Squark flavor mixing and CP violation of neutral B mesons at LHCb

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Collaborated with A.Hayakawa, Y.Shimizu, M.Tanimoto (Niigata Univ.)

A. Hayakawa, Y. Shimizu, M. Tanimoto and K. Yamamoto,PLB **710**446(2012)
Y. Shimizu, M. Tanimoto and K. Yamamoto, PTP Vol.128 No.2(2012)

LHCb has reported CP asymmetries of Bs meson.

e.g.

- Time dependent CP asymmetry S_f of $B_s \to J/\psi\phi$ and $B_s \to J/\psi f_0(980)$ decays (2011)

$$\phi_s(\mathrm{exp}) = 0.07 \pm 0.17 \pm 0.06 \quad \mathrm{rad}$$

On the other hand, SUSY particles have not been detected, and lower-bounds of these masses have pushed up.

Few years ago		Now
$m_{\tilde{g}}, m_{\tilde{q}} \simeq$ O(100)GeV	$\longrightarrow$	$m_{\tilde{g}}, m_{\tilde{q}} \geq$ 1 TeV

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$$m_{\tilde{g}}, m_{\tilde{q}} \simeq \mathrm{O(100)GeV} \longrightarrow m_{\tilde{g}}, m_{\tilde{q}} \gtrsim 1\ \mathrm{TeV}$$

Can we find effects of SUSY in non-leptonic B decays ?

Plan

1. Effect of SUSY on B physics
2. Recent experimental result
3. Numerical analysis
4. Conclusion

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SUSY

Framework which we use in this work.

Universality (degeneracy)

High energy

Quantum Corrections etc.

- Masses are degenerated.

$$\mathbf{m_Q^2} = m_Q^2 \mathbf{1} \quad \mathbf{m_U^2} = m_U^2 \mathbf{1} \quad \mathbf{m_D^2} = m_D^2 \mathbf{1} \quad \mathbf{m_E^2} = m_E^2 \mathbf{1} \quad \mathbf{m_L^2} = m_L^2 \mathbf{1}$$

- Coupling constants of trilinear scalar coupling are proportional to Yukawa couplings (A-term) .

$$\mathbf{A_U} = \mathcal{A}_{U0} \mathbf{y_U} \quad \mathbf{A_D} = \mathcal{A}_{D0} \mathbf{y_D} \quad \mathbf{A_E} = \mathcal{A}_{E0} \mathbf{y_E}$$

Low energy

Off diagonal elements remain in the basis of diagonal quark mass matrix. (Super-CKM basis)

Size of Mixing of flavor $\left(\delta_d\right)_{ij}$ **Mass insertion parameter** $\left[\delta_d << 1\right]$

SUSY

The down-type squark mass matrix in the Super-CKM basis

$$\begin{pmatrix} M^2_{\tilde{d}_{LL}} & M^2_{\tilde{d}_{LR}} \\ M^2_{\tilde{d}_{RL}} & M^2_{\tilde{d}_{RR}} \end{pmatrix} = \mathrm{diag}\left(m^2_{\tilde{q}}\right) + m^2_{\tilde{q}} \begin{pmatrix} \delta_d^{LL} & \delta_d^{LR} \\ \delta_d^{RL} & \delta_d^{RR} \end{pmatrix}$$

$\tilde{s}_L \to \tilde{d}_L$ $\qquad$ $\tilde{b}_L \to \tilde{d}_L$

$$M^2_{\tilde{d}LL} = m^2_{\tilde{q}} \begin{pmatrix} 1 + \left(\delta_d^{LL}\right)_{11} & \left(\delta_d^{LL}\right)_{12} & \left(\delta_d^{LL}\right)_{13} \\ \left(\delta_d^{LL}\right)^*_{12} & 1 + \left(\delta_d^{LL}\right)_{22} & \left(\delta_d^{LL}\right)_{23} \\ \left(\delta_d^{LL}\right)^*_{13} & \left(\delta_d^{LL}\right)^*_{23} & 1 + \left(\delta_d^{LL}\right)_{33} \end{pmatrix}$$

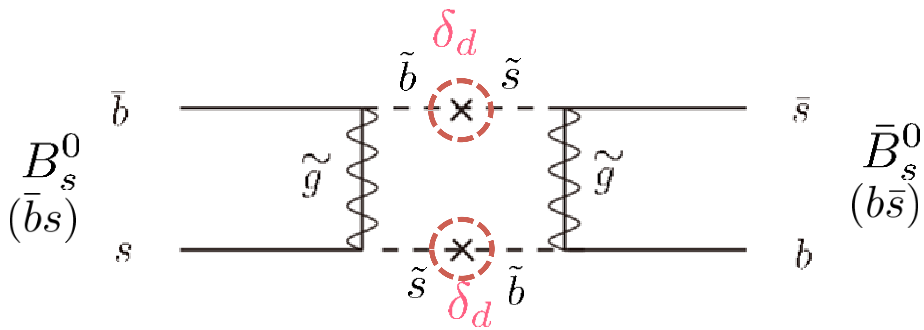
$\tilde{b}_L \to \tilde{s}_L$

SUSY

$$M^2_{\tilde{d}_{RR}} = m^2_{\tilde{q}} \begin{pmatrix} 1 + (\delta_d^{RR})_{11} & (\delta_d^{RR})_{12} & (\delta_d^{RR})_{13} \\ (\delta_d^{RR})^*_{12} & 1 + (\delta_d^{RR})_{22} & (\delta_d^{RR})_{23} \\ (\delta_d^{RR})^*_{13} & (\delta_d^{RR})^*_{23} & 1 + (\delta_d^{RR})_{33} \end{pmatrix}$$

$$M^2_{\tilde{d}_{LR}} = (M^2_{\tilde{d}_{RL}})^\dagger = m^2_{\tilde{q}} \begin{pmatrix} (\delta_d^{LR})_{11} & (\delta_d^{LR})_{12} & (\delta_d^{LR})_{13} \\ (\delta_d^{LR})_{21} & (\delta_d^{LR})_{22} & (\delta_d^{LR})_{23} \\ (\delta_d^{LR})_{31} & (\delta_d^{LR})_{32} & (\delta_d^{LR})_{33} \end{pmatrix}$$

Squark Flavor mixing



Gluino-squark box diagram

- The SUSY contribution to the dispersive part of the $B_s - \bar{B}_s$ mixing

$$
\begin{aligned}
M_{12}^{M,\mathrm{SUSY}} = -\frac{\alpha_S^2}{216 m_{\tilde{q}}^2}\frac{2}{3}M_M f_M^2 \Bigg[& \left\{(\delta_d^{LL})_{ij}^2 + (\delta_d^{RR})_{ij}^2\right\}\left\{24 x f_6(x) + 66 \tilde{f}_6(x)\right\} \\
& + (\delta_d^{LL})_{ij}(\delta_d^{RR})_{ij}\left(\left\{384\left(\frac{M_M}{m_j+m_i}\right)^2 + 72\right\} x f_6(x) + \left\{-24\left(\frac{M_M}{m_j+m_i}\right)^2 + 36\right\}\tilde{f}_6(x)\right) \\
& + \left\{(\delta_d^{LR})_{ij}^2 + (\delta_d^{RL})_{ij}^2\right\}\left\{-132\left(\frac{M_M}{m_j+m_i}\right)^2\right\} x f_6(x) \\
& + (\delta_d^{LR})_{ij}(\delta_d^{RL})_{ij}\left\{-144\left(\frac{M_M}{m_j+m_i}\right)^2 - 84\right\}\tilde{f}_6(x)\Bigg]
\end{aligned}
$$

$$
\begin{aligned}
f_6(x) &= \frac{6(1+3x)\log x + x^3 - 9x^2 - 9x + 17}{6(x-1)^5} \\
\tilde{f}_6(x) &= \frac{6x(1+x)\log x - x^3 - 9x^2 + 9x + 1}{3(x-1)^5} \\
x &= \frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}
\end{aligned}
$$

F. Gabbiani, et all Nucl. Phys. B **477** (1996)
W. Altmannshofer, et all Nucl. Phys. B **830** (2010)

ΔB=1 Effective Theory

Effective Hamiltonian

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \left[\sum_{q'=u,c} V_{q'b} V^*_{q's} \sum_{i=1,2} C_i O_i^{(q')} - V_{tb} V^*_{ts} \sum_{i=3-6,7\gamma,8G} \left(C_i O_i + \widetilde{C}_i \widetilde{O}_i \right) \right]$$

Local operators (dim.6)

$$O_1^{(q')} = (\bar{s}_\alpha \gamma_\mu P_L q'_\beta)(\bar{q}'_\beta \gamma^\mu P_L b_\alpha), \qquad O_2^{(q')} = (\bar{s}_\alpha \gamma_\mu P_L q'_\alpha)(\bar{q}'_\beta \gamma^\mu P_L b_\beta),$$

$$O_3 = (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_q (\bar{q}_\beta \gamma^\mu P_L q_\beta), \quad O_4 = (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_q (\bar{q}_\beta \gamma^\mu P_L q_\alpha),$$

$$O_5 = (\bar{s}_\alpha \gamma_\mu P_L b_\alpha) \sum_q (\bar{q}_\beta \gamma^\mu P_R q_\beta), \quad O_6 = (\bar{s}_\alpha \gamma_\mu P_L b_\beta) \sum_q (\bar{q}_\beta \gamma^\mu P_R q_\alpha),$$

$$O_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R b_\alpha F_{\mu\nu}, \qquad O_{8G} = \frac{g_s}{16\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} P_R T^a_{\alpha\beta} b_\beta G^a_{\mu\nu},$$

$$P_R = (1+\gamma_5)/2, \; P_L = (1-\gamma_5)/2$$

ΔB=1 Effective Theory

Effective Hamiltonian

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \left[\sum_{q'=u,c} V_{q'b} V^*_{q's} \sum_{i=1,2} C_i O_i^{(q')} - V_{tb} V^*_{ts} \sum_{i=3-6,7\gamma,8G} \left(C_i O_i + \widetilde{C}_i \widetilde{O}_i \right) \right]$$

Wilson coefficients

- It has two contributions from SM and NP.

$$C_i = C_i(SM) + C_i(NP)$$

- The terms with tilde are obtained by flipping chiralities.

$$\tilde{C}^{\tilde{g}}_{8G} \ : \ C^{\tilde{g}}_{8G}(L \leftrightarrow R)$$

ΔB=1 Effective Theory

Wilson coefficients (gluino-squark-quark couplings)

$$C_3^{\tilde g} \simeq \frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde q}^2}(\delta_d^{LL})_{23}\left[-\frac{1}{9}B_1(x)-\frac{5}{9}B_2(x)-\frac{1}{18}P_1(x)-\frac{1}{2}P_2(x)\right],$$

$$C_4^{\tilde g} \simeq \frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde q}^2}(\delta_d^{LL})_{23}\left[-\frac{7}{3}B_1(x)+\frac{1}{3}B_2(x)+\frac{1}{6}P_1(x)+\frac{3}{2}P_2(x)\right],$$

$$C_5^{\tilde g} \simeq \frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde q}^2}(\delta_d^{LL})_{23}\left[\frac{10}{9}B_1(x)+\frac{1}{18}B_2(x)-\frac{1}{18}P_1(x)-\frac{1}{2}P_2(x)\right],$$

$$C_6^{\tilde g} \simeq \frac{\sqrt{2}\alpha_s^2}{4G_F V_{tb}V_{ts}^* m_{\tilde q}^2}(\delta_d^{LL})_{23}\left[-\frac{2}{3}B_1(x)+\frac{7}{6}B_2(x)+\frac{1}{6}P_1(x)+\frac{3}{2}P_2(x)\right],$$

$$C_{7\gamma}^{\tilde g} \simeq -\frac{\sqrt{2}\alpha_s\pi}{6G_F V_{tb}V_{ts}^* m_{\tilde q}^2}\left[(\delta_d^{LL})_{23}\left(\frac{8}{3}M_3(x)-\mu\tan\beta\frac{m_{\tilde g}}{m_{\tilde q}^2}\frac{8}{3}M_a(x)\right)+(\delta_d^{LR})_{23}\frac{m_{\tilde g}}{m_b}\frac{8}{3}M_1(x)\right]$$

$$C_{8G}^{\tilde g} \simeq -\frac{\sqrt{2}\alpha_s\pi}{2G_F V_{tb}V_{ts}^* m_{\tilde q}^2}\left[(\delta_d^{LL})_{23}\left\{\left(\frac{1}{3}M_3(x)+3M_4(x)\right)\right.\right.$$
$$\left.\left.-\mu\tan\beta\frac{m_{\tilde g}}{m_{\tilde q}^2}\left(\frac{1}{3}M_a(x)+3M_b(x)\right)\right\}+(\delta_d^{LR})_{23}\frac{m_{\tilde g}}{m_b}\left(\frac{1}{3}M_1(x)+3M_2(x)\right)\right].$$

$\tan\beta = v_u / v_d$: the ratio of the two Higgs VEVs

Effect of SUSY on B physics

We predict

- Time dependent CP asymmetry S_f
  of $B_d \to \phi K_S, \eta^{'} K^0$ decay

Constraint

- Branching ratio of b→sγ decay BR(b→sγ)
- Direct CP violation of b→sγ $A_{cp}^{b\to s\gamma}$
- chromo electric dipole moment of strange-quark (CEDM) d_s^c

