# EDM constraints and CP asymmetries of $B$ processes in supersymmetric models

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## Summary

- **Introduction**
- **CP asymmetries of $B$-processes,** *is it a hint for new physics?*
- **CP asymmetries of $B \to \phi K_S$ in SUSY models**
- **CP asymmetries of $B \to \eta' K_S$ in SUSY models**
- **EDM constraints & possible SUSY contributions to the CP asymmetries**

# Introduction

- The result of $B \to J/\psi K_S$ CP asymmetry is $\boxed{S_{J/\psi K_s} = \sin 2\beta = 0.734 \pm 0.049}$, in a good agreement with the SM.

- The most recent measurements for the CP asymmetry of $B \to \phi K_S$ are
  $\boxed{S_{\phi K_s} = 0.06 \pm 0.33 \pm 0.09 \quad \textbf{(Belle) : } 2\ \sigma \textbf{ deviation from } \sin 2\beta}$
  $\boxed{S_{\phi K_s} = 0.50 \pm 0.25^{+0.07}_{-0.04} \quad \textbf{(BaBar) : compatible with the SM prediction}}$ *i.e.*, the average $\boxed{S_{\phi K_s} = 0.34 \pm 0.20.}$ displays a $1.7\sigma$ deviation $S_{J/\psi K_s}$.

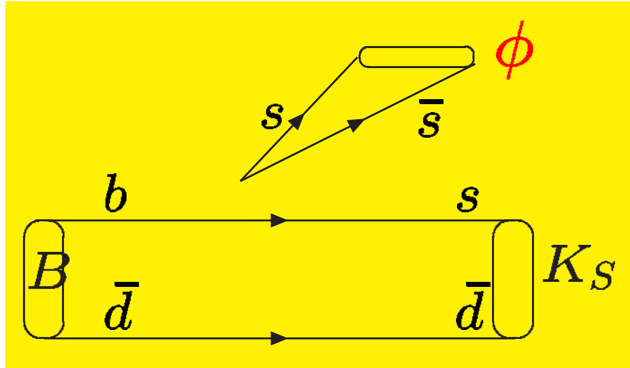
- The measurment of the CP asymmetry of $B \to \eta' K_S$ leads to
  $\boxed{S_{\eta' K_s} = 0.27 \pm 0.14 \pm 0.03 \quad \textbf{(BaBar)} \quad S_{\eta' K_s} = 0.65 \pm 0.18 \pm 0.04 \quad \textbf{(Belle)}}$ *i.e.*, the average $\boxed{S_{\eta' K_s} = 0.41 \pm 0.11.}$ displays a $2.5\sigma$ discrepancy.

- New Physcis must have new sources of flavour and CP violation to explain the discrepancy between the CP asymmetries $S_{J/\psi K_s}$, $S_{\eta' K_s}$ and $S_{\phi K_s}$.

# New Physics contributions to $S_{\phi K_S}$

- The time dependent CP asymmetry for $B \to \phi K_S$ can be described by

$$a_{\phi K_s}(t) = \frac{\Gamma(\overline{B}^0(t) \to \phi K_S) - \Gamma(B^0(t) \to \phi K_S)}{\Gamma(\overline{B}^0(t) \to \phi K_S) + \Gamma(B^0(t) \to \phi K_S)} = C_{\phi K_s} \cos \Delta M_{B_d} t + S_{\phi K_s} \sin \Delta M_{B_d} t$$




$C_{\phi K_s}(S_{\phi K_s})$ is direct (mixing) CP asymmetry.

$$C_{\phi K_s} = \frac{|\overline{\rho}(\phi K_S)|^2 - 1}{|\overline{\rho}(\phi K_S)|^2 + 1}, \quad S_{\phi K_s} = \frac{2Im\left[\frac{q}{p}\ \overline{\rho}(\phi K_S)\right]}{|\overline{\rho}(\phi K_S)|^2 + 1}.$$

where $\overline{\rho}(\phi K_S) = \frac{\overline{A}(\phi K_S)}{A(\phi K_S)}$. The mixing parameters $\frac{q}{p} = -e^{-2i\theta_d} \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$.

- We can parametrise the SM and SUSY effects as :

$A^{SM}(\phi K_S) = |A^{SM}| e^{i\delta_{SM}}, \quad A^{NP}(\phi K_S) = |A^{NP}| e^{i\theta_{NP}} e^{i\delta_{NP}}, \quad \delta_{SM(NP)}$ is the strong phase.

- Using this parameterization, we have

$$\boxed{S_{\phi K_S} = \frac{\sin 2\beta + 2R\cos\delta_{12}\sin(\theta+2\beta) + R^2\sin(2\theta+2\beta)}{1+2R\cos\delta_{12}\cos\theta + R^2},}$$

$$\boxed{C_{\phi K_S} = -\frac{2R\sin\delta_{12}\sin\theta}{1+2R\cos\delta_{12}\cos\theta+R^2},}$$

where $R = |A^{\mathrm{NP}}|/|A^{\mathrm{SM}}|$.

Assuming that $|A^{\mathrm{NP}}| < |A^{\mathrm{SM}}|$ we find

$$\begin{aligned} S_{\phi(\eta)K_s} &= \sin 2\beta + 2\cos 2\beta \sin\theta\cos\delta_{12} R, \\ C_{\phi K_s} &= -2\sin\theta\sin\delta_{12} R, \end{aligned}$$

- The Effective Hamiltonian for the $\Delta B = 1$ transitions is given by

$$\mathcal{H}_{\mathrm{eff}}^{\Delta B=1} = \left\{ \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left( C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3}^{10} C_i Q_i + C_{7\gamma} Q_{7\gamma} + C_{8g} Q_{8g} \right) \right\} + \{ Q_i \to \tilde{Q}_i, C_i \to \tilde{C}_i \}$$

where $\lambda_p = V_{pb} V_{ps}^*$, $C_i$ are the Wilson coefficients.

$$
\begin{aligned}
Q_2 &= (\bar{p}b)_{V-A} \quad (\bar{s}p)_{V-A}\,, & Q_1 &= (\bar{p}_\alpha b_\beta)_{V-A} \quad (\bar{s}_\beta p_\alpha)_{V-A}\,,\\
Q_3 &= (\bar{s}b)_{V-A} \quad \sum_q (\bar{q}q)_{V-A}\,, & Q_4 &= (\bar{s}_\alpha b_\beta)_{V-A} \quad \sum_q (\bar{q}_\beta q_\alpha)_{V-A}\,,\\
Q_5 &= (\bar{s}b)_{V-A} \quad \sum_q (\bar{q}q)_{V+A}\,, & Q_6 &= (\bar{s}_\alpha b_\beta)_{V-A} \quad \sum_q (\bar{q}_\beta q_\alpha)_{V+A}\,,\\
Q_7 &= (\bar{s}b)_{V-A} \quad \sum_q \frac{3}{2} e_q (\bar{q}q)_{V+A}\,, & Q_8 &= (\bar{s}_\alpha b_\beta)_{V-A} \quad \sum_q \frac{3}{2} e_q (\bar{q}_\beta q_\alpha)_{V+A}\,,\\
Q_9 &= (\bar{s}b)_{V-A} \quad \sum_q \frac{3}{2} e_q (\bar{q}q)_{V-A}\,, & Q_{10} &= (\bar{s}_\alpha b_\beta)_{V-A} \quad \sum_q \frac{3}{2} e_q (\bar{q}_\beta q_\alpha)_{V-A}\,,\\
Q_{7\gamma} &= \frac{-e}{8\pi^2} m_b \bar{s} \sigma^{\mu\nu} (1+\gamma_5) F_{\mu\nu} b\,, & Q_{8g} &= \frac{-g_s}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu} (1+\gamma_5) G^a_{\mu\nu} \frac{\lambda^a_{\alpha\beta}}{2} b_\beta\,.
\end{aligned}
$$

