$B_s - \bar{B}_s$ mixing and $B_s \to KK$ decays within supersymmetry

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S.B, D. London, J. Matias, J. Virto, JHEP0602, 027(2006);
S.B, JHEP0609, 077(2006);
S.B, D. London, J. Matias, J. Virto, JHEP0612, 019(2006);
S.B, D. London, work in progress

In collaboration with D. London, J. Matias, J. Virto

Outline

- Motivation: "$B \to \pi K$ puzzle"
- SUSY model with large isospin violation-Grossman-Neubert-Kagan (GNK) scenario
- Strong constraint from Δm_s
- $B_s \to KK$ decays in GNK scenario
- Conclusions

$B \to \pi K$ puzzle

In the SM,

$$A(B^+ \to \pi^+ K^0) = -P'$$

$$\sqrt{2} A(B^+ \to \pi^0 K^+) = P' - T' e^{i\gamma} - P'_{EW} - C' e^{i\gamma}$$

$$A(B^0 \to \pi^- K^+) = P' - T' e^{i\gamma}$$

$$\sqrt{2} A(B^0 \to \pi^0 K^0) = -P' - P'_{EW} - C' e^{i\gamma}$$

- In the SM:

  - ✓ $P' \gg T' \approx P'_{EW} \gg C'$
  - ✓ $R_c \approx R_n$

$$R_n \equiv \frac{1}{2}\frac{BR[B_d^0 \to \pi^- K^+] + BR[\bar{B}_d^0 \to \pi^+ K^-]}{BR[B_d^0 \to \pi^0 K^0] + BR[\bar{B}_d^0 \to \pi^0 \bar{K}^0]} ,$$

$$R_c \equiv 2\frac{BR[B_d^+ \to \pi^0 K^+] + BR[B_d^- \to \pi^0 K^-]}{BR[B_d^+ \to \pi^+ K^0] + BR[B_d^- \to \pi^- \bar{K}^0]} .$$

  - ✓ $A_{CP}(B^+ \to \pi^0 K^+) \approx A_{CP}(B^0 \to \pi^- K^+)$
  - ✓ $S_{CP}(B^0 \to \pi^0 K^0) \approx \sin 2\beta$

[G. Hou's talk]

- R_c / R_n problem has disappeared!!

  Buras, Fleischer, Recksiegel, Schwab (04,05,06)

- $A_{CP}(\pi^0 K^+)$ = 0.047±0.026

  $A_{CP}(\pi^- K^+)$=−0.093±0.015

  [G. Hou's talk]

- $S(\pi^0 K^0)$ = 0.33±0.21

  $\sin(2\beta)$(charmonium)=0.675±0.026

- |C'/T'|=1.6±0.3 mainly due to A_{CP}, $S(\pi^0 K^0)$

  SB, London, hep-ph/0701181

cf. In $b \to d$ transition, |C/T|=0.28±0.15 (Combined analysis of $B\to\pi\pi$, $B\to K\bar{K}$).