Time dependent CP asymmetry Sf

$$\mathcal{A} = \frac{\Gamma\left(B^0(t) \to f\right) - \Gamma\left(\bar{B}^0(t) \to f\right)}{\Gamma\left(B^0(t) \to f\right) + \Gamma\left(\bar{B}^0(t) \to f\right)}$$

$$= \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \cos\left(\Delta m_B t\right) + \underbrace{\frac{2\mathrm{Im}\lambda}{|\lambda|^2 + 1}}_{\mathcal{S}_f} \sin\left(\Delta m_B t\right)$$

$$\lambda_f = \frac{q}{p}\bar{\rho}\,, \qquad \frac{q}{p} = \sqrt{\frac{M_{12}^{q*} - \frac{i}{2}\Gamma_{12}^{*}}{M_{12}^{q} - \frac{i}{2}\Gamma_{12}}}, \qquad \bar{\rho} \equiv \frac{\bar{A}(\bar{B}_q^0 \to f)}{A(B_q^0 \to f)}$$

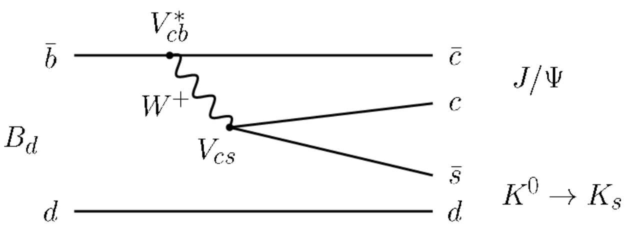
Mass eigenstates

$$\begin{cases} |P_1\rangle = p|P^0\rangle - q|\bar{P}^0\rangle \\ |P_2\rangle = p|P^0\rangle + q|\bar{P}^0\rangle \end{cases}$$

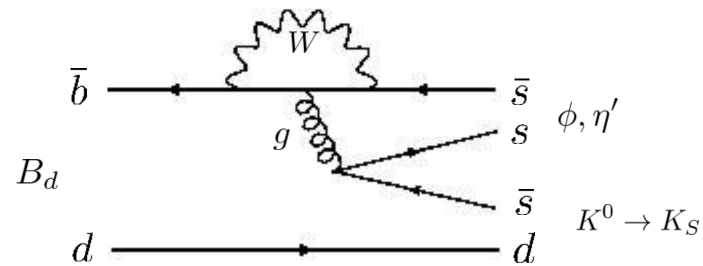
Time dependent CP asymmetry Sf

Let's discuss about CP asymmetries of B_d meson .

$B_d \to J/\psi K_S$



$B_d \to \phi K_S, \eta' K^0$



- **SM prediction**

  There is only one CP violation phase.

  Time dependent CP asymmetries $\quad S_{J/\psi K_S} = S_{\phi K_S, \eta' K_S}$

- **Experimental results**

$$S_{J/\psi K_S} = 0.658 \pm 0.024 \quad \overset{?}{\neq} \quad \left(\begin{array}{l} S_{\phi K_S} = 0.39 \pm 0.17 \\ S_{\eta' K^0} = 0.60 \pm 0.07 \end{array} \right.$$

[PDG (2011)]

There may be deviation between SM prediction and experimental results !

Time dependent CP asymmetry S_f

Parameterization of New Physics(NP)

- The dispersive part of the B_q^0–$\overline{B}_q^0$ mixing

$$M_{12}^q = (M_{12}^q)^{SM} + (M_{12}^q)^{NP}$$
$$= (M_{12}^q)^{SM}\left(1 + \frac{(M_{12}^q)^{NP}}{(M_{12}^q)^{SM}}\right)$$
$$= (M_{12}^q)^{SM}\left(1 + h_q e^{2i\sigma_q}\right)$$

$(q = d, s)$

Hamiltonian inducing mixing

$$H = M - \frac{i}{2}\Gamma$$

dispersive part absorptive part

h_q : Magnitude of NP normalized to SM

σ_q : NP relative phase

- The absorptive part of the B_q^0–$\overline{B}_q^0$ mixing

$$\Gamma_{12}^q = (\Gamma_{12}^q)^{SM}$$

(We neglect NP at tree level decay in our work)

Time dependent CP asymmetry S_f

$$S_f = \frac{2\mathrm{Im}(\lambda_f)}{1 + |\lambda_f|^2} \qquad \left(\lambda = \frac{q}{p} \frac{\bar{A}^{SM} + \bar{A}^{SUSY}}{A^{SM} + A^{SUSY}} \right)$$

mixing part

amplitude part

- **mixing part**

$$\frac{q}{p} \simeq \sqrt{\frac{M_{12}^*}{M_{12}}} = \sqrt{\frac{M_{12}^{SM\,*}}{M_{12}^{SM}}} \sqrt{\frac{1 + h_d e^{-2i\sigma_d}}{1 + h_d e^{2i\sigma_d}}}$$

This part is NP contribution.

Mass eigenstates
$$\begin{cases} |P_1\rangle = p|P^0\rangle - q|\bar{P}^0\rangle \\ |P_2\rangle = p|P^0\rangle + q|\bar{P}^0\rangle \end{cases}$$

Time dependent CP asymmetry Sf

$$S_f = \frac{2\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2} \qquad \left(\lambda = \frac{q}{p} \frac{\bar{A}^{SM} + \bar{A}^{SUSY}}{A^{SM} + A^{SUSY}} \right)$$

mixing part

amplitude part

- amplitude part

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \left[\sum_{q'=u,c} V_{q'b} V^*_{q's} \sum_{i=1,2} C_i O_i^{(q')} - V_{tb} V^*_{ts} \sum_{i=3\sim 6,7\gamma,8G} \left(C_i O_i + \tilde{C}_i \tilde{O}_i \right) \right]$$

These terms include NP.

Dominant SUSY contribution comes from gluon penguin, $C_{8G}^{\tilde{g}}$ and $\tilde{C}_{8G}^{\tilde{g}}$.

$$A^{SUSY}(B_d \to \phi K_s) \propto C_{8G}^{\tilde{g}}(m_b) + \tilde{C}_{8G}^{\tilde{g}}(m_b)$$
$$A^{SUSY}(B_d \to \eta' K_s) \propto C_{8G}^{\tilde{g}}(m_b) - \tilde{C}_{8G}^{\tilde{g}}(m_b)$$

(M. Endo, S. Mishima and M. Yamaguchi, PLB **609** (2005))

$$\langle f|O_i|B_d\rangle = -(-1)^{P_f} \langle f|\tilde{O}_i|B_d\rangle$$

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Constraint

- Branching ratio of b→sγ decay BR(b→sγ)
- Direct CP violation of b→sγ $A_{cp}^{b\to s\gamma}$
- chromo electric dipole moment of strange-quark (CEDM) d_s^c

Branching ratio of b→sγ decay : BR(b→sγ)

$$\boxed{\frac{\mathrm{BR}(b \to X_s \gamma)}{\mathrm{BR}(b \to X_c e \bar{\nu}_e)} = \frac{|V_{ts}^* V_{tb}|^2}{|V_{cb}|^2} \frac{6\alpha}{\pi f(z)} |C_{7\gamma}^{eff}|^2}$$

[A. J. Buras, hep-ph/9806471]

$$\left[\alpha = \frac{e^2}{4\pi} \ , z = \frac{m_c^2}{m_b^2} , \ f(z) = 1 - 8z + 8z^3 - z^4 - 12z^2 \ln z \ , \ \mathrm{BR}(b \to X_c e \bar{\nu}_e) \simeq 0.1 \right]$$

$$|C_{7\gamma}^{eff}|^2 = |C_{7\gamma}^{SM} + C_{7\gamma}^{\tilde{g}}|^2 + |\tilde{C}_{7\gamma}^{\tilde{g}}|^2$$

experimental results : $\mathrm{BR}(b \to s\gamma) = (3.60 \pm 0.23) \times 10^{-4}$ [PDG (2011)]

SM prediction: $\mathrm{BR}(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ [M. Misiak *et al.*, PRL**98** (2007)]

Direct CP violation of b→sγ : $A_{CP}^{b\to s\gamma}$

$$A_{\rm CP}^{b\to s\gamma} = \left.\frac{\Gamma(\bar{B}\to X_s\gamma)-\Gamma(B\to X_{\bar{s}}\gamma)}{\Gamma(\bar{B}\to X_s\gamma)+\Gamma(B\to X_{\bar{s}}\gamma)}\right|_{E_\gamma>(1-\delta)E_\gamma^{\rm max}}$$

Dominant term in SM

$$= \frac{\alpha_s(m_b)}{|C_{7\gamma}|^2}\left[\frac{40}{81}{\rm Im}[C_2C_{7\gamma}^*] - \frac{8z}{9}[v(z)+b(z,\delta)]{\rm Im}\left[\left(1+\frac{V_{us}^*V_{ub}}{V_{ts}^*V_{tb}}\right)C_2C_{7\gamma}^*\right]\right.$$
$$\left. -\frac{4}{9}{\rm Im}[C_{8G}C_{7\gamma}^*] + \frac{8z}{27}b(z,\delta){\rm Im}\left[\left(1+\frac{V_{us}^*V_{ub}}{V_{ts}^*V_{tb}}\right)C_2C_{8G}^*\right]\right]$$

(A. L. Kagan and M. Neubert PRD **58** 094012(1998))

Experimental results : $A_{\rm CP}^{b\to s\gamma} = -0.008 \pm 0.029$ (PDG)

SM prediction : $A_{\rm CP}^{b\to s\gamma} \simeq 0.005$

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Non-leptonic CP asymmetry of B mesons @ LHCb

[R. Aaij *et all* arXiv:1112.3056 [hep-ex]]

- LHCb has reported CP asymmetries of Bs meson. (2011)

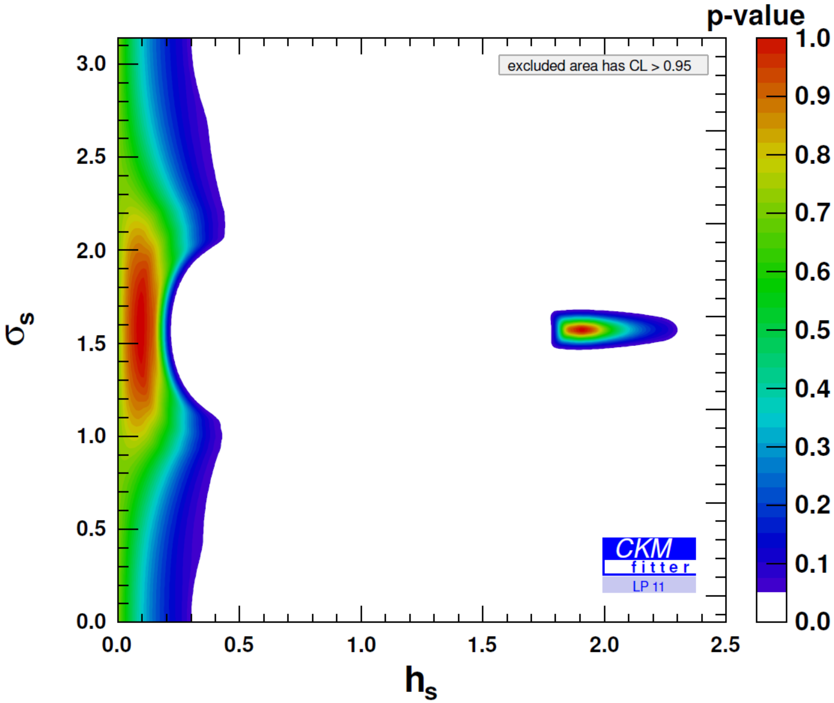
$$B_s^0 \to J/\psi\phi \text{ \& } B_s^0 \to J/\psi f_0(980)$$

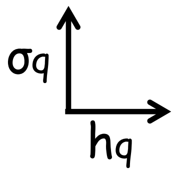
$$\lambda_{J/\psi\phi} = e^{-i\phi_s}, \qquad \phi_s = -2\beta_s + \arg(1 + h_s e^{2i\sigma_s})$$

$$h_q \mathrm{e}^{2i\sigma_q} = \frac{M_{12}^{q,SUSY}}{M_{12}^{q,SM}}$$

Non-leptonic CP asymmetry of B mesons @ LHCb

[R. Aaij *et all* arXiv:1112.3056 [hep-ex]]





(CKMfitter(2011))

Experimental result   Moriond(2012)

$$\phi_s(\exp) = 0.07 \pm 0.17 \pm 0.06 \quad \text{rad}$$

Consistent with SM...

SM prediction

$$\phi_s(\mathrm{SM}) = -0.0363 \pm 0.0017 \quad \text{rad}$$

but error is still large !
so we can expect
New Physics .

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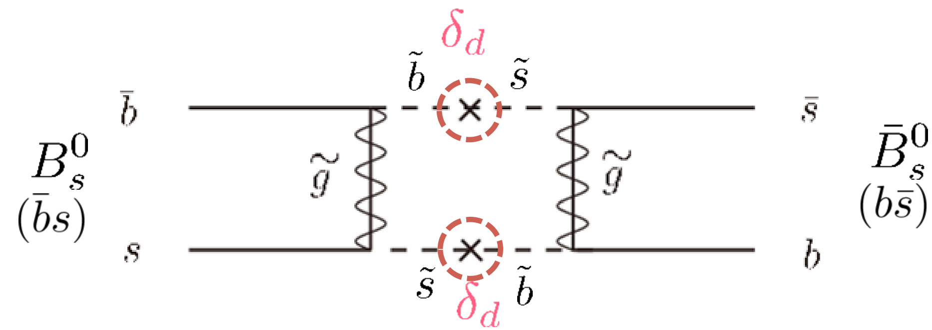
Squark Flavor mixing



Gluino-squark box diagram

- The SUSY contribution to the dispersive part of the $B_s - \bar{B}_s$ mixing

$$M_{12}^{B_s,\mathrm{SUSY}} = A_1^{B_s}\Big[\underset{-1}{\underline{A_2^{B_s}}}\underset{:}{\{(\delta_d^{LL})_{23}^2 + (\delta_d^{RR})_{23}^2\}} + \underset{30}{\underline{A_3^{B_s}}}\underset{:}{(\delta_d^{LL})_{23}(\delta_d^{RR})_{23}}$$

$$+ \underset{-10}{\underline{A_4^{B_s}}}\underset{:}{\{(\delta_d^{LR})_{23}^2 + (\delta_d^{RL})_{23}^2\}} + \underset{10}{\underline{A_5^{B_s}}}(\delta_d^{LR})_{23}(\delta_d^{RL})_{23}\Big].$$

If we take $m_{\tilde{q}}$, $m_{\tilde{g}} = 1\mathrm{TeV}.$

Cross term of LL and RR part mostly contributes to M12.