- **In addition, operators $\tilde{Q}_i$ are obtained from $Q_i$ by the exchange $L \leftrightarrow R$.**

- **$Q_{1,2}$ refer to the current-current operators, $Q_{3-6}$ to the QCD penguin operators, and $Q_{7-10}$ to the electroweak penguin operators, while $Q_{7\gamma}$ and $Q_{8g}$ are the magnetic and the chromomagnetic dipole operators, respectively.**

# Hadronic matrix elements

- To get the decay amplitudes, the most difficult theoretical work is to compute the hadronic matrix elements of the effective operators, $\langle M_1 M_2 | Q_i | B \rangle$

- These matrix elements are usually parametreized by the product of the decay constants and the transition form factors: (Naive factorization)
  i.e. if $Q = j_1 \bigotimes j_2$, then $\langle M_1 M_2 | Q_i | \bar{B} \rangle_F = \langle M_1 | j_1 | \bar{B} \rangle \langle M_2 | j_2 | 0 \rangle$ or $\langle M_2 | j_1 | \bar{B} \rangle \langle M_1 | j_2 | 0 \rangle$.

$$
\begin{aligned}
\langle \phi \bar{K}^0 | Q_1 | \bar{B}^0 \rangle &= 0, & \langle \phi \bar{K}^0 | Q_2 | \bar{B}^0 \rangle &= 0, & \langle \phi \bar{K}^0 | Q_3 | \bar{B}^0 \rangle &= \frac{4}{3} X, \\
\langle \phi \bar{K}^0 | Q_4 | \bar{B}^0 \rangle &= \frac{4}{3} X, & \langle \phi \bar{K}^0 | Q_5 | \bar{B}^0 \rangle &= X, & \langle \phi \bar{K}^0 | Q_6 | \bar{B}^0 \rangle &= \frac{1}{3} X \\
\langle \phi \bar{K}^0 | Q_7 | \bar{B}^0 \rangle &= \frac{3}{2} e_s X, & \langle \phi \bar{K}^0 | Q_8 | \bar{B}^0 \rangle &= \frac{1}{2} e_s X, & \langle \phi \bar{K}^0 | Q_9 | \bar{B}^0 \rangle &= 3 e_s X, \\
\langle \phi \bar{K}^0 | Q_{10} | \bar{B}^0 \rangle &= e_s X, & \langle \phi \bar{K}^0 | Q_{7\gamma} | \bar{B}^0 \rangle &= 0,
\end{aligned}
$$

$$
\langle \phi \bar{K}^0 | Q_{8g} | \bar{B}^0 \rangle = -\frac{\alpha_s}{4\pi} \frac{m_b}{\sqrt{q^2}} \left[ \langle Q_4 \rangle + \langle Q_6 \rangle - \frac{1}{3} \left( \langle Q_3 \rangle + \langle Q_5 \rangle \right) \right].
$$

where $X = 2 F_1^{B \to K}(m_\phi^2) f_\phi m_\phi (p_K \cdot \epsilon_\phi)$.

- However the NF is renormalization scheme and scale dependent. Non-factorizable contributions from higher order corrections must be taken into account

- The QCDF is one of the methods to evaluate these matrix elements. In heavy quark limit $m_b \gg \Lambda_{QCD}$, the QCDF basic formula is

$$\langle \phi \bar{K}^0 | Q_i | \bar{B}^0 \rangle = \langle \phi \bar{K}^0 | Q_i | \bar{B}^0 \rangle_{NF} \left[ 1 + \sum r_n \alpha_s^n + \mathcal{O}\left( \frac{\Lambda_{QCD}}{m_b} \right) \right]$$

- In QCDF approach, the hard gluon (H) and annhilation (A) diagrams contain infrard divergences which are parametrized by $X_{H,A} = \left(1 + \rho_{H,A} e^{i\phi_{H,A}}\right) \ln \left( \frac{\Lambda_{QCD}}{m_b} \right)$

- With $\rho_{H,A} \leq 1$, *i.e. QCDF is well defined*, the results of $A(B \to \phi K_S)$ are very close to the NF predictions.

  If it assumed that these terms are large or dominated then the results are different but the QCDF becomes ill-defined.

- Using the QCDF approach, the amplitude of $B \to \phi K_S$ is given by

$$A(B \to \phi K_S) = -i\frac{G_F}{\sqrt{2}} m_B^2 F_+^{B\to K_S} f_\phi \sum_{i=1..10,7\gamma,8g} H_i(\phi)(\mathrm{C_i} + \tilde{\mathrm{C}}_\mathrm{i})$$

where

$$\begin{array}{rcl}
H_1(\phi) & \simeq & -0.0002 - 0.0002i, \qquad H_2(\phi) \simeq 0.011 + 0.009i \\
H_3(\phi) & \simeq & -1.23 + 0.089i - 0.005X_A - 0.0006X_A^2 - 0.013X_H, \\
H_4(\phi) & \simeq & -1.17 + 0.13i - 0.014X_H, \\
H_5(\phi) & \simeq & -1.03 + 0.053i + 0.086X_A - 0.008X_A^2 \\
H_6(\phi) & \simeq & -0.29 - 0.022i + 0.028X_A - 0.024X_A^2 + 0.014X_H, \\
H_7(\phi) & \simeq & 0.52 - 0.026i - 0.006X_A + 0.004X_A^2, \\
H_8(\phi) & \simeq & 0.18 + 0.037i - 0.019X_A + 0.012X_A^2 - 0.007X_H, \\
H_9(\phi) & \simeq & 0.62 - 0.037i + 0.003X_A + 0.0003X_A^2 + 0.007X_H, \\
H_{10}(\phi) & \simeq & 0.62 - 0.037i + 0.007X_A, \\
H_{7\gamma}(\phi) & \simeq & -0.0004, \qquad H_{8g}(\phi) \simeq 0.047.
\end{array}$$

- The QCDF amplitude has 2 contributions. The terms independent on $X_{A,H}$ supposed to be the dominant. The result is similar to the NF with $q^2 = mb^2/4$.

  Note $\langle \phi \bar{K}_S | Q_i | \bar{B}^0 \rangle = \langle \phi \bar{K}_S | \tilde{Q}_i | \bar{B}^0 \rangle$ where the initial and final states have parity.

- $O_{8g}$ (which plays important rule in SUSY) annihilation is completely ignored in QCDF since it is $\alpha_s$ suppressed in SM.

- Assuming the ahhnilation contribution is large ($\rho_A \sim 10$), then it is not consistent to include it only to $Q_i$.

- The QCDF leads to a small strong phase. Hence direct CP asymmetry is expected to be small.

- $\eta'$ is a mixture of $SU(3)$ singlet $\eta_s = |s\bar{s}\rangle$ and octet $\eta_q = (|u\bar{u}\rangle + |d\bar{d}\rangle)/2$.

  Fixing the hadronic parametres with their center values, we obtain

$$A(B \to \eta' K_S) = -i\frac{G_F}{\sqrt{2}} m_B^2 F_+^{B\to K_s} f_{\eta'}^s \sum_{i=1..10,7\gamma,8g} H_i(\eta')(\mathrm{C_i} - \tilde{\mathrm{C}}_\mathrm{i})$$

  The sign difference between $\mathrm{C_i}$ and $\tilde{\mathrm{C}}_\mathrm{i}$ is due to $\langle \eta' \bar{K}_S | Q_i | \bar{B}^0 \rangle = -\langle \eta' \bar{K}_S | \tilde{Q}_i | \bar{B}^0 \rangle$. Since the initial and final states have opposite parity.