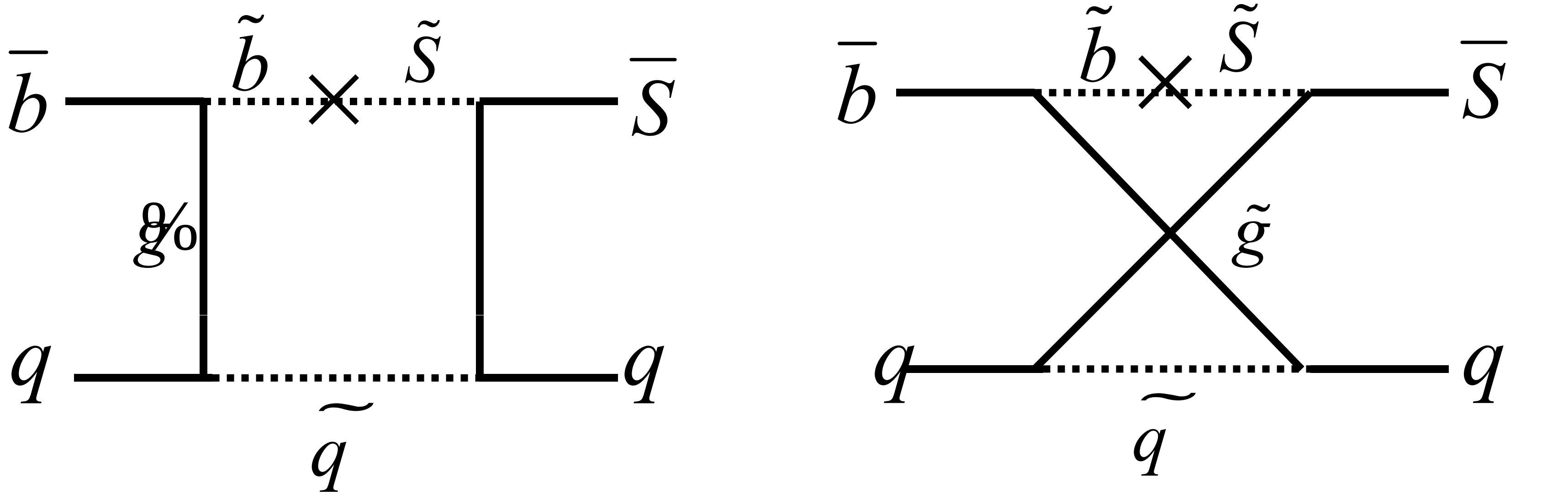
  SB, arXiv:0707.2838

→can be solved by NP in the EW-penguin

GNK scenario

- Z-mediated EW-peguin in SUSY is suppressed.

- "Trojan penguin?" Grossman, Neubert, Kagan(99)



- Large enhancement in EW-peguin sector: $\dfrac{\alpha_s^2 / M_{SUSY}^2}{\alpha_{ew}^2 / M_W^2}$

Structure of squark mass matrix

Squark mass matrix:

$K - \bar{K}$

$B_d - \bar{B}_d$

$$M^2_{\tilde{d},LL} = \begin{pmatrix} \tilde{m}^{d,2}_{L_{11}} & 0 & 0 \\ 0 & \tilde{m}^{d,2}_{L_{22}} & \tilde{m}^{d,2}_{L_{23}} \\ 0 & \tilde{m}^{d,2}_{L_{32}} & \tilde{m}^{d,2}_{L_{33}} \end{pmatrix}, \quad M^2_{\tilde{d},LR(RL)} \equiv 0_{3\times 3}.$$

$B(B \to X_s \gamma)$

$$M^2_{\tilde{d},RR} = M^2_{\tilde{d},LL}|_{L\leftrightarrow R}$$

Squark mixing:

$$\Gamma_L M^2_{\tilde{d},LL} \Gamma_L^\dagger = \mathrm{diag}(m^2_{\tilde{d}_L}, m^2_{\tilde{s}_L}, m^2_{\tilde{b}_L}),$$

$$\Gamma_L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L\, e^{i\delta_L} \\ 0 & -\sin\theta_L\, e^{-i\delta_L} & \cos\theta_L \end{pmatrix}.$$

$$\tilde{s}_L = \cos\theta_L\, \tilde{s}_L^0 - \sin\theta_L\, e^{-i\delta_L}\, \tilde{b}_L^0$$

$$\tilde{b}_L = \sin\theta_L\, e^{i\delta_L}\, \tilde{s}_L^0 + \cos\theta_L\, \tilde{b}_L^0$$

Large 2-3 mixing motivated by SUSY GUT.

S.B., T. Goto, Y. Okada, K. Okumura(01), Chang, Masiero, Murayama(02)

Oversimplified but useful in constraining 2-3 mixing.

$$H_{\rm eff}^{NP} = \frac{G_F}{\sqrt{2}} \left[\sum_{i,q=u,d} \left(c_i^q(\mu)\, O_i^q + \tilde{c}_i^q(\mu)\, \tilde{O}_i^q \right) + C_{8g}(\mu)\, Q_{8g} + \tilde{C}_{8g}(\mu)\, \tilde{Q}_{8g} \right] ,$$

$$\begin{aligned}
O_1^q &= (\bar{b}_\alpha s_\alpha)_{V-A} (\bar{q}_\beta q_\beta)_{V+A} \quad , \qquad O_2^q = (\bar{b}_\alpha s_\beta)_{V-A} (\bar{q}_\beta q_\alpha)_{V+A} \ , \\
O_3^q &= (\bar{b}_\alpha s_\alpha)_{V-A} (\bar{q}_\beta q_\beta)_{V-A} \quad , \qquad O_4^q = (\bar{b}_\alpha s_\beta)_{V-A} (\bar{q}_\beta q_\alpha)_{V-A} \ , \\
O_5^q &= (\bar{b}_\alpha q_\alpha)_{V-A} (\bar{q}_\beta s_\beta)_{V+A} \quad , \qquad O_6^q = (\bar{b}_\alpha q_\beta)_{V-A} (\bar{q}_\beta s_\alpha)_{V+A} \ , \\
Q_{8g} &= (g_s/8\pi^2) m_b \bar{b} \sigma_{\mu\nu} (1-\gamma_5) G^{\mu\nu} s \ .
\end{aligned}$$