Magnitude of $(\delta_d^{LL,RR})_{23}$

$$\left(\delta_d^{LL}\right)_{23} = \left|(\delta_d^{LL})_{23}\right| \ e^{2i\theta_{23}^{LL}}$$

$$\left(\delta_d^{RR}\right)_{23} = \left|(\delta_d^{LL})_{23}\right| \ e^{2i\theta_{23}^{RR}}$$

$$\left(\delta_d^{LR}\right)_{23} = \left(\delta_d^{RL}\right)_{23} = 0$$

We neglect $(\delta_d^{LR})_{23}$, $(\delta_d^{RL})_{23}$

Input $h_s \leq 0.1$

We get allowed range of $\delta_d^{LL,\ RR}$

$$\left|(\delta_d^{LL})_{23}\right|, \left|(\delta_d^{RR})_{23}\right| \leq \left(\frac{m_{\tilde{q}}}{1\mathrm{TeV}}\right) 0.02$$

Let us include non-zero $(\delta_d^{LR})_{23}, (\delta_d^{RL})_{23}$.

Enhancement factor

$$C_{7\gamma}^{\tilde{g}} \simeq -\frac{\sqrt{2}\alpha_s\pi}{6G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}\left[(\delta_d^{LL})_{23}\left(\frac{8}{3}M_3(x) - \mu\tan\beta\frac{m_{\tilde{g}}}{m_{\tilde{q}}^2}\frac{8}{3}M_a(x)\right) + (\delta_d^{LR})_{23}\frac{m_{\tilde{g}}}{m_b}\frac{8}{3}M_1(x)\right]$$

$$C_{8G}^{\tilde{g}} \simeq -\frac{\sqrt{2}\alpha_s\pi}{2G_F V_{tb}V_{ts}^* m_{\tilde{q}}^2}\left[(\delta_{LL}^d)_{23}\left\{\left(\frac{1}{3}M_3(x) + 3M_4(x)\right)\right.\right.$$
$$\left.\left. - \mu\tan\beta\frac{m_{\tilde{g}}}{m_{\tilde{q}}^2}\left(\frac{1}{3}M_a(x) + 3M_b(x)\right)\right\} + (\delta_{LR}^d)_{23}\frac{m_{\tilde{g}}}{m_b}\left(\frac{1}{3}M_1(x) + 3M_2(x)\right)\right]$$

- If we take μtanβ∼O(1TeV), contribution from LR and RL may become larger than contribution from LL and RR.
- Let's consider contribution from LR and RL in the case of $\left|(\delta_d^{LL})_{23}\right|, \left|(\delta_d^{RR})_{23}\right| \simeq 0.02$.

Our set up for $\delta_d^{LR,\ RL}$

$$(\delta_d^{LL})_{23} \gg (\delta_d^{LR})_{23}$$

$$|(\delta_d^{LL})_{23}|, |(\delta_d^{RR})_{23}| \simeq 0.02$$

$$(\delta_d^{LR})_{23} = |(\delta_d^{LR})_{23}| e^{2i\theta_{23}^{LR}}$$

$$(\delta_d^{RL})_{23} = |(\delta_d^{LR})_{23}| e^{2i\theta_{23}^{RL}}$$

Input parameters

$$\left\{ \begin{array}{l} m_{\tilde{q}} = 1 \text{ TeV} \quad m_{\tilde{g}} = 1.5 \text{ TeV} \\ \theta_{23}^{LR} = [0, \pi] \quad \theta_{23}^{RL} = [0, \pi] \\ h_s \simeq 0.1 \quad \sigma_s \simeq 0.9 - 2.2 \text{ rad} \\ \mu \tan\beta (\mu = 100 - 500\text{GeV} \ , \ \tan\beta = 3 - 50) \end{array} \right.$$

Numerical analysis

Step 1 We consider range of **Mass Insertion parameters** which are consistent with LHCb new result.

We constrain Mass Insertion parameters from **BR($b \to s\gamma$)** **and** $A_{cp}^{b\to s\gamma}$.

With this constraint.

Step 2 We predict time dependent CP asymmetries S_f of B mesons.

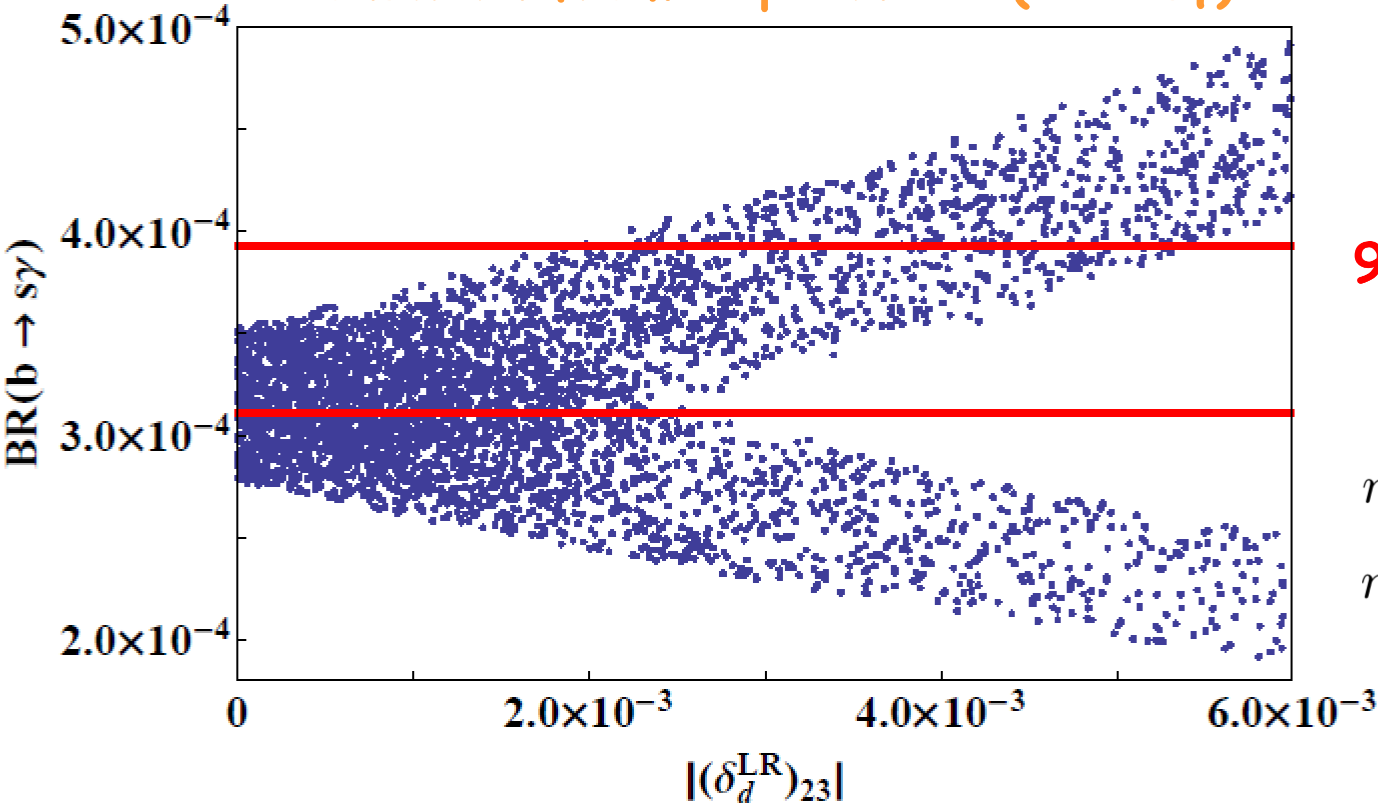
We show correlation between $A_{cp}^{b\to s\gamma}$ and S_f.

Step 1

Numerical analysis for $(\delta_d^{LR,RL})_{23}$

Magnitude of $(\delta_d^{LR})_{23}$

Constrain from $A_{CP}^{b\to s\gamma}$ and BR(b → sγ)



90% C.L.

$m_{\tilde{q}} = 1\text{TeV},$

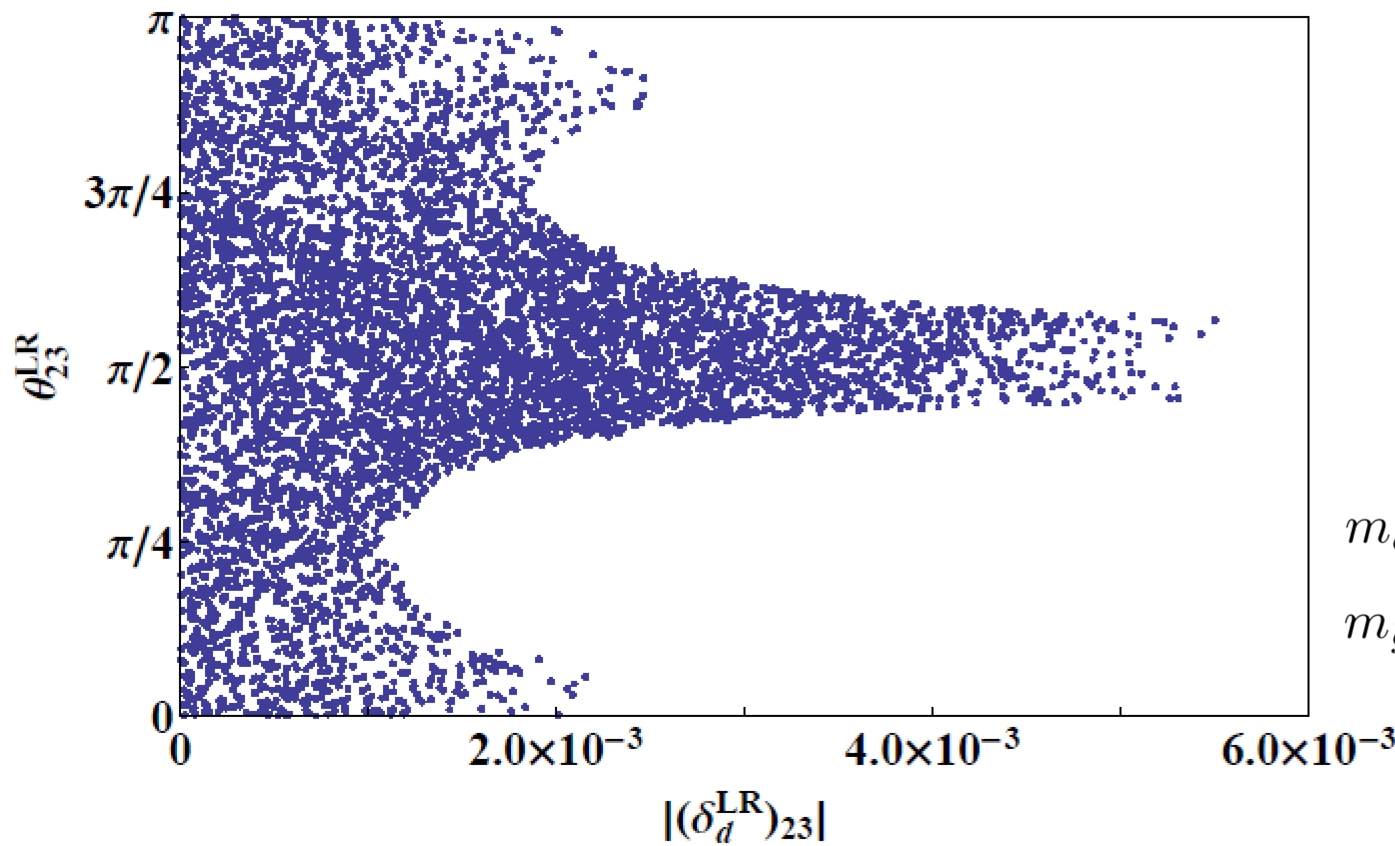
$m_{\tilde{g}} = 1.5\text{TeV}$

$$|(\delta_d^{LR})_{23}| \leq 5.5 \times 10^{-3}$$

Step 1

Numerical analysis for $(\delta_d^{LR,RL})_{23}$

Magnitude and phase of $(\delta_d^{LR})_{23}$



$m_{\tilde{q}} = 1\text{TeV},$

$m_{\tilde{g}} = 1.5\text{TeV}$

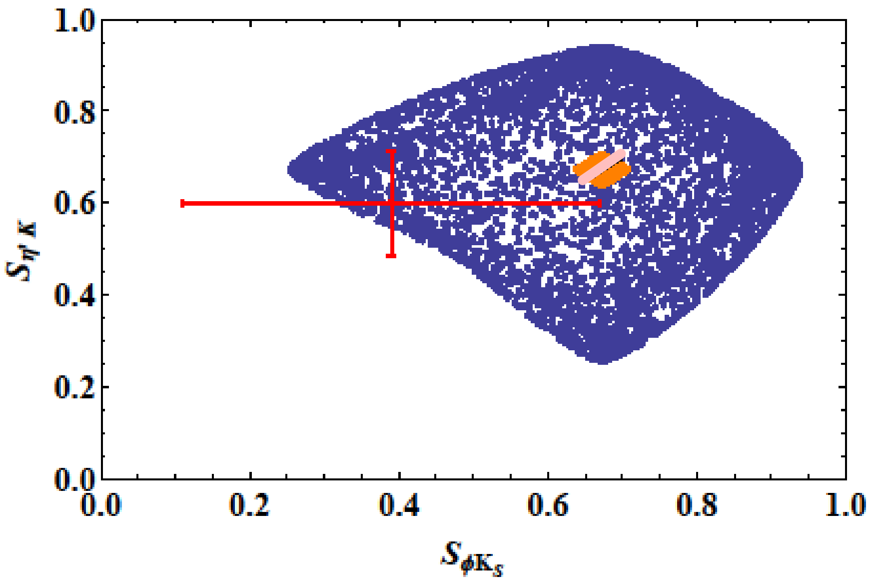
$$|(\delta_d^{LR})_{23}| \leq 5.5 \times 10^{-3}$$