- **The cofficients $H_i(\eta')$ are given by**

$$\begin{aligned}
H_1(\eta') &\simeq -0.0002 - 0.0002i, \qquad H_2(\eta') \simeq 0.011 + 0.009i \\
H_3(\eta') &\simeq -1.23 + 0.089i - 0.005X_A - 0.0006X_A^2 - 0.013X_H, \\
H_4(\eta') &\simeq -1.17 + 0.13i - 0.014X_H, \\
H_5(\eta') &\simeq -1.03 + 0.053i + 0.086X_A - 0.008X_A^2 \\
H_6(\eta') &\simeq -0.29 - 0.022i + 0.028X_A - 0.024X_A^2 + 0.014X_H, \\
H_7(\eta') &\simeq 0.52 - 0.026i - 0.006X_A + 0.004X_A^2, \\
H_8(\eta') &\simeq 0.18 + 0.037i - 0.019X_A + 0.012X_A^2 - 0.007X_H, \\
H_9(\eta') &\simeq 0.62 - 0.037i + 0.003X_A + 0.0003X_A^2 + 0.007X_H, \\
H_{10}(\eta') &\simeq 0.62 - 0.037i + 0.007X_A, \\
H_{7\gamma}(\eta') &\simeq -0.0004, \qquad H_{8g}(\eta') \simeq 0.047.
\end{aligned}$$

- $H_i(\phi)$ **&** $H_i(\eta')$ **show that, apart from the sign difference of $\tilde{C}_i(\phi)$ & $\tilde{C}_i(\eta')$, in QCDF these amplitudes are expected to be different, unlike the case of NF.**

# CP asymmetries in SUSY models

- In SUSY models there are many new CP violating phases beyond $\delta_{CKM}$. These phases can be classified into two categories:

  Flavor-independent phases: phases of $M_i$, $\mu$, $B$, and the diagonal $A_{ii}$.

  Flavor-dependent phases: phases of off–diagonal elements of $A_{ij}$ and $m^2_{ij}$.

- The phases of the first class are strongly constrained by EDMs.

- We find that EDMs can be suppressed in SUSY models with Flavor off-diagonal CP violation. Abel, Bailin, S.K, Lebedev ('00)

- Large phases are allowed if they do not appear in flavor diagonal SUSY breaking in the basis of calculating the EDMs.

- Flavor non-universality and $\delta_{CKM}$ is the only source of CP violation.

  S.K.,V.Sanz ('03)

# Gluino contributions to $S_{\phi K_S}$

- In the super-CKM basis, the quark-squark-gluino interaction is given by

$$\mathcal{L}_{d\tilde{d}\tilde{g}} = \sqrt{2}\, g_s\, T^A_{\alpha\beta} \left[ \left(\bar{d}^\alpha\, P_L\, \tilde{g}^A\right)\, \tilde{d}^\beta_R - \left(\bar{d}^\alpha\, P_R\, \tilde{g}^A\right)\, \tilde{d}^\beta_L + h.c. \right]$$

The dominant gluino contributions are due to the QCD penguin diagrams, and the magnetic and chromoganetic dipole operators.

$$\begin{aligned}
C_3^{\tilde{g}} &= -\frac{\alpha_s^2}{2\sqrt{2}G_F m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[-\frac{1}{9}B_1(x) - \frac{5}{9}B_2(x) - \frac{1}{18}P_1(x) - \frac{1}{2}P_2(x)\right], \\
C_4^{\tilde{g}} &= -\frac{\alpha_s^2}{2\sqrt{2}G_F m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[-\frac{7}{3}B_1(x) + \frac{1}{3}B_2(x) + \frac{1}{6}P_1(x) + \frac{3}{2}P_2(x)\right], \\
C_5^{\tilde{g}} &= -\frac{\alpha_s^2}{2\sqrt{2}G_F m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[\frac{10}{9}B_1(x) + \frac{1}{18}B_2(x) - \frac{1}{18}P_1(x) - \frac{1}{2}P_2(x)\right], \\
C_6^{\tilde{g}} &= -\frac{\alpha_s^2}{2\sqrt{2}G_F m_{\tilde{q}}^2}(\delta^d_{LL})_{23}\left[-\frac{2}{3}B_1(x) + \frac{7}{6}B_2(x) + \frac{1}{6}P_1(x) + \frac{3}{2}P_2(x)\right],
\end{aligned}$$

$$
\begin{aligned}
C^{\tilde{g}}_{7\gamma} &= \frac{8\alpha_s\pi}{9\sqrt{2}G_F m^2_{\tilde{q}}}\left[\left(\delta^d_{LL}\right)_{23} M_3(x) + \left(\delta^d_{LR}\right)_{23}\frac{m_{\tilde{g}}}{m_b} M_1(x)\right], \\
C^{\tilde{g}}_{8g} &= \frac{\alpha_s\pi}{\sqrt{2}G_F m^2_{\tilde{q}}}\left[\left(\delta^d_{LL}\right)_{23}\left(\frac{1}{3}M_3(x) + 3M_4(x)\right) + \left(\delta^d_{LR}\right)_{23}\frac{m_{\tilde{g}}}{m_b}\left(\frac{1}{3}M_1(x) + 3M_3(x)\right)\right],
\end{aligned}
$$

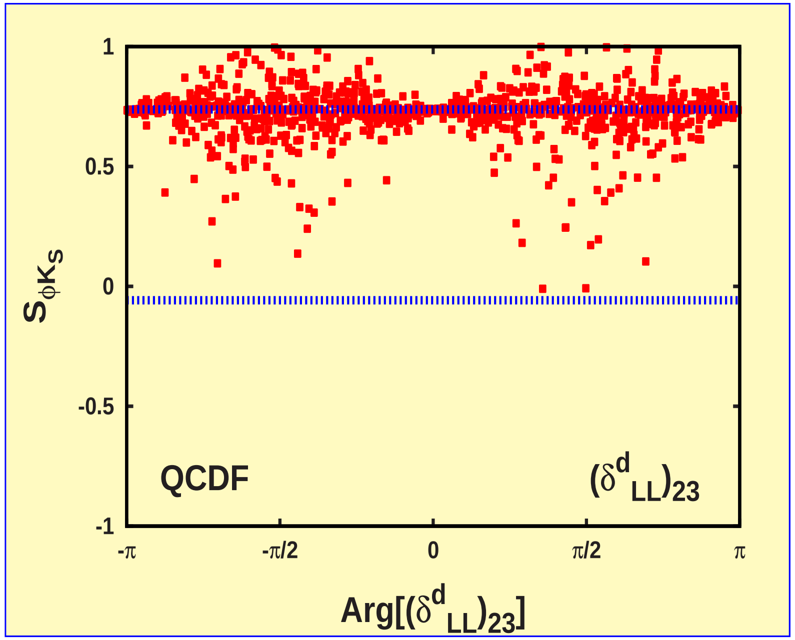
- For $m_{\tilde{q}} = m_g = 500$**GeV** we have

