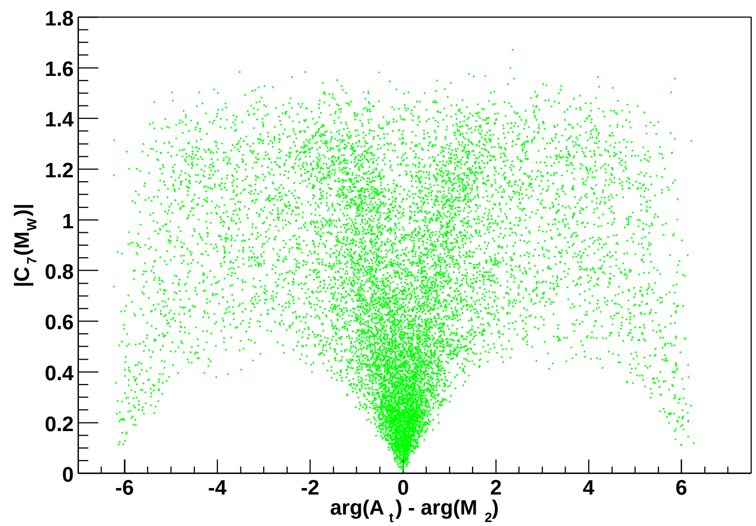
$$C^H_{7\gamma,8g} = -\frac{1}{2}\frac{m_t^2 A_t \mu \tan\beta}{m^2_{\tilde{t}_L} m^2_{\tilde{t}_R}(1+\widetilde{\epsilon}_3 \tan\beta)} g_{7,8}\left(\frac{|\mu|^2}{m^2_{\tilde{t}_L}}, \frac{|\mu|^2}{m^2_{\tilde{t}_R}}\right) \tag{6}$$


0
-0.5
-1
-1.5
-2
-2.5
-3
g_7/f_7
-4
-3.5
-3
-2.5
-2
-1.5
-1
-0.5
0
g_8/f_8

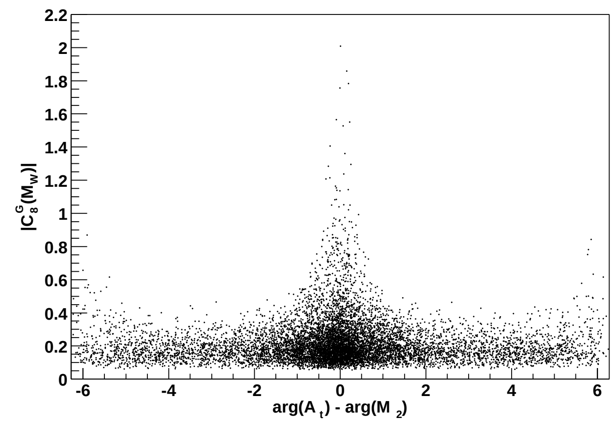
Numerical results

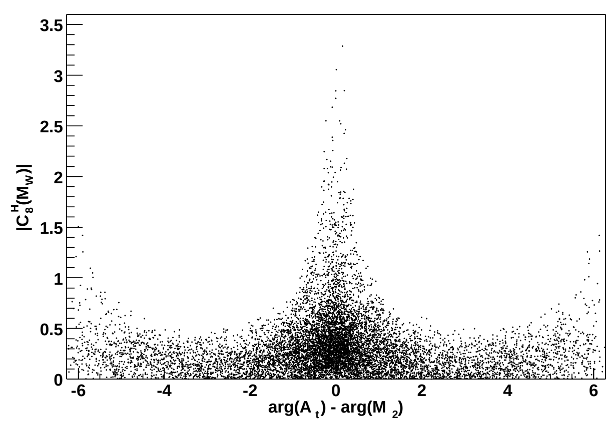


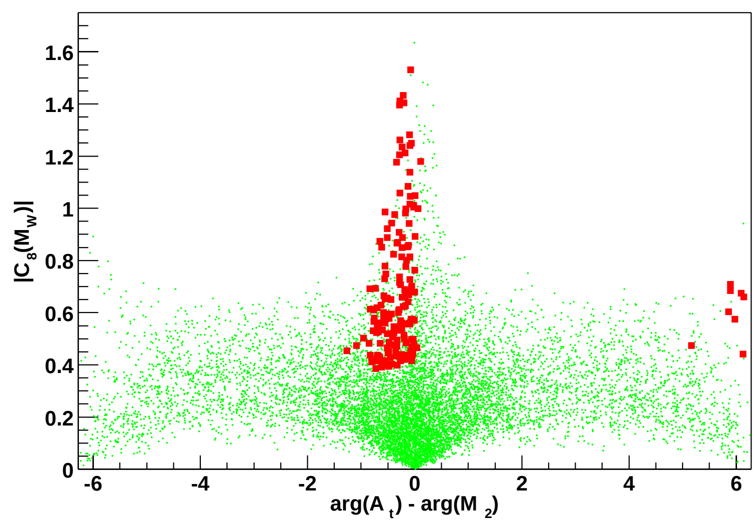




Numerical results







Conclusions

- Large deviation from the SM in $S_{\phi K}$ is possible in the MSSM without new flavor structure if $\tan\beta$ is large. SUSY QCD/EW corrections play important role.
- Our scenario may be distinguished from others by the following predictions
  - $A_{CP}(B \to X_s\gamma)$ can be large
  - Since $C'_{7\gamma}$ is small, the mixing induced CP asymmetry is small.

$$\frac{\Gamma(\overline{B}(t) \to M^0 + \gamma) - \Gamma(B(t) \to M^0 + \gamma)}{\Gamma(\overline{B}(t) \to M^0 + \gamma) + \Gamma(B(t) \to M^0 + \gamma)} = \xi A_t \sin \Delta m_d t$$

  with

$$A_t = \frac{2\mathrm{Im}(C_7 C_7' e^{-i\phi_M})}{|C_7|^2 + |C_7'|^2}$$

  - Δm_s is close to the SM prediction in the most region of parameter space