Step 2

Our prediction

$S_{\eta' K^0}$ vs $S_{\phi K_S}$

LR,RL dominant

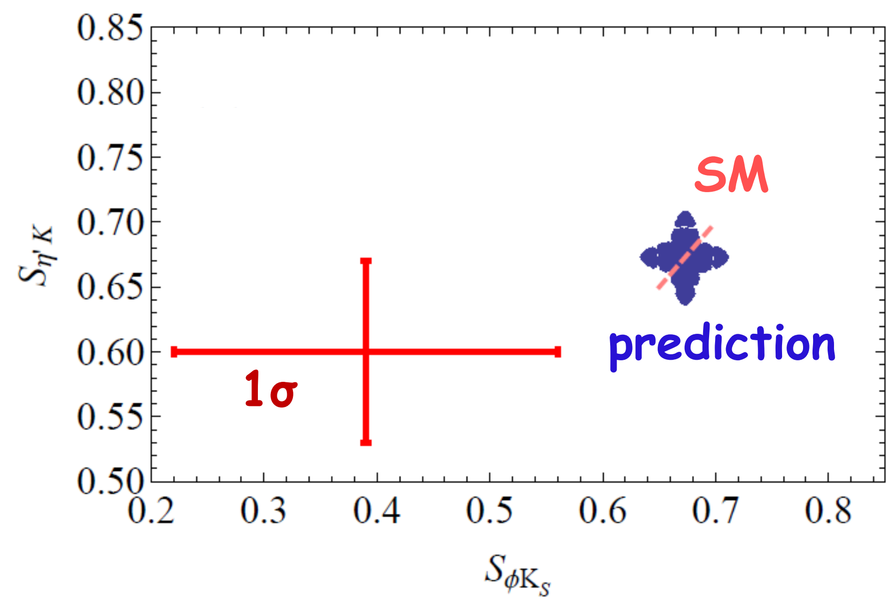


— : $|(\delta_d^{LR})_{23}| = 10^{-3}$

— : $|(\delta_d^{LR})_{23}| = 10^{-4}$

LL,RR dominant

(without LR,RL)

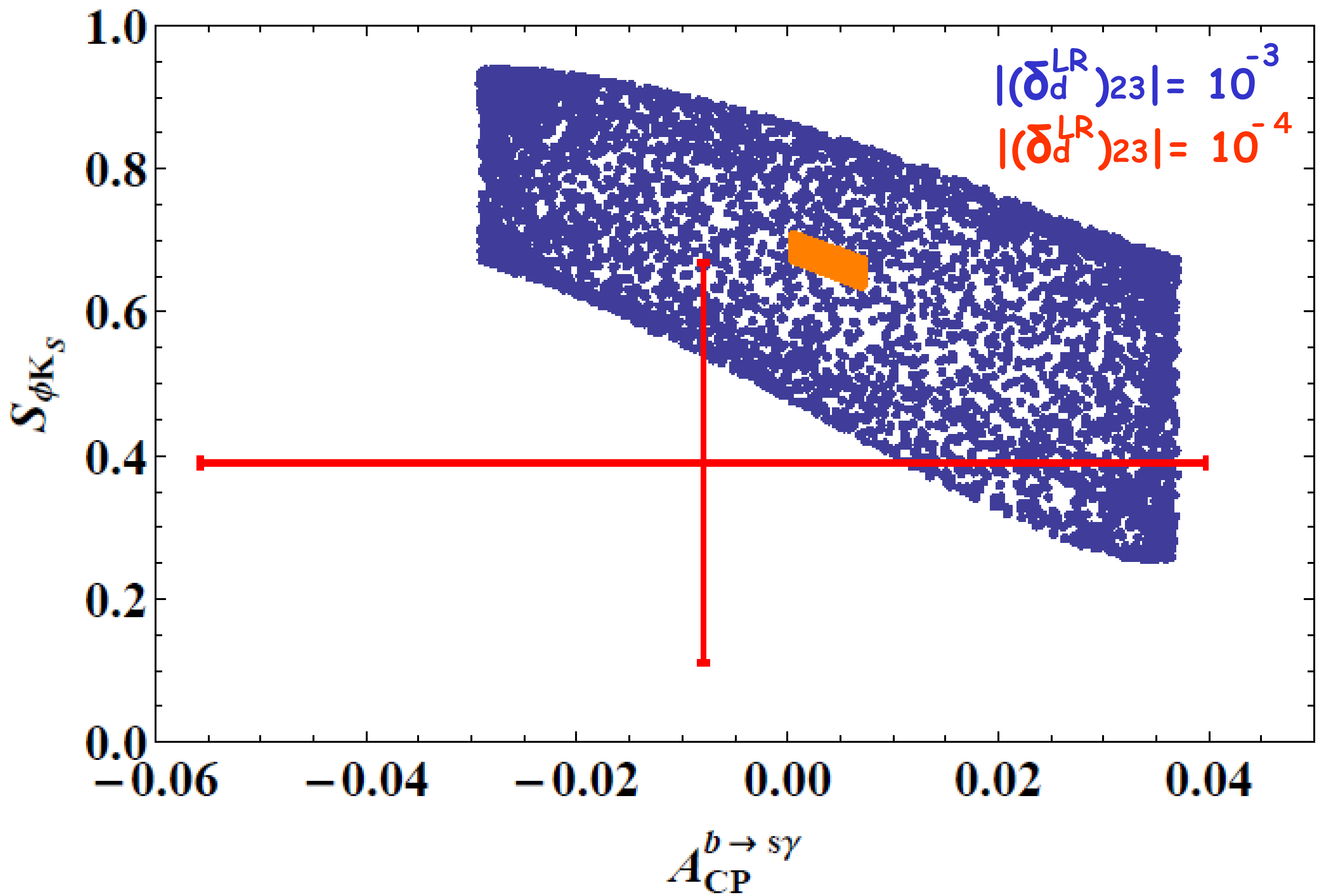


$\mu \tan\beta = 5000$ GeV

Step 2

Our prediction

$S_{\phi K_S}$ vs $A_{cp}^{b\to s\gamma}$

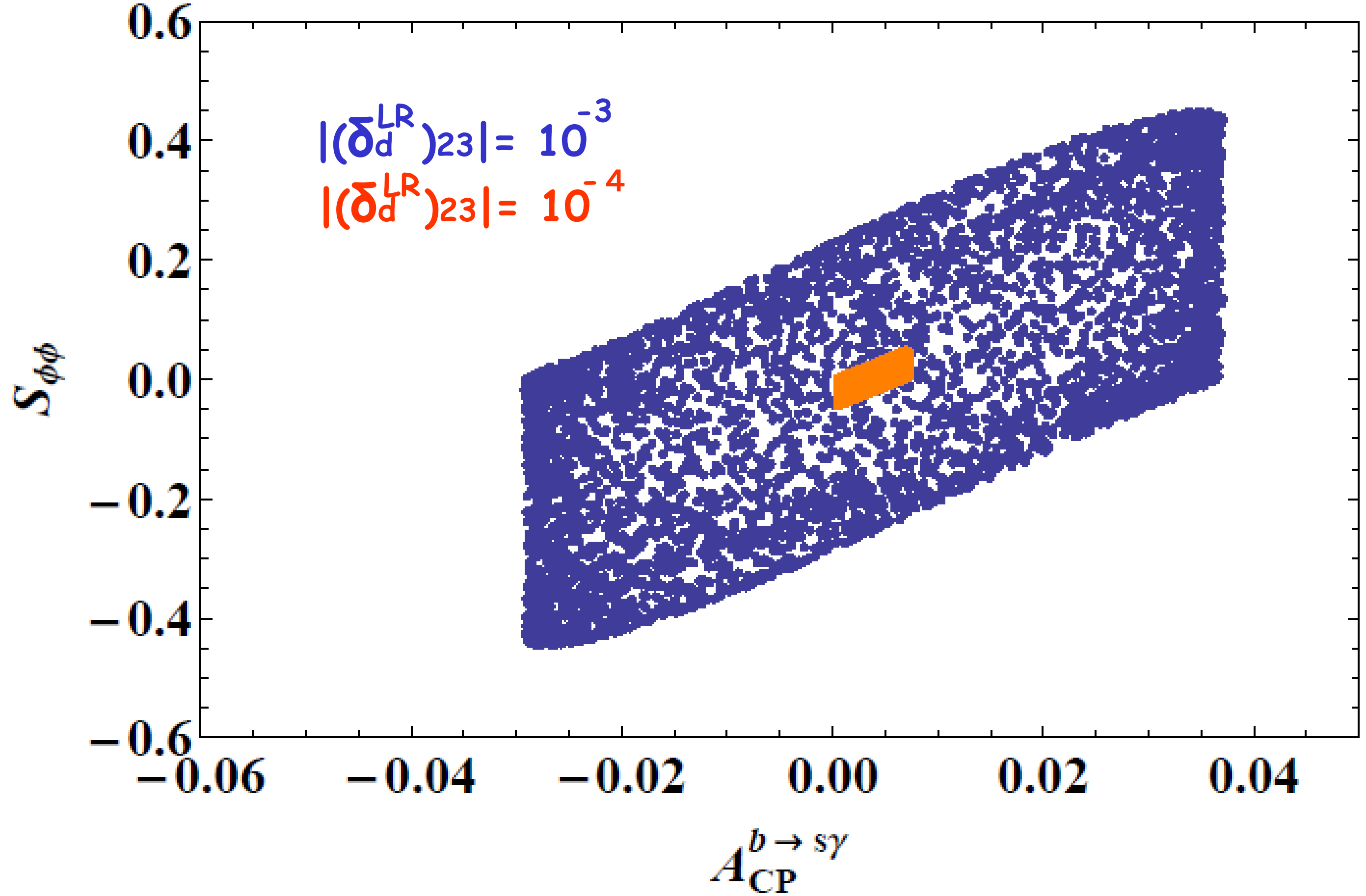


Step 2

Our prediction

$B_s \to \phi\phi$

$S_{\phi\phi}$ vs $A_{cp}^{b\to s\gamma}$



Plan

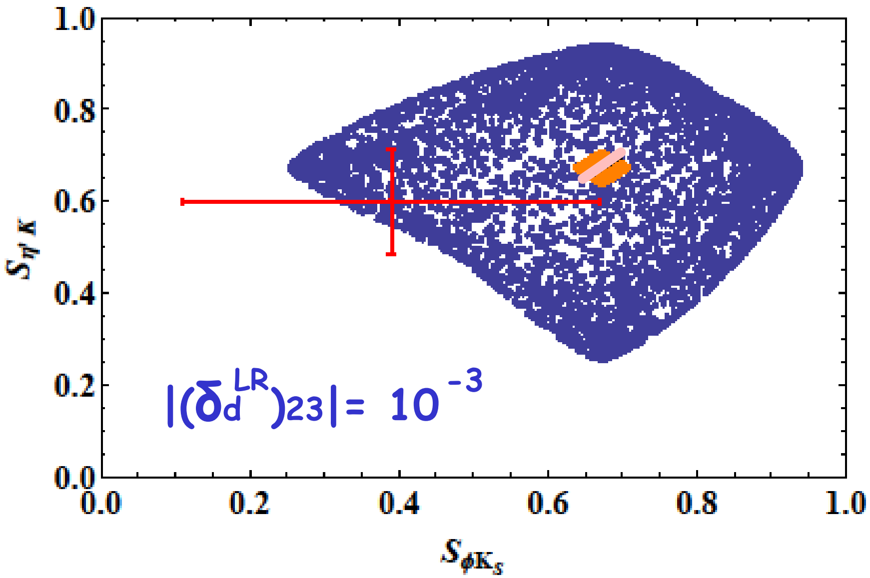
1. Effect of SUSY on B physics
2. Recent experimental result
3. Numerical analysis
4. **Conclusion**

Conclusion

- We discuss the effect of squark flavor mixing on time dependent CP asymmetries Sf of B mesons.

$$\left|(\delta_d^{LL})_{23}\right|, \left|(\delta_d^{RR})_{23}\right| \leq \left(\frac{m_{\tilde{q}}}{1\mathrm{TeV}}\right) 0.02$$

$$\left|(\delta_d^{LR})_{23}\right|, \left|(\delta_d^{RL})_{23}\right| \leq 5.5 \times 10^{-3}$$



The prediction could be deviated from SM significantly.