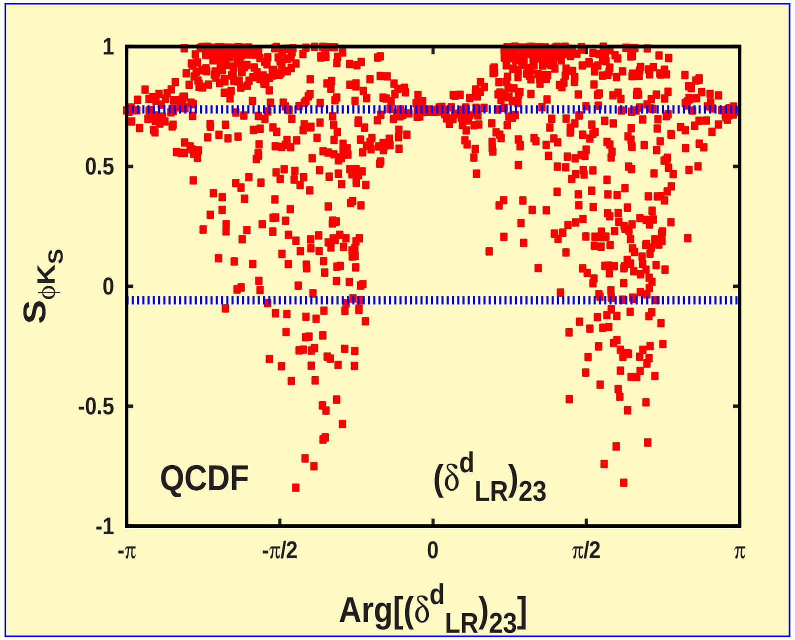
$$
\begin{aligned}
\mathcal{R}_\phi|^{NF}_{\tilde{g}} &\simeq \left\{-0.08\left(\delta^d_{LL}\right)_{23} - 120\left(\delta^d_{LR}\right)_{23}\right\} + \{L \leftrightarrow R\}, \\
\mathcal{R}_\phi|^{QCDF}_{\tilde{g}} &\simeq \left\{-0.14 \times e^{-i\,0.1}\left(\delta^d_{LL}\right)_{23} - 127 \times e^{-i\,0.08}\left(\delta^d_{LR}\right)_{23}\right\} + \{L \leftrightarrow R\}
\end{aligned}
$$

- Using the constraints on each $(\delta^d_{AB})_{23}$ the maximum contributions are:

$$
\left|\mathbf{R_{LL(RR)}}\right| \lesssim \mathbf{0.14}, \quad \left|\mathbf{R_{LR(RL)}}\right| \lesssim \mathbf{1.2}.
$$

- The largest SUSY effect is provided by the gluino contributions to the chromo-magnetic operator which are proportional to $\left(\delta^d_{LR}\right)_{23}$ and $\left(\delta^u_{LL}\right)_{32}$.




Gluino contribution to $S_{\Phi K_S}$ as a function of arg[$\left(\delta^d_{LL}\right)_{23}$] and arg[$\left(\delta^d_{LR}\right)_{23}$].

- We scanned over the full range of the parameters $\rho_{A,H}$ and $\phi_{A,H}$. Howevere we found that by requiring that the SUSY contribution to the branching ratio and asymmetries of $B \to \phi K_S$ is inside the $2\sigma$ experimental range, an upper bound on $\rho_A$ of order $\rho_A \simeq 2$ is obtained.

- **In minmal supergravity model, for $m_{1/2} \simeq m_0 \simeq A_0 \simeq 200$ GeV we find the following values of the relevant mass insertions:**

$$\begin{aligned}(\delta^d_{LL})_{23} &\simeq 0.009 + i\ 0.001,\\ (\delta^d_{RR})_{23} &\simeq -2.1\times 10^{-7} - i\ 2.5\times 10^{-8},\\ (\delta^d_{LR})_{23} &\simeq -2.5\times 10^{-5} - i\ 1.9\times 10^{-5}.\end{aligned}$$

- **Thus the total $S_{\phi K_s}$ in this case is given by $S_{\phi K_s} = 0.729$, which is about the value of $\sin 2\beta$.**

- **Non-universal soft terms with large Yukawa mixings lead to the following values of the mass insertion $(\delta^d_{LR})_{23}$:**

  $|(\delta^d_{LR})_{23}| \simeq 0.005$ and $\mathrm{Arg}[(\delta^d_{LR})_{23}] \simeq 1.2$ **which leads to** $\boxed{S_{\phi K_s} \simeq -0.2}$

# Chargino contributions to $S_{\phi K_S}$

- Chargino is light in many SUSY models, so it might lead to significant contributions.

- The chargino contributions depend on the flavour structure of the up-squark, which is not strongly constrained by $B-\bar{B}$ or $BR(b \to s\gamma)$.

- The Wilson coefficients of the chargino contributions are give by:

$$
\begin{aligned}
C_3^{\chi^+} &= \frac{\alpha}{6\pi}\frac{1}{\sin^2\theta_w}\left(B_d^{\chi^+} + B_u^{\chi^+}/2 + C^{\chi^+}\right) - \frac{\alpha_s}{24\pi}E^{\chi^+}, \quad C_4^{\chi^+} = \frac{\alpha_s}{8\pi}E^{\chi^+}, \quad C_5^{\chi^+} = -\frac{\alpha_s}{24\pi}E^{\chi^+}, \\
C_6^{\chi^+} &= \frac{\alpha_s}{8\pi}E^{\chi^+}, \qquad C_7^{\chi^+} = \frac{\alpha}{6\pi}\left(4C^{\chi^+} + D^{\chi^+}\right), \qquad C_8^{\chi^+} = 0, \\
C_9^{\chi^+} &= \frac{\alpha}{6\pi}\left(4C^{\chi^+} + D^{\chi^+} + \frac{1}{\sin^2\theta_w}\left(-B_d^{\chi^+} + B_u^{\chi^+} - 4C^{\chi^+}\right)\right), \\
C_{10}^{\chi^+} &= 0, \qquad C_{7\gamma}^{\chi^+} = M^{\gamma}, \qquad C_{8g}^{\chi^+} = M^{g}.
\end{aligned}
$$

- At the first order in MIA, the chargino functions are given by

$$\begin{aligned} F^{\chi} &= [\sum_{a,b} K^{\star}_{a2} K_{b3} (\delta^u_{LL})_{ba}] R^{LL}_F + [\sum_{a} K^{\star}_{a2} K_{33} (\delta^u_{RL})_{3a}] Y_t\, R^{RL}_F \\ &+ [\sum_{a} K^{\star}_{32} K_{a3} (\delta^u_{LR})_{a3}] Y_t\, R^{LR}_F + [K^{\star}_{32} K_{33} (\delta^u_{RR})_{33}] Y_t^2 R^{RR}_F, \end{aligned}$$

- The dominant contributions which turn out to be due to the chromomagnetic ($M^g$) penguin and $Z$-penguin ($C$) diagrams.

- From the above expressions, it is clear that $LR$ and $RR$ contributions are suppressed by order $\lambda^2$ or $\lambda^3$.

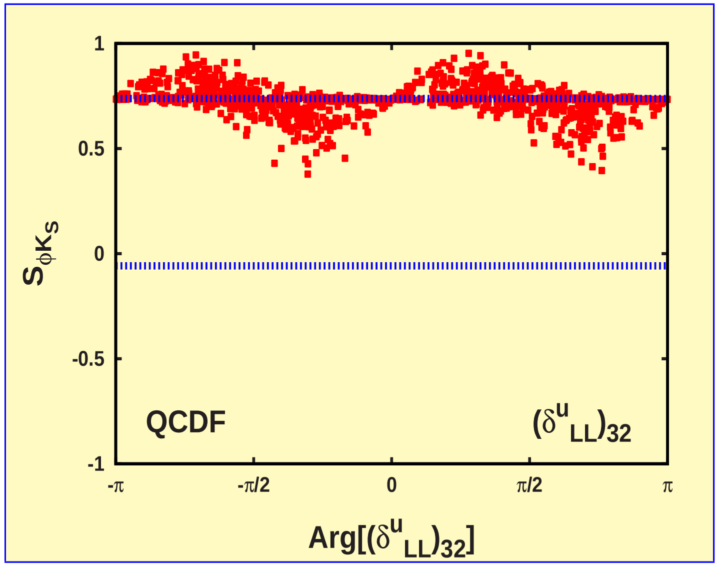
$$\begin{aligned} R^{LL}_C &= \sum_{i=1,2} |V_{i1}|^2 P^{(0)}_C(\bar{x}_i) + \sum_{i,j=1,2} \left[ U_{i1} V_{i1} U^{\star}_{j1} V^{\star}_{j1}\, P^{(2)}_C(x_i, x_j) + |V_{i1}|^2 |V_{j1}|^2 \left( \frac{1}{8} - P^{(1)}_C(x_i, x_j) \right) \right] \\ R^{RL}_C &= -\frac{1}{2} \sum_{i=1,2} V^{\star}_{i2} V_{i1}\, P^{(0)}_C(\bar{x}_i) - \sum_{i,j=1,2} V^{\star}_{j2} V_{i1} \left( U_{i1} U^{\star}_{j1}\, P^{(2)}_C(x_i, x_j) + V^{\star}_{i1} V_{j1}\, P^{(1)}_C(x_i, x_j) \right) \\ R^{LL}_{M^{\gamma,g}} &= \sum_i |V_{i1}|^2 x_{Wi} P^{LL}_{M^{\gamma,g}}(x_i) - Y_b \sum_i V_{i1} U_{i2} x_{Wi} \frac{m_{\chi_i}}{m_b} P^{LR}_{M_{\gamma,g}}(x_i), \quad R^{RL}_{M^{\gamma,g}} = -\sum_i V_{i1} V^{\star}_{i2} x_{Wi} P^{LL}_{M_{\gamma,g}}(x_i) \end{aligned}$$