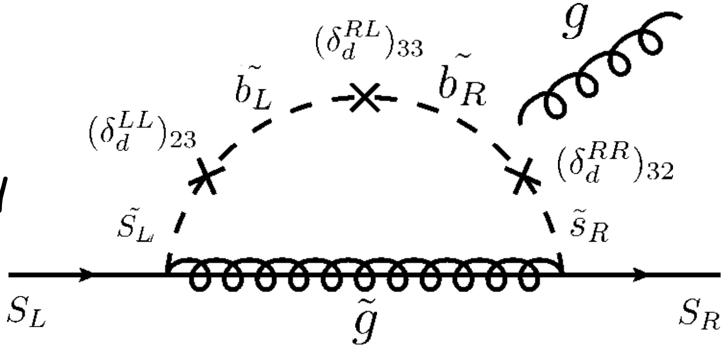
- We expect that LHCb and Super-Belle can test our framework.

Buck Up

CEDM, LL and RR dominant

Chromo electric dipole moment (CEDM) of strange quark d_s^c

The T violation is expected to be observed in the EDM of the neutron.
The experimental upper-bound of the EDM of the neutron provides us the upper-bound of the CEDM of the strange quark.



$$d_s^C = c\frac{\alpha_s}{4\pi}\frac{m_{\tilde{g}}}{m_{\tilde{q}}^2}\left(-\frac{1}{3}N_1(x) - 3N_2(x)\right)\mathrm{Im}((\delta_d^{LL})_{23}(\delta_d^{LR})_{33}(\delta_d^{RR})_{23}^*)$$

$$(\delta_d^{LR})_{33} = \frac{m_b(A_b - \mu\tan\beta)}{m_{\tilde{q}}^2}$$

[J. Hisano and Y. Shimizu, PRD **70** (2004)]

Experimental upper bound : $e\left|d_s^C\right| < 1.0\times 10^{-25}$ ecm

Magnitude of $(\delta_d^{LL,RR})_{23}$

$$h_q \mathrm{e}^{2i\sigma_q} = \frac{M_{12}^{q,SUSY}}{M_{12}^{q,SM}} \qquad (q = d, s)$$

input
$$\begin{cases} (\delta_d^{LL})_{ij} = r_{ij}\ e^{2i\theta_{ij}^{LL}} \\ (\delta_d^{RR})_{ij} = r_{ij}\ e^{2i\theta_{ij}^{RR}} \\ (\delta_d^{LR})_{ij} = (\delta_d^{RL})_{ij} = 0 \end{cases}$$
into $M_{12}^{M,\mathrm{SUSY}}$

And solve for $r_{ij} = \left|(\delta_d^{LL,RR})_{ij}\right|$

Condition of magnitude of $(\delta_d^{LL,RR})_{ij}$

$$r_{ij} = \sqrt{\frac{h_q |M_{12}^{q,SM}|}{\left|A_1^q \left(2\ A_2^q\ \cos 2\left(\theta_{ij}^{LL} - \theta_{ij}^{RR}\right) + A_3^q\right)\right|}}$$

Condition of phase sum of $(\delta_d^{LL,RR})_{ij}$

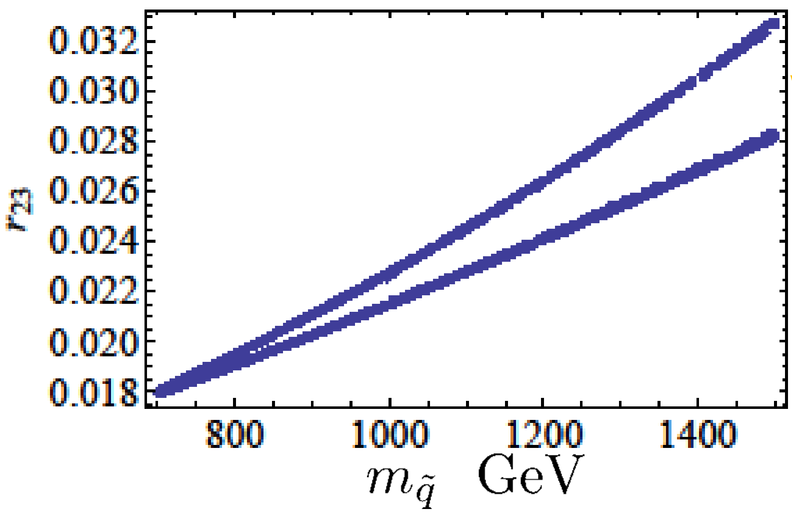
$$\theta_{ij}^{LL} + \theta_{ij}^{RR} = \sigma_q + \phi_q^{SM} + \frac{n}{2}\pi \qquad (n = 0, \pm 1, \pm 2 \ldots)$$

Numerical analysis for $\delta_d^{LL,\ RR}$

Input parameters

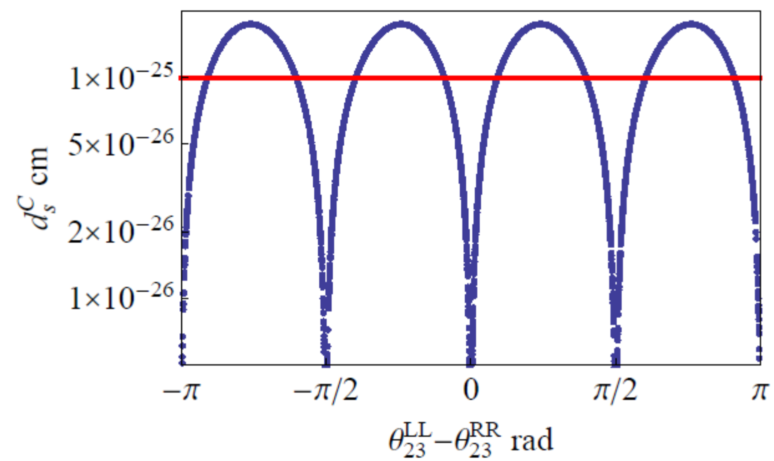
$$\begin{cases} m_{\tilde{g}} = 1000\ \text{GeV} \quad m_{\tilde{q}} = 1000\ \text{GeV} \\ \theta_{LL} = [0, \pi] \quad \theta_{RR} = [0, \pi] \\ h_d \simeq 0.3 \quad \sigma_d \simeq 1.8\ \text{rad} \\ h_s \simeq 0.1 \quad \sigma_s \simeq\ 0.9 - 2.2\ \text{rad} \\ \mu\tan\beta(\mu = 100 - 500\text{GeV}\ ,\ \tan\beta = 3 - 50) \end{cases}$$

Magnitude of $(\delta_d^{LL,RR})_{23}$



excluded

Phase difference $\theta_{23}^{LL} - \theta_{23}^{RR}$



$\mu \tan\beta = 5000$ GeV

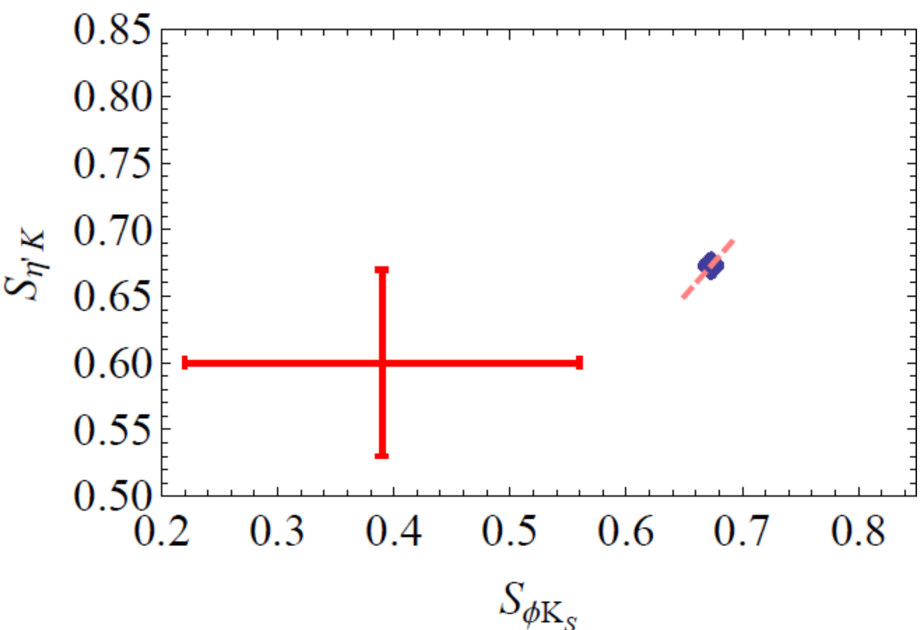
Prediction of time dependent CP asymmetry Sf of B meson

$$B_d \to \phi K_S, \eta' K^0$$

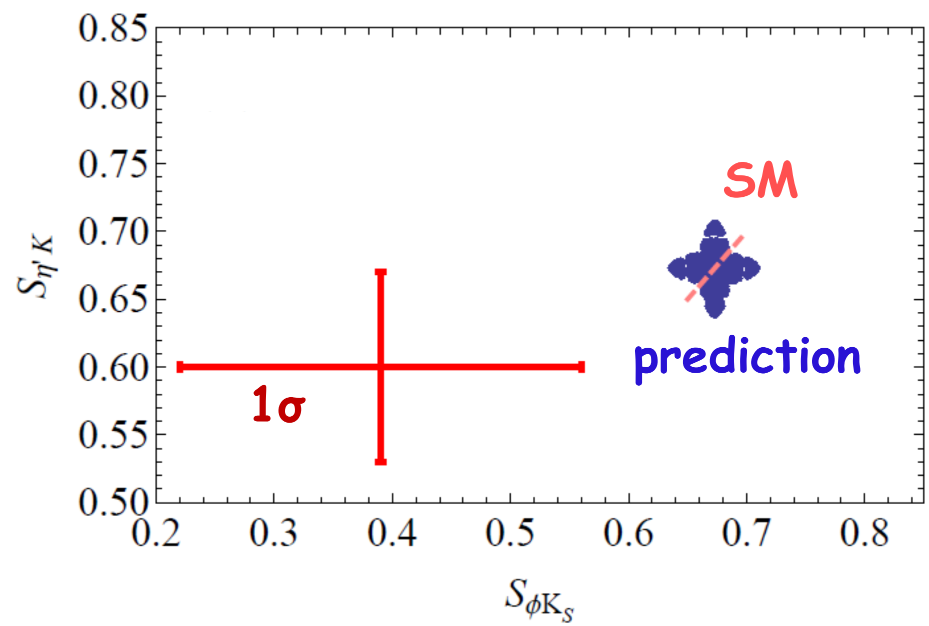
$$\left|(\delta_d^{LL})_{ij}\right| = \left|(\delta_d^{RR})_{ij}\right| = 0.02$$

$$(\delta_d^{LR})_{ij} = (\delta_d^{RL})_{ij} = 0$$

$\mu\tan\beta = 1000$ GeV



$\mu\tan\beta = 5000$ GeV



$$\begin{cases} S_{\phi K} = 0.39 \pm 0.17 \\ S_{\eta' K} = 0.60 \pm 0.07 \end{cases} \quad (S_{J/\psi K_S} = 0.671 \pm 0.023)$$

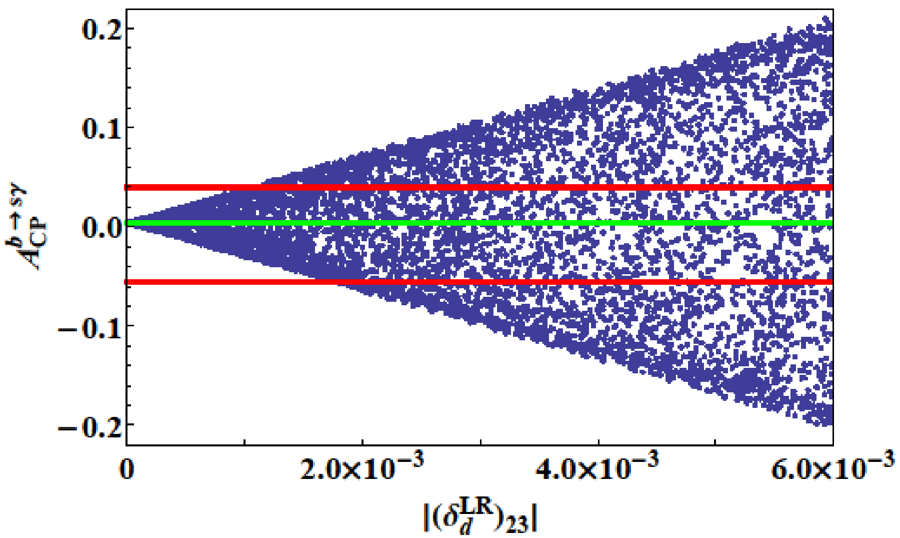
Buck Up

Numerical analysis

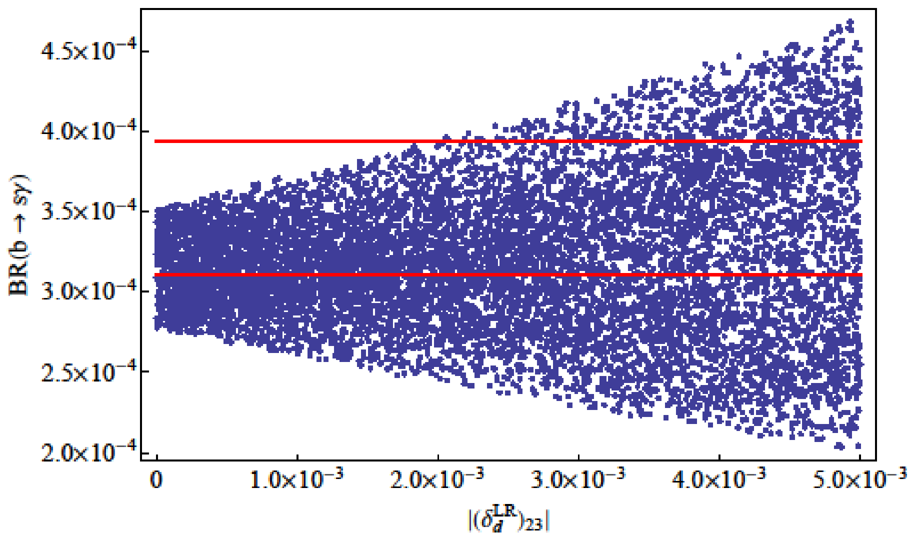
Numerical analysis for $(\delta_d^{LR,RL})_{23}$

Magnitude of $(\delta_d^{LR})_{23}$

From Acp



From BR(b->sγ)



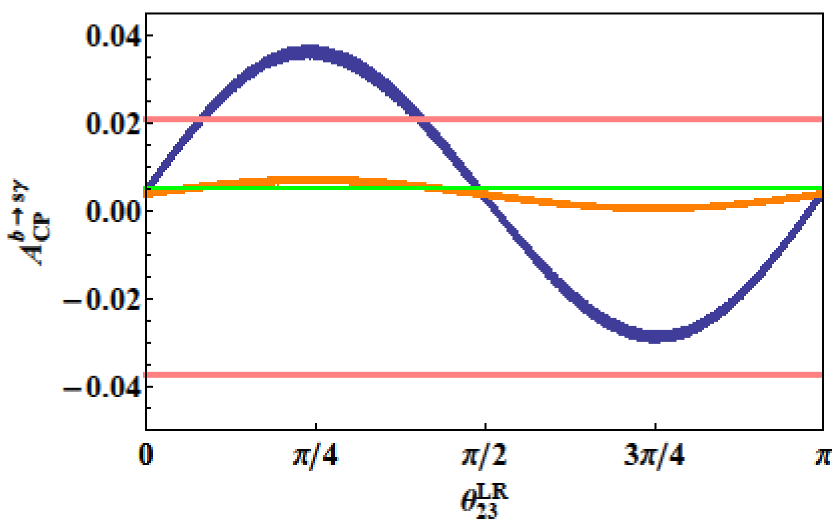
— : 90% C.L. error bar

— : SM prediction

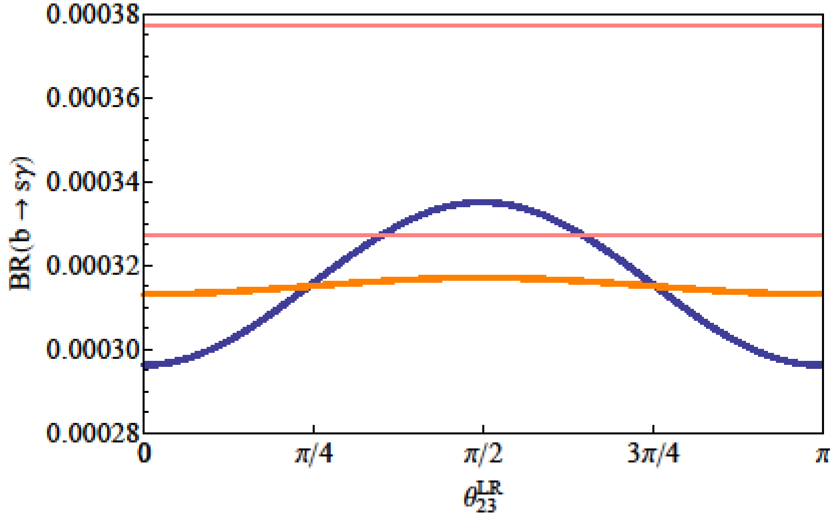
Numerical analysis for $(\delta_d^{LR,RL})_{23}$

Phase of $(\delta_d^{LR})_{23}$

From Acp



From BR($b \to s\gamma$)



— : 1σ error bar

— : SM prediction

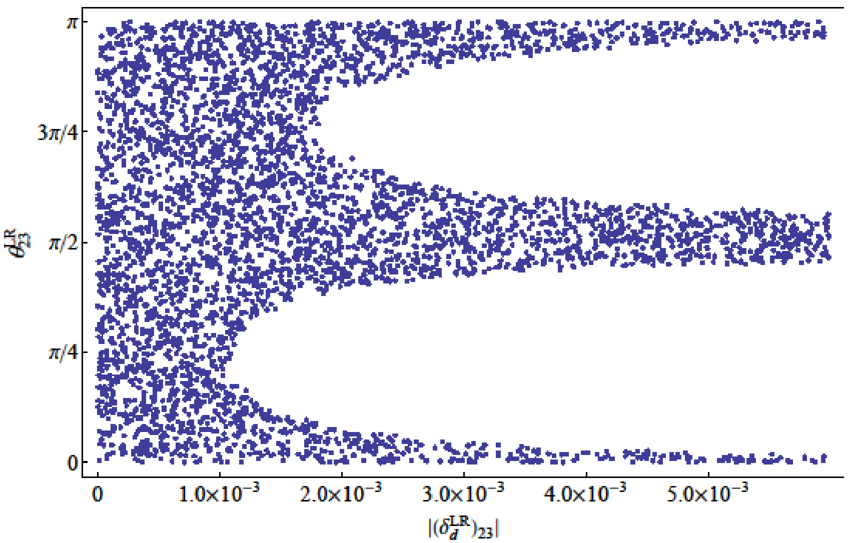
— : $|(\delta_d^{LR})_{23}| = 10^{-3}$

— : $|(\delta_d^{LR})_{23}| = 10^{-4}$

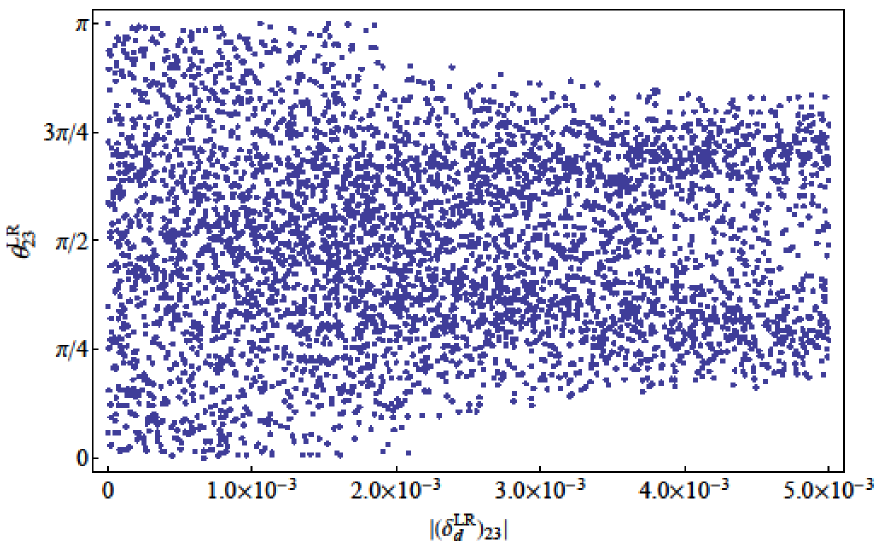
Numerical analysis for $(\delta_d^{LR,RL})_{23}$

Phase of $(\delta_d^{LR})_{23}$

From Acp



From BR(b → sγ)



Time dependent CP asymmetry Sf

★ $B_d \to \phi K_S, \eta^{'} K^0$

$$\lambda_{\phi K_S,\ \eta' K^0} = -e^{-i\phi_d} \frac{\sum_{i=3-6,7\gamma,8G} \left(C_i^{\mathrm{SM}} \langle O_i \rangle + C_i^{\tilde{g}} \langle O_i \rangle + \widetilde{C}_i^{\tilde{g}} \langle \widetilde{O}_i \rangle \right)}{\sum_{i=3-6,7\gamma,8G} \left(C_i^{\mathrm{SM}*} \langle O_i \rangle + C_i^{\tilde{g}*} \langle O_i \rangle + \widetilde{C}_i^{\tilde{g}*} \langle \widetilde{O}_i \rangle \right)}$$

R. Harnik, D. T. Larson, H. Murayama and A. Pierce, PRD **69** 094024 (2004)

- $\langle O_{8G} \rangle$ is dominant.
  We can estimate NLO $\langle O_3 \rangle \sim \langle O_{7\gamma} \rangle$ using factorization relation.

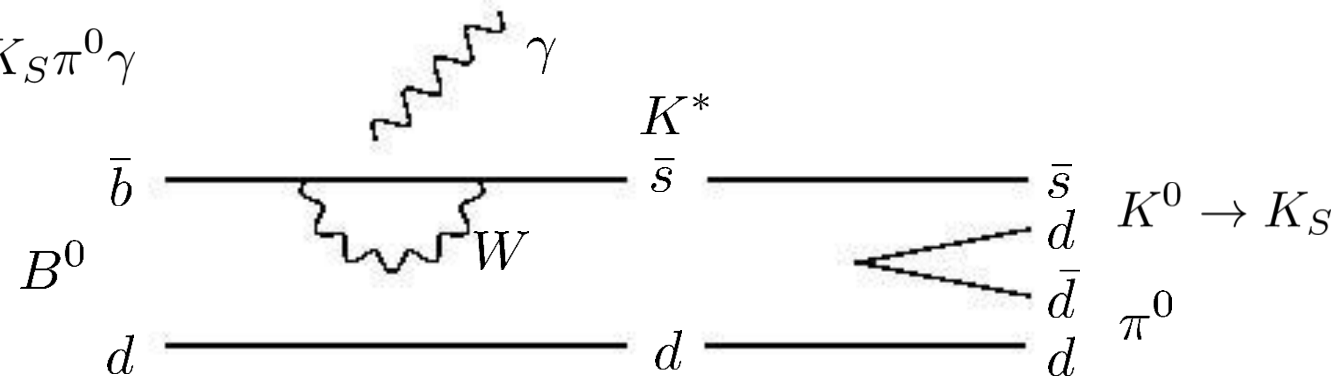
- Sign between $\langle O_i \rangle$ and $\langle \widetilde{O}_i \rangle$ is different due to parity of final state.

$$\langle f | O_i | B_d \rangle = -(-1)^{P_f} \langle f | \widetilde{O}_i | B_d \rangle$$

$$\langle \phi K_S | O_i | B_d^0 \rangle = \langle \phi K_S | \widetilde{O}_i | B_d^0 \rangle \qquad \langle \eta' K^0 | O_i | B_d^0 \rangle = -\langle \eta' K^0 | \widetilde{O}_i | B_d^0 \rangle$$

Time dependent CP asymmetry Sf

★ $B_d \to K^*\gamma \to K_S\pi^0\gamma$



- $\langle O_{7\gamma}\rangle$ is dominant. $\langle O_2\rangle$ and $\langle O_{8G}\rangle$ are sub-leading.

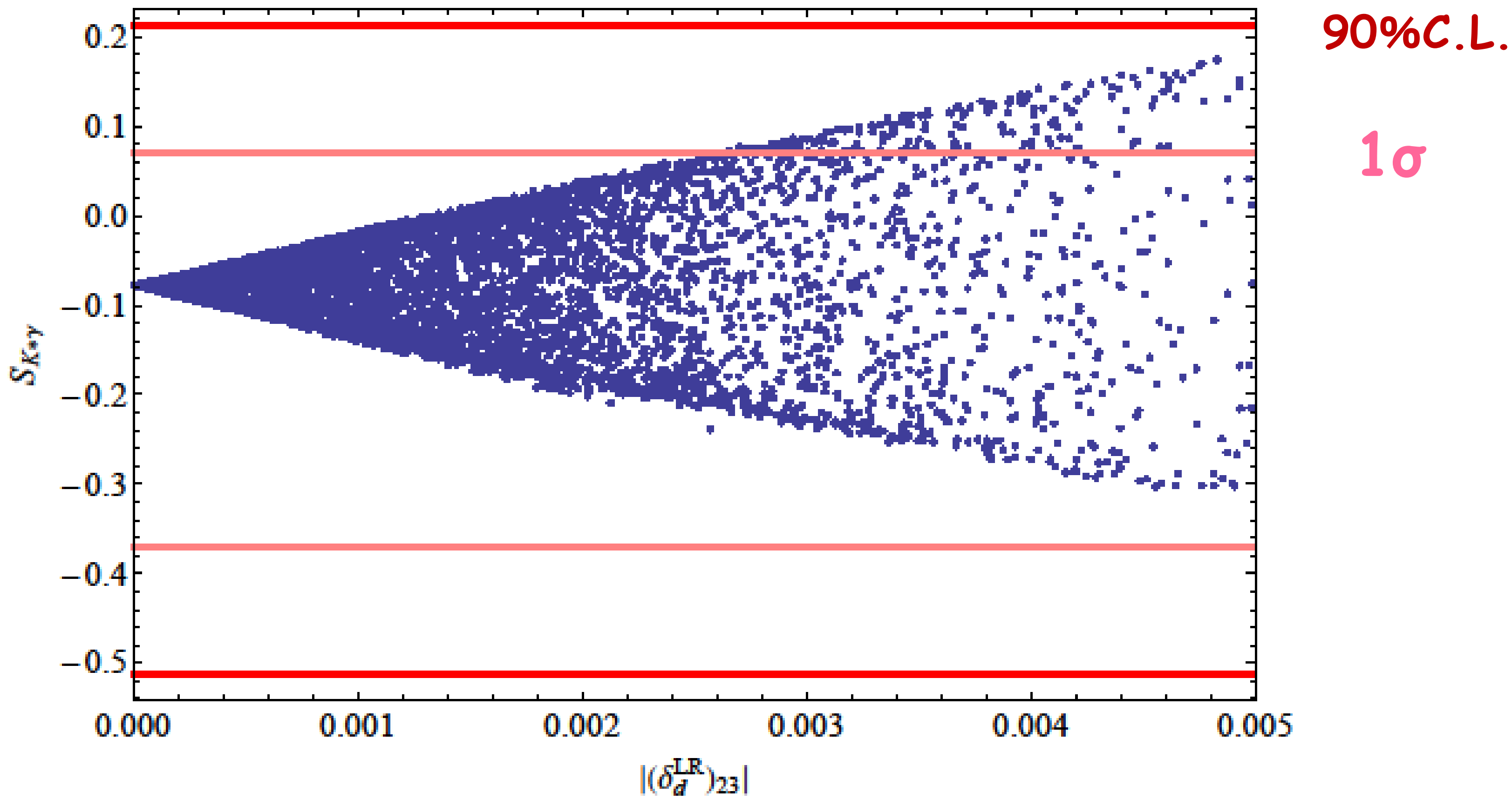
$$S_{K^*\gamma} = \frac{2\,\mathrm{Im}\left[e^{-2i\,\phi_1}\tilde{C}_{7\gamma}(m_b)/C_{7\gamma}(m_b)\right]}{\left|\tilde{C}_{7\gamma}(m_b)/C_{7\gamma}(m_b)\right|^2 + 1}$$