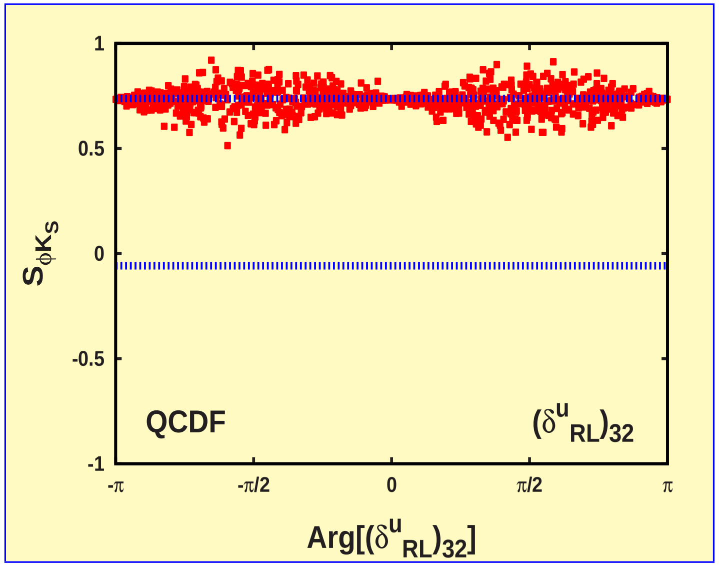
- **For** $M_2 = 200$ **GeV,** $\mu = 300$ **GeV,** $\tilde{m}_{\tilde{t}_R} = 150$ **GeV, and** $\tan\beta = 40$, **we have**

$\mathcal{R}_\phi|_\chi^{NF} \simeq 1.83(\delta^u_{LL})_{32} - 0.32(\delta^u_{RL})_{32} + 0.41(\delta^u_{LL})_{31} - 0.07(\delta^u_{RL})_{31},$

$\mathcal{R}_\phi|_\chi^{QCDF} \simeq 1.89\ e^{-i0.07}(\delta^u_{LL})_{32} - 0.11\ e^{-i0.17}(\delta^u_{RL})_{32} + 0.43\ e^{-i0.07}(\delta^u_{LL})_{31} - 0.02\ e^{-i0.17}(\delta^u_{RL})_{31}$

**The** $b \to s\gamma$ **constraint:** $|(\delta^u_{LL})_{23}| < 0.2$, **implies that** $|R^\chi| \lesssim 0.35$




**Chargino contribution to** $S_{\Phi K_S}$ **as a function of arg[**$\left(\delta^u_{LL}\right)_{32}$**] and arg[**$\left(\delta^u_{RL}\right)_{32}$**].**

**Therefore, the gluino contribution can easily give the dominant contribution to** $S_{\phi K_s}$ **while chragino is subdominant.**

# CP asymmetry in $B \to \eta' K_S$ decay

- Recent measurements of CP asymmetry in $B \to \eta' K_S$ show another discrepancy with SM predictions, although less pronounced than in $B \to \phi K_S$.

$$S_{B\to\eta' K_s} = 0.27 \pm 0.21$$

which is about $2.2\sigma$ deviation from SM one.

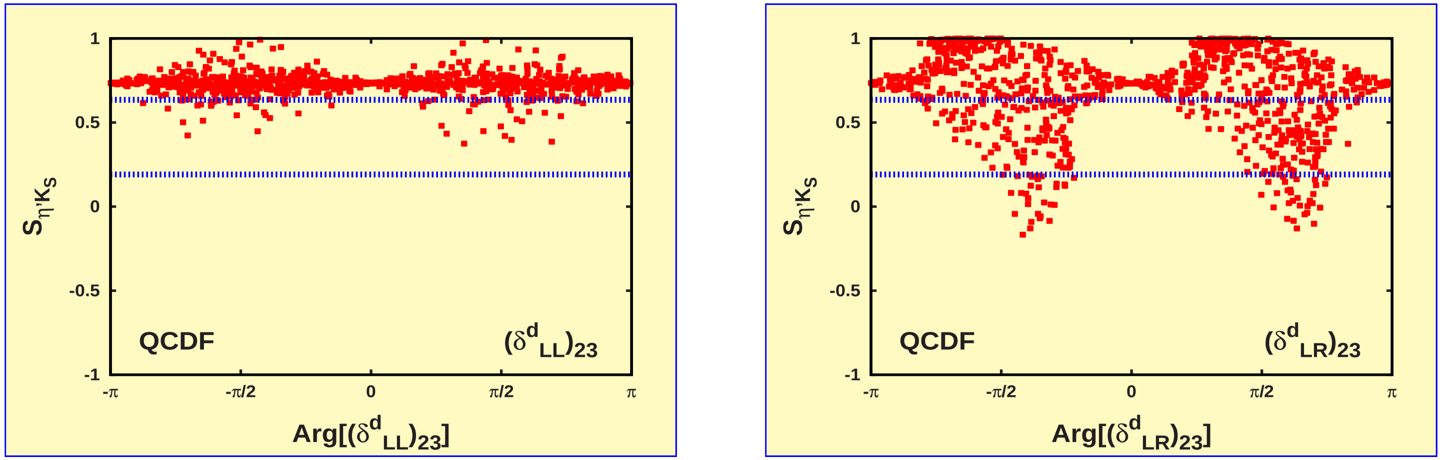
- For gluino contributions we have

$$\begin{aligned}
\mathcal{R}_{\eta'}|_{\tilde{g}}^{NF} &\simeq \left\{-0.08\,(\delta^d_{LL})_{23} - 79\,(\delta^d_{LR})_{23}\right\} - \{L \leftrightarrow R\}, \\
\mathcal{R}_{\eta'}|_{\tilde{g}}^{QCDF} &\simeq \left\{-0.07 \times e^{i\,0.24}(\delta^d_{LL})_{23} - 64(\delta^d_{LR})_{23}\right\} - \{L \leftrightarrow R\},
\end{aligned}$$

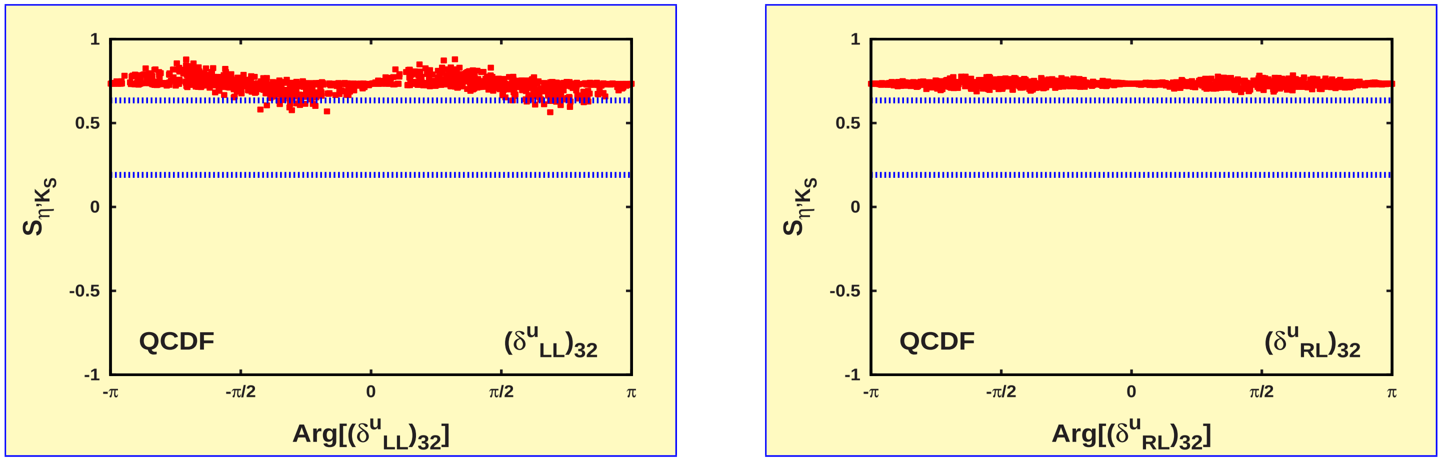
while for chargino exchanges we obtain

$$\begin{aligned}
\mathcal{R}_{\eta'}|_{\chi}^{NF} &\simeq 1.2\,(\delta^u_{LL})_{32} - 0.01\,(\delta^u_{RL})_{32} + 0.27\,(\delta^u_{LL})_{31} - 0.002\,(\delta^u_{RL})_{31}, \\
\mathcal{R}_{\eta'}|_{\chi}^{QCDF} &\simeq 0.95\,(\delta^u_{LL})_{32} - 0.025 \times e^{-i\,0.19}(\delta^u_{RL})_{32} + 0.21(\delta^u_{LL})_{31} - 0.006 \times e^{-i0.19}(\delta^u_{RL})_{31}.
\end{aligned}$$

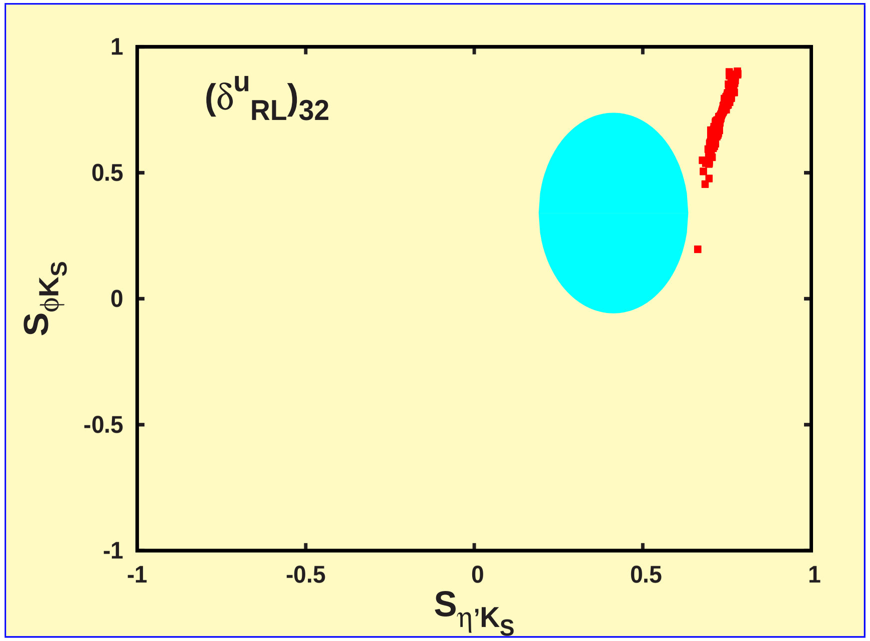
- The coefficients of $\left(\delta^d_{LR}\right)_{23}$ and $\left(\delta^u_{LL}\right)_{32}$ are smaller than those in $B \to \phi K_S$, due to the fact that the SM amplitude of $A(B \to \eta' K_S)$ receives contribution from tree-level W exchanges and it is larger than $A(B \to \phi K_S)$.

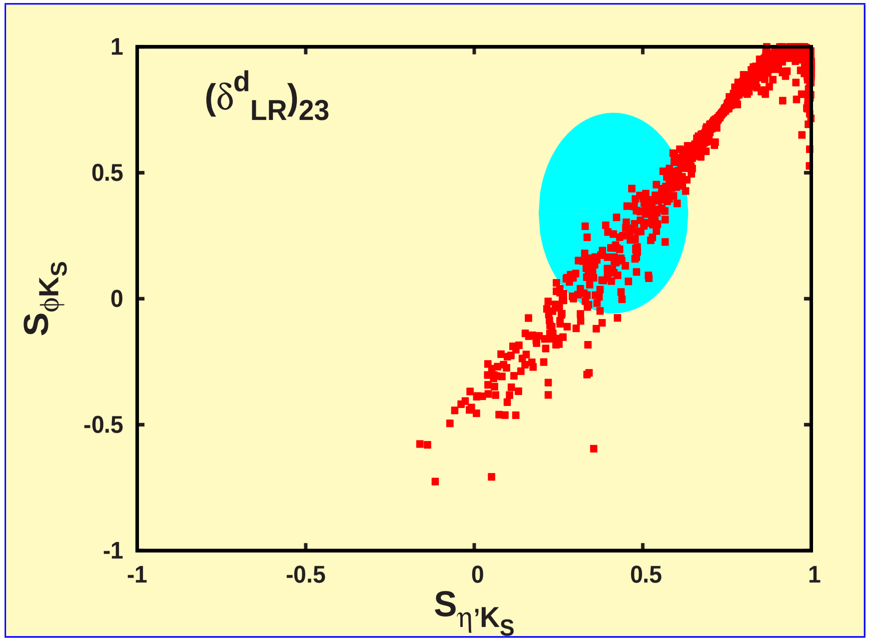



Gluino contribution to $S_{\eta' K_S}$ as a function of arg[$\left(\delta^d_{LL}\right)_{23}$] and arg[$\left(\delta^d_{RL}\right)_{23}$].