$$S_{B_d\to K^*\gamma}(SM) = -\frac{2m_s}{m_b}\sin 2\beta$$

$$S_{B_d\to K^*\gamma}(exp) = -0.15 \pm 0.22$$

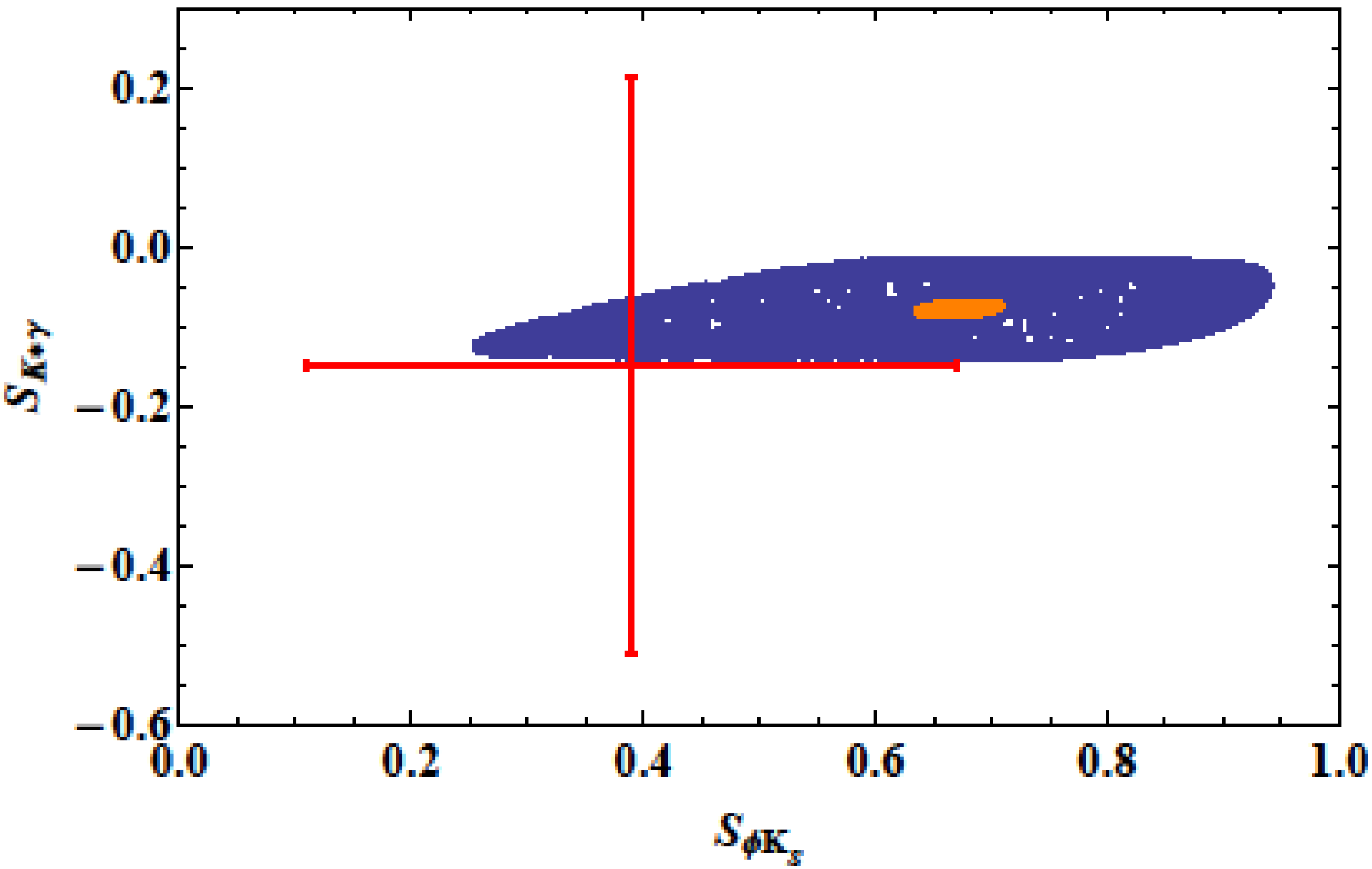
Numerical analysis result

$S_{K^*\gamma}$



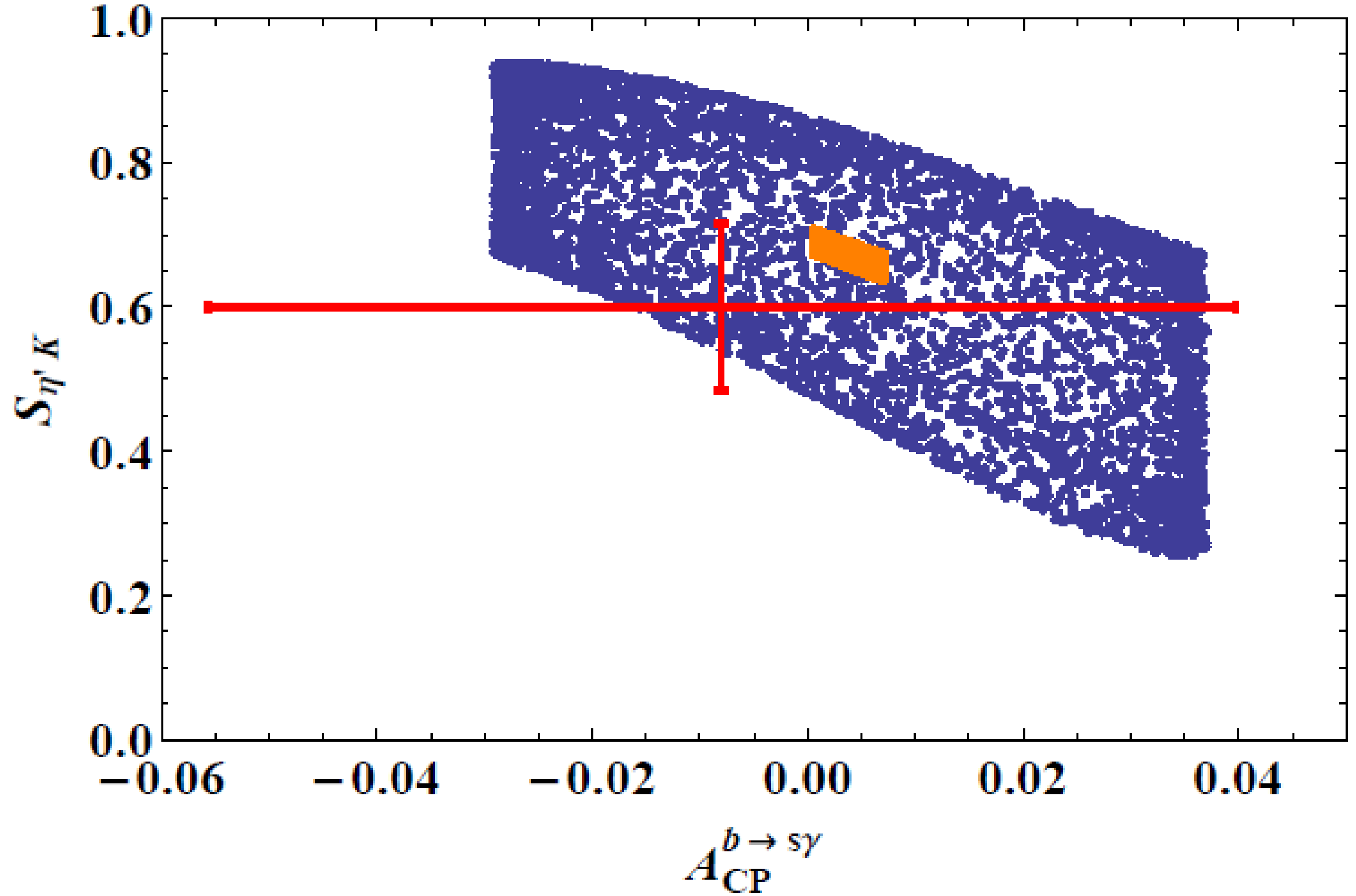
Numerical analysis result

$S_{\varphi K_s}$ vs $S_{K^*\gamma}$



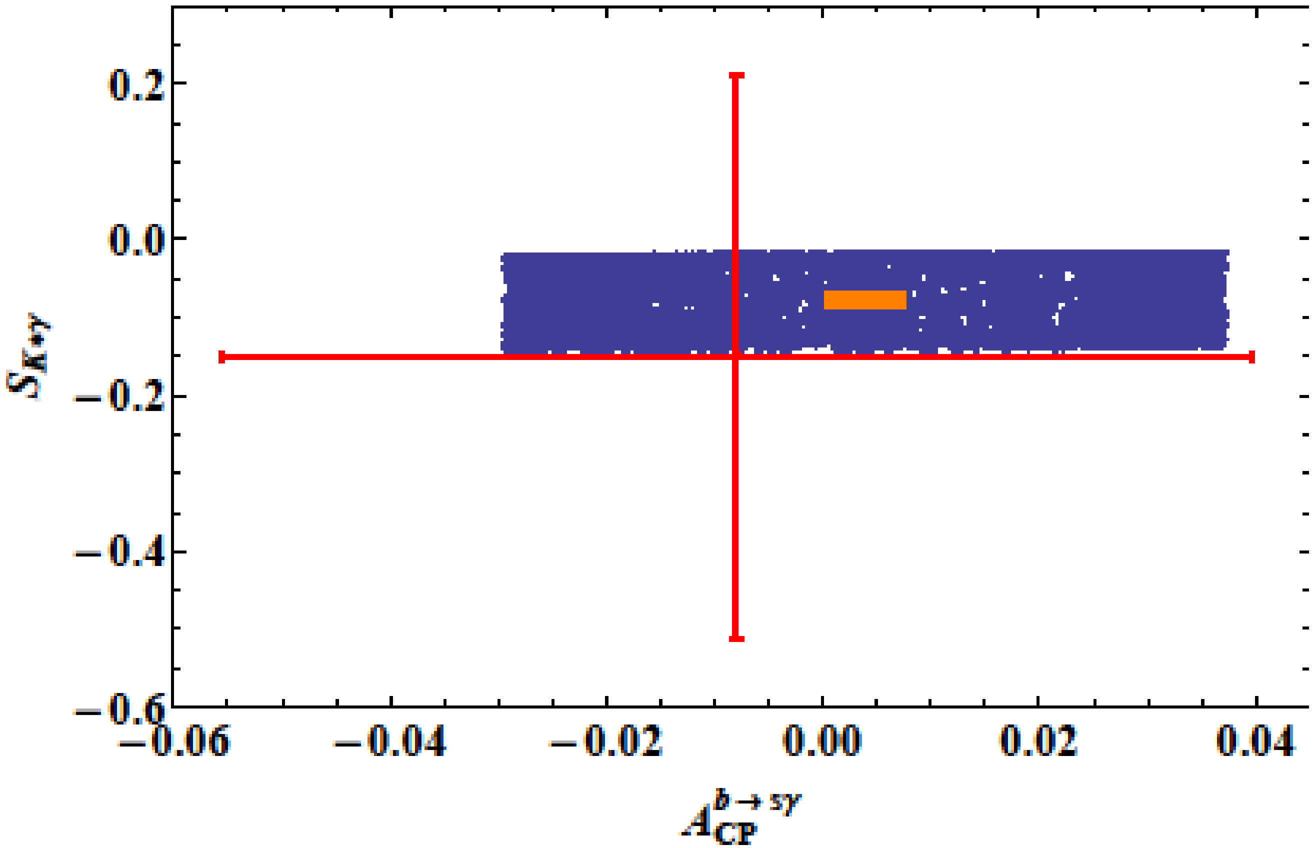
Numerical analysis result

Acp vs Sηκ



Numerical analysis result

A_{CP} vs $S_{K\gamma}^{*}$



Buck Up

DØ anomaly

h_q and σ_q plot with DØ and CDF collaboration results

[V. M. Abazov *et al.* [D0 Collaboration], PRD **82** (2010), PRL**105** (2010) PRD **84** (2011)]

Like-sign dimuon charge asymmetry

$$\mathcal{A}^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

[N_b^{++} : event number of $b\bar{b} \to \mu^+\mu^+ X$]

Experimental result By DØ and CDF collaboration @Tevatron

$$\mathcal{A}^b_{sl}\,(\mathrm{exp}) = -(7.87 \pm 1.72 \pm 0.93) \times 10^{-3}$$

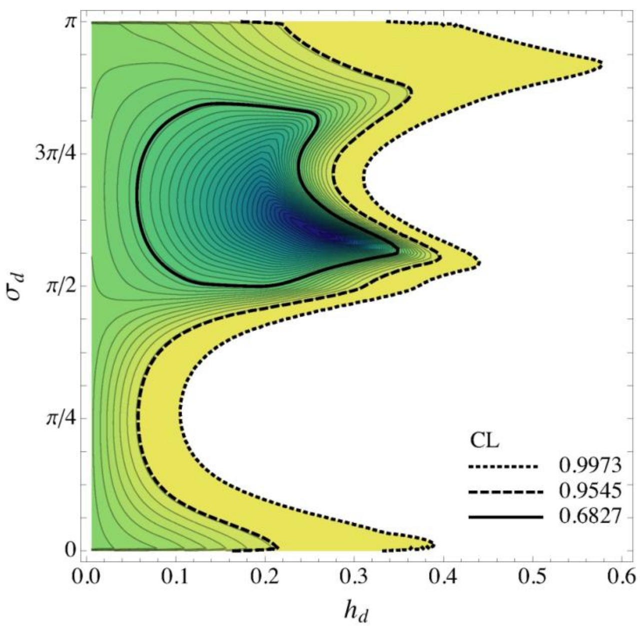
Large deviation !