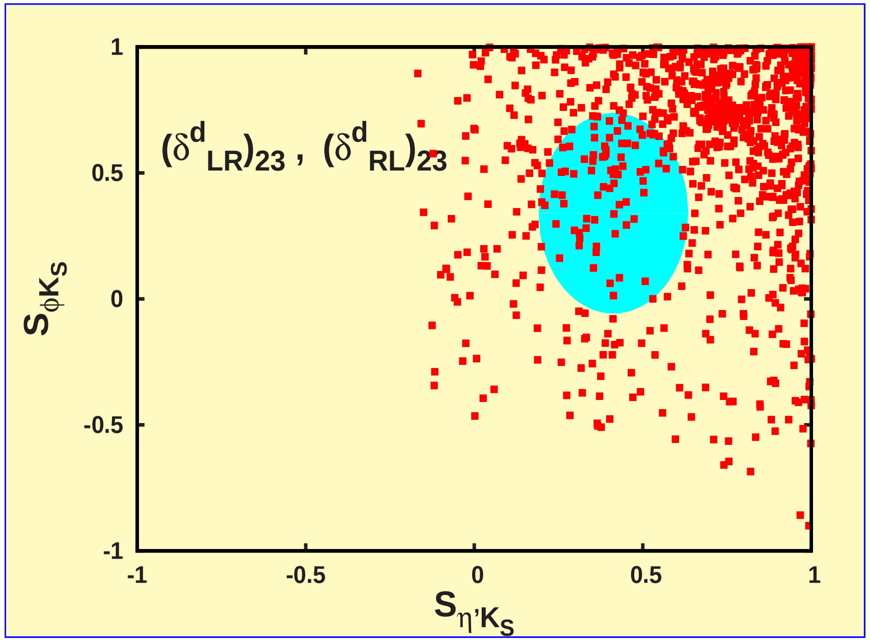


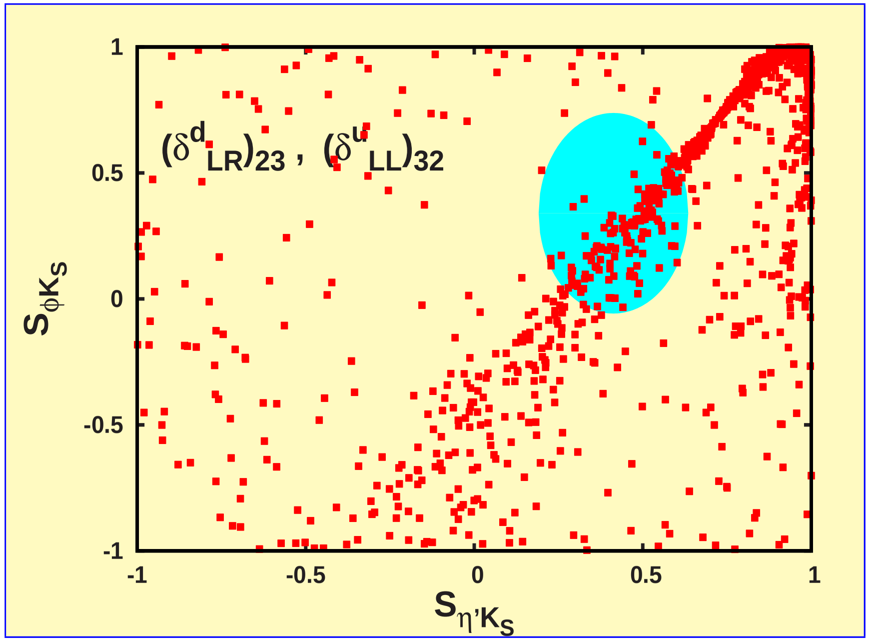

Chargino contribution to $S_{\eta' K_S}$ as a function of arg[$\left(\delta^u_{LL}\right)_{32}$] and arg[$\left(\delta^u_{RL}\right)_{32}$].




**Correlation of asymmetries $S_{\Phi K_S}$ versus $S_{\eta' K_S}$ with the contribution of one mass insertion $\left(\delta^u_{RL}\right)_{32}$ (left) and $\left(\delta^d_{LR}\right)_{23}$ (right), for chargino (left) and gluino (right) exchanges. Colored area corresponds to experimental allowed region of the $2\sigma$ ellipse.**




**Correlation of asymmetries $S_{\Phi K_s}$ versus $S_{\eta' K_s}$ for arg[$(\delta^d_{LR})_{23}$]=arg[$(\delta^d_{RL})_{23}$] (left) and arg[$(\delta^d_{LR})_{23}$]=arg[$(\delta^u_{LL})_{32}$] (right), with the contribution of two mass insertions $(\delta^d_{LR})_{23}$ & $(\delta^d_{RL})_{23}$ (left) for gluino exchanges, and $(\delta^d_{LR})_{23}$ & $(\delta^u_{LL})_{32}$ (right) for both gluino and chargino exchanges.**

# SUSY contributions to strange quark EDM

- The major contributions to the EDMs come from electric and chromoelectric dipole operators and the Weinberg three-gluon operator:

$$\mathcal{L} = -\frac{i}{2} d_q^E \bar{q} \sigma_{\mu\nu} \gamma_5 q F^{\mu\nu} - \frac{i}{2} d_q^C \bar{q} \sigma_{\mu\nu} \gamma_5 T^a q G^{a\mu\nu} - \frac{1}{6} d^G f_{abc} G_{a\mu\rho} G_{b\nu}^{\rho} G_{c\lambda\sigma} \epsilon^{\mu\nu\lambda\sigma}$$

- The resulting EDM of the mercury atom is given by

$$d_{H_g} = -e(d_d^C - d_u^C - 0.012 d_s^C) \times 3.2 \times 10^{-2}$$

- The 1-loop gluino contribution to the $d_s^C$ is given by $d_s^C = \frac{g_s \alpha_s}{4\pi} \frac{m_{\tilde{g}}}{m_{\tilde{d}}^2} \mathbf{Im}(\delta_{LR}^d)_{22} \, M_2(x)$,

- The exper. limit on $d_{Hg}$ leads to the stringent bounds:

$$\mathbf{Im}(\delta_{LR}^d)_{11} < 6.7 \times 10^{-8}, \qquad \mathbf{Im}(\delta_{LR}^d)_{22} < 5.6 \times 10^{-6}.$$

- **The explicit dependencies of $(\delta^d_{LR})_{22}$ and $(\delta^d_{RL})_{22}$ on the LL and RR mixing between the second and the third generations are given by**

$$(\delta^d_{LR})_{22} = (\delta^d_{LL})_{23}\ (\delta^d_{LR})_{33}\ (\delta^d_{RR})_{32} + \left[(\delta^d_{RR})_{23}\ (\delta^d_{RL})_{33}\ (\delta^d_{LL})_{32}\right]^*,$$

**where** $(\delta^d_{LR})_{33} = (\delta^d_{RL})^*_{33} \sim \frac{m_b(A_b - \mu\tan\beta)}{m^2_{\tilde{d}}}$.

- **Since $(\delta^d_{LR})_{33} \sim m_b/m_{\tilde{d}} \sim 10^{-2}$ and $(\delta^d_{LL(RR)})_{32} = (\delta^d_{LL(RR)})^*_{23}$, one finds**

$$(\delta^d_{LR})_{22} \simeq 10^{-2}\left[(\delta^d_{LL})_{23}\ (\delta^d_{RR})^*_{23} + \left((\delta^d_{RR})_{23}\ (\delta^d_{LL})^*_{23}\right)^*\right]$$

**Furthermore, $(\delta^d_{LR})_{22}$ can also be expressed as**

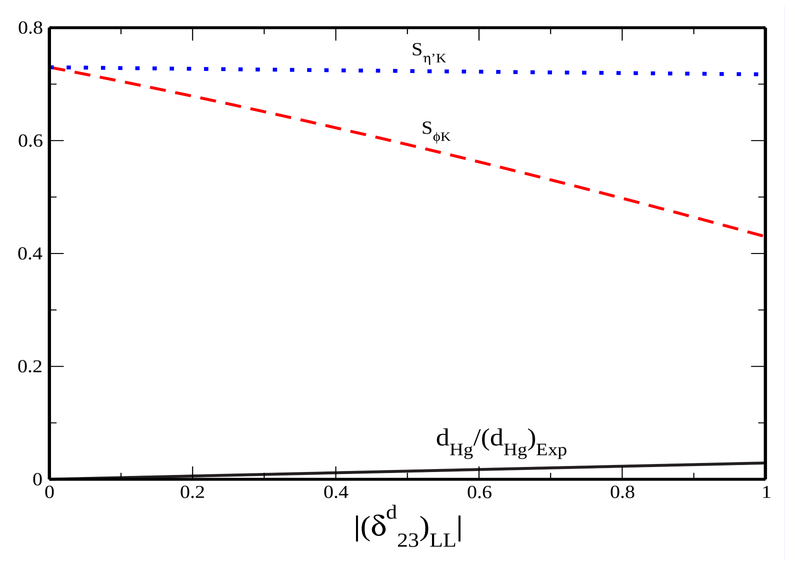
$$(\delta^d_{LR})_{22} = (\delta^d_{LL})_{23}\ (\delta^d_{LR})_{32} + \left[(\delta^d_{RR})_{23}\ (\delta^d_{RL})_{32}\right]^*, \tag{1}$$