SM prediction

$$\mathcal{A}^b_{sl}\,(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

B

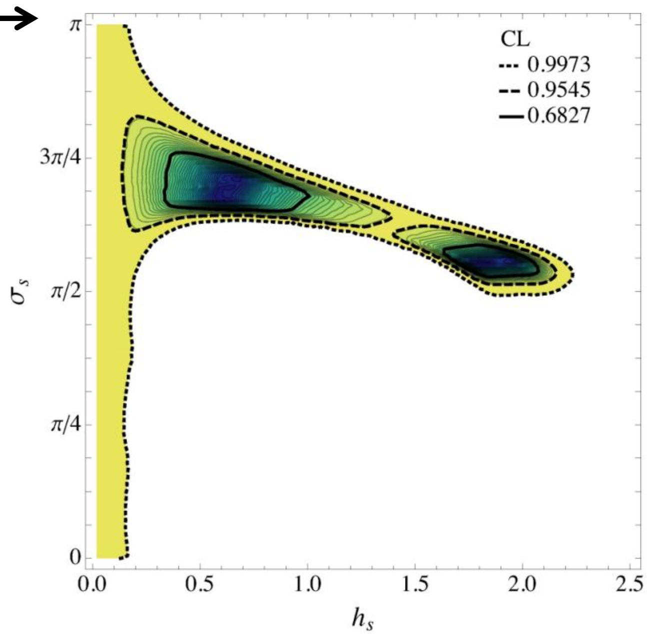
B_d



σ_q

h_q

B_s



[Z. Ligeti, M. Papucci, G. Perez and J. Zupan, PRL**105** (2010)]

SM is disfavored at 3.9 σ level !

New Physics ??

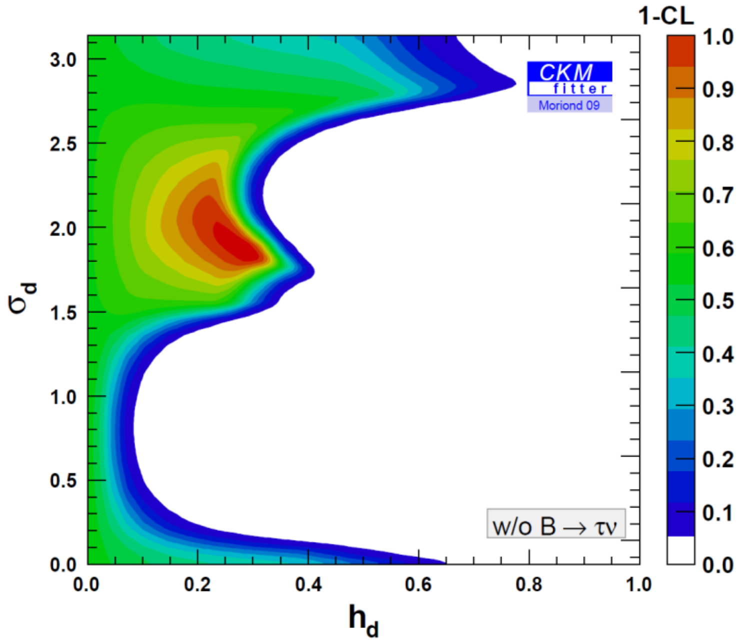
But...

[P. Ko and J. -h. Park, PRD **80** (2009), PRD **82** (2010)
M. Endo, S. Shirai and T. T. Yanagida, PTP **125** (2011)
M. Endo and N. Yokozaki, JHEP **1103** (2011)]

h_q and σ_q plot with including LHCb results (2011 Dec.)

[R. Aaij *et all* arXiv:1112.3056 [hep-ex]]

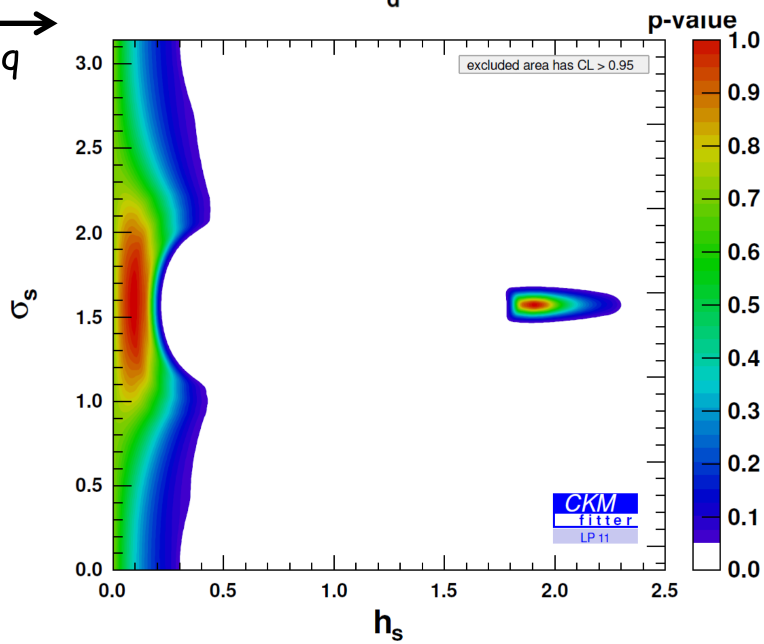
B_d



σ_q

h_q

B_s



(CKMfitter(2011))

CP asymmetry of non-leptonic decay

$$B_s^0 \to J/\psi\phi \;\; \& \;\; B_s^0 \to J/\psi f_0(980)$$

Experimental result By LHCb collaboration @LHC

$$\beta_s(\mathrm{exp}) = 0.07 \pm 0.17 \pm 0.06 \quad \mathrm{rad}$$

Consistent with SM...

SM prediction

$$\beta_s(\mathrm{SM}) = -0.0363 \pm 0.0017 \quad \mathrm{rad}$$

but error is still large !
so we have prospect of
New Physics .

Like-sign dimuon charge asymmetry @ D0 (Tevatron)

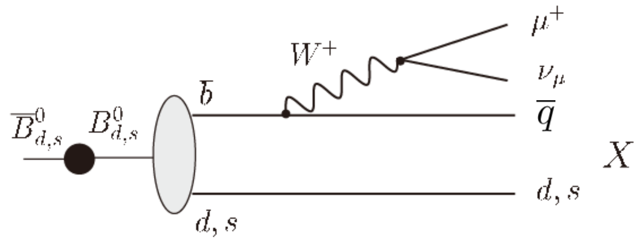
$$A_{sl}^{q} \equiv \frac{N_q^{++} - N_q^{--}}{N_q^{++} + N_q^{--}}$$

$$N_q^{++} \quad : b\bar{b} \to \mu^+\mu^+ X$$

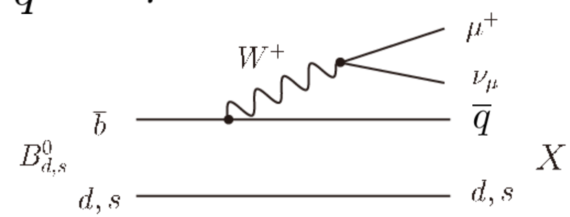
$$A_{sl}^{b} = (0.506 \pm 0.043)\, a_{sl}^{d} + (0.494 \pm 0.043)\, a_{sl}^{s}$$

$$a_{sl}^{q} \equiv \frac{\Gamma\left(\overline{B}_q^0 \to \mu^+ X\right) - \Gamma\left(B_q^0 \to \mu^- X\right)}{\Gamma\left(\overline{B}_q^0 \to \mu^+ X\right) + \Gamma\left(B_q^0 \to \mu^- X\right)}$$

$$\overline{B}_q^0 \Longrightarrow B_q^0 \to \mu^+ X$$



$$B_q^0 \to \mu^+ X$$



Like-sign dimuon charge asymmetry @ D0 (Tevatron)

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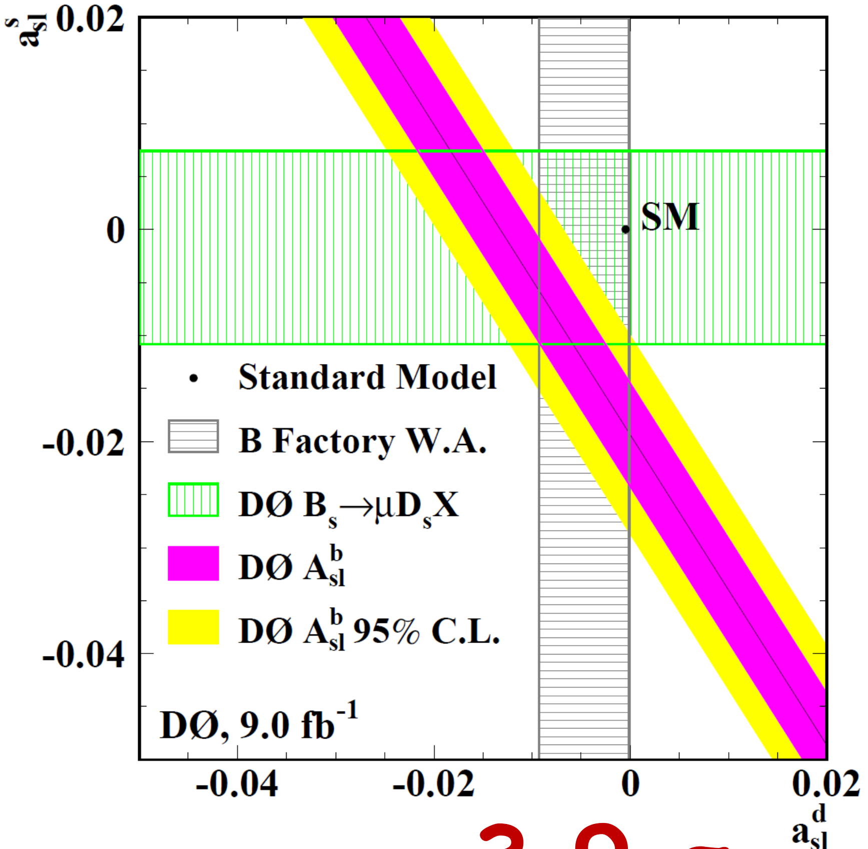
$N_q^{++} \quad : b\bar{b} \rightarrow \mu^+\mu^+ X$

$$A_{sl}^{b} = (0.506 \pm 0.043)\, a_{sl}^{d} + (0.494 \pm 0.043)\, a_{sl}^{s}$$

$$a_{sl}^{q} \equiv \frac{\Gamma\left(\overline{B}_q^0 \rightarrow \mu^+ X\right) - \Gamma\left(B_q^0 \rightarrow \mu^- X\right)}{\Gamma\left(\overline{B}_q^0 \rightarrow \mu^+ X\right) + \Gamma\left(B_q^0 \rightarrow \mu^- X\right)}$$



Experimental result

$$\mathcal{A}_{sl}^{b}\,(\mathrm{exp}) = -(7.87 \pm 1.72 \pm 0.93) \times 10^{-3}$$

Large deviation !

SM prediction

$$\mathcal{A}_{sl}^{b}\,(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

3.9 σ

D0 anomaly

Comment on DØresult

Like-sign dimuon charge asymmetry

$$\mathcal{A}^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$\left[N_b^{++} \right.$: event number of $b\bar{b} \to \mu^+\mu^+ X$ $\left. \right]$

$$= (0.506 \pm 0.043) a^d_{sl} + (0.494 \pm 0.043) a^s_{sl}$$

$$a^q_{sl} = \mathrm{Im}\left(\frac{\Gamma_{12}^{q,SM}}{M_{12}^{q,SM}(1 + h_q e^{2i\sigma_q})} \right)$$

Our NP parameters give

$$\mathcal{A}^b_{sl} = -(0.75 \sim 1.0) \times 10^{-3}$$

3.5 σ deviation

D0 result

$$\mathcal{A}^b_{sl}\,(D\text{Ø}) = -(7.87 \pm 1.72 \pm 0.93) \times 10^{-3}$$

3.9 σ deviation

SM prediction

$$\mathcal{A}^b_{sl}\,(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

So it is difficult to explain the Tevatron anomaly in our framework of the squark flavor mixing.