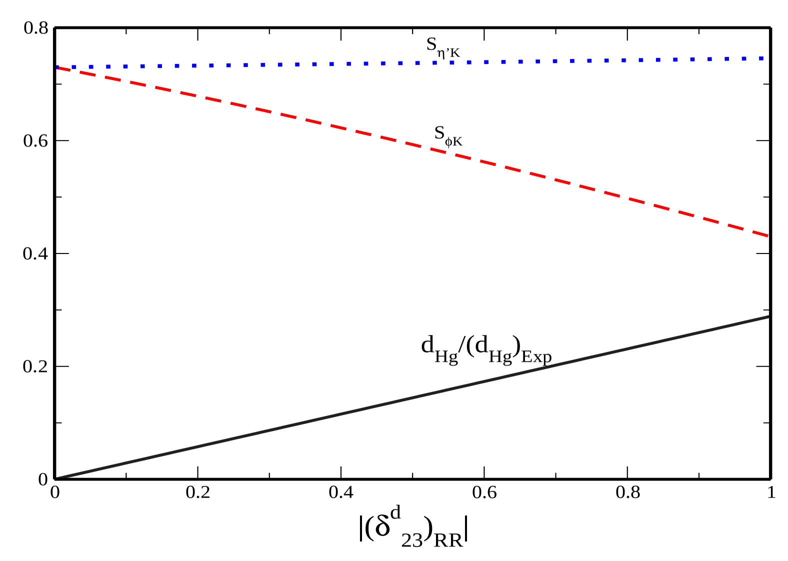
**where** $(\delta^d_{LR})_{32} = (\delta^d_{RL})^*_{23}$.

# EDM constraints on $S_{\phi K}$ and $S_{\eta' K}$

- Large values for $(\delta^d_{LL})_{23}$ & $(\delta^d_{RR})_{23}$ may significantly enhance the strange quark EDM, overproduce $d_{Hg}$ and possibly $d_n$.

- With dominated $(\delta^d_{LL})_{23}$ or $(\delta^d_{RR})_{23}$, the Im$(\delta^d_{LR})_{22}$ can easily be below the experimental bound.



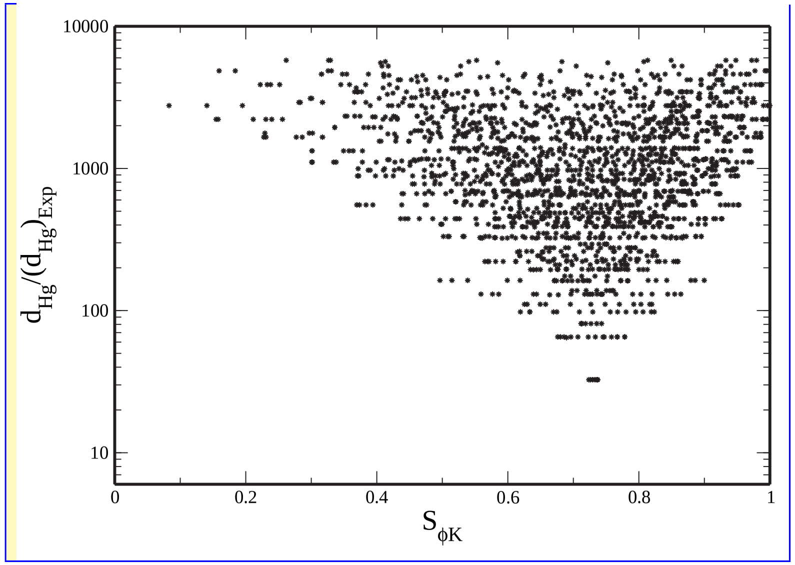
- **In these scenarios, Hg EDM is well below the current experimental limit.**

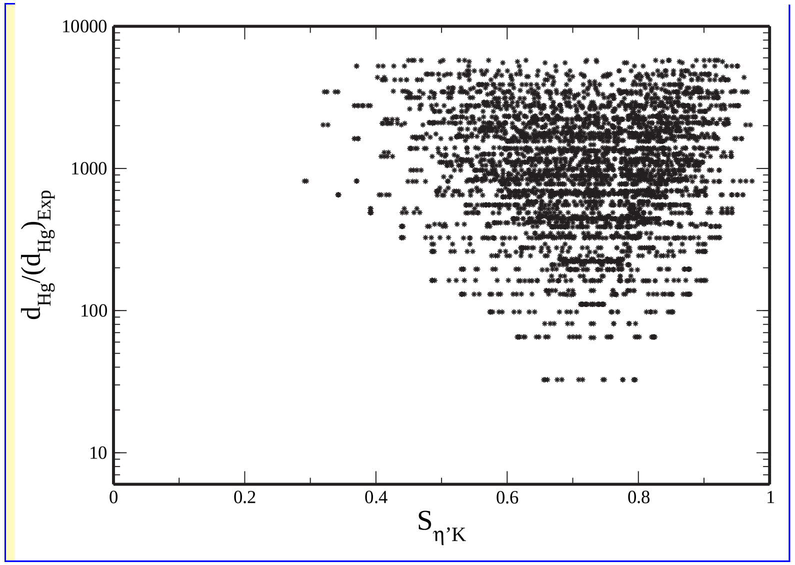
- **However, we cannot account for the CP asymmetries $S_{\phi K}$ and $S_{\eta' K}$, particularly $S_{\eta' K}$**

- **Thus, if the present $S_{\eta' K}$ result is confirmed, these models will be disfavored.**

- **In the case of combined effects of $(\delta^d_{LL})_{23}$ and $(\delta^d_{RR})_{23}$, $S_{\phi K}$ and $S_{\eta' K}$ can fit the experimental data, BUT the Hg EDM exceeds with many order of magnitudes its experimental bound.**

- **This imposes severe constraints on this scenario of simultaneous contribution from $LL$ and $RR$ mixing to accommodate both the experimental results of $S_{\phi K}$ and $S_{\eta K}$.**




- $m_0 = m_g = 400$ **GeV, other parameters are scanned as follows:** $|(\delta^d_{LL})_{23}|$ **varies from** 0 **to** 1**,** $\arg[(\delta^d_{LL})_{23}]$ **and** $\arg[(\delta^d_{RR})_{23}]$ **are in the region** $[-\pi, \pi]$**.**

- **Even if the** $d_s$ **contribution to the** $d_{Hg}$ **were reduced by an order of magnitude, this conclusion is unchanged.**

# Conclusions

- we can safely conclude that SUSY models with dominant $LL$ and/or $RR$ large mixing between second and third generations will be ruled out if the experimental results of $S_{\phi K}$, $S_{\eta K}$ are confirmed.

- SUSY models with dominant $LR$ and/or $RL$ mixing via non-universal $A$-terms, seem to be the simplest way to account for CP asymmetry $S_{\phi K}$ and $S_{\eta K}$ without conflicting with EDMs or any other experimental results.

- More precise measurements would certainly allow us to draw more definite conclusions on the SUSY models that can accommodate these data.