$$\begin{aligned}
c_1^q &= \frac{\alpha_s^2 \sin 2\theta_L e^{i\delta_L}}{4\sqrt{2} G_F m_{\tilde{g}}^2} \left[\frac{1}{18} F(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) - \frac{5}{18} G(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) + \frac{1}{2} A(x_{\tilde{b}_L \tilde{g}}) + \frac{2}{9} B(x_{\tilde{b}_L \tilde{g}}) \right] \\
&\qquad - (x_{\tilde{b}_L \tilde{g}} \to x_{\tilde{s}_L \tilde{g}}) \\
c_2^q &= \frac{\alpha_s^2 \sin 2\theta_L e^{i\delta_L}}{4\sqrt{2} G_F m_{\tilde{g}}^2} \left[\frac{7}{6} F(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) + \frac{1}{6} G(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_R \tilde{g}}) - \frac{3}{2} A(x_{\tilde{b}_L \tilde{g}}) - \frac{2}{3} B(x_{\tilde{b}_L \tilde{g}}) \right] \\
&\qquad - (x_{\tilde{b}_L \tilde{g}} \to x_{\tilde{s}_L \tilde{g}}) \\
c_3^q &= \frac{\alpha_s^2 \sin 2\theta_L e^{i\delta_L}}{4\sqrt{2} G_F m_{\tilde{g}}^2} \left[-\frac{5}{9} F(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_L \tilde{g}}) + \frac{1}{36} G(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_L \tilde{g}}) + \frac{1}{2} A(x_{\tilde{b}_L \tilde{g}}) + \frac{2}{9} B(x_{\tilde{b}_L \tilde{g}}) \right] \\
&\qquad - (x_{\tilde{b}_L \tilde{g}} \to x_{\tilde{s}_L \tilde{g}}) \\
c_4^q &= \frac{\alpha_s^2 \sin 2\theta_L e^{i\delta_L}}{4\sqrt{2} G_F m_{\tilde{g}}^2} \left[\frac{1}{3} F(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_L \tilde{g}}) + \frac{7}{12} G(x_{\tilde{b}_L \tilde{g}}, x_{\tilde{q}_L \tilde{g}}) - \frac{3}{2} A(x_{\tilde{b}_L \tilde{g}}) - \frac{2}{3} B(x_{\tilde{b}_L \tilde{g}}) \right] \\
&\qquad - (x_{\tilde{b}_L \tilde{g}} \to x_{\tilde{s}_L \tilde{g}})
\end{aligned}$$

- Large SUSY contribution is possible when
  - small gluino mass
  - $m^2_{\tilde{s}_{L,R}} \gg m^2_{\tilde{b}_{L,R}}$
  - $|\sin 2\theta_L|$ or $|\sin 2\theta_R|$ not far below 1
  - $m^2_{\tilde{d}_R} \gg m^2_{\tilde{u}_R}$ cf. $m^2_{\tilde{d}_L} = m^2_{\tilde{u}_L}$ by SU(2)

- $c_1^{\rm EW}$, $c_2^{\rm EW}$, $\tilde{c}_3^{\rm EW}$ and $\tilde{c}_4^{\rm EW}$ can get large SUSY contributions ($c_i^{\rm EW} \equiv c_i^u - c_i^d$).

$B_s - \bar{B}_s$ mixing

- $B_s - \bar{B}_s$ mass difference:

$$17\ \mathrm{ps}^{-1} < \Delta m_s < 21\ \mathrm{ps}^{-1} \quad (90\%\ \mathrm{CL}), \qquad \text{(D0)}$$

$$\Delta m_s = 17.33^{+0.42}_{-0.21} \pm 0.07\ \mathrm{ps}^{-1}, \qquad \text{(CDF)}$$

$$\Delta m_s^{\mathrm{SM}}(\mathrm{UTfit}) = 21.5 \pm 2.6\ \mathrm{ps}^{-1}, \quad \Delta m_s^{\mathrm{SM}}(\mathrm{CKMfit}) = 21.7^{+5.9}_{-4.2}\ \mathrm{ps}^{-1}$$

- Consistent with the SM CKM fits.
- Constrains NP models sensitive to Δm_s [G. Hou's talk]

Effective Hamiltonian

$$H_{\rm eff} = \sum_{i=1}^{5} C_i O_i + \sum_{i=1}^{3} \widetilde{C}_i \widetilde{O}_i$$

$$\begin{aligned}
O_1 &= (\overline{s}_L \gamma_\mu b_L)\,(\overline{s}_L \gamma^\mu b_L),\\
O_2 &= (\overline{s}_R b_L)\,(\overline{s}_R b_L),\\
O_3 &= (\overline{s}_R^\alpha b_L^\beta)\,(\overline{s}_R^\beta b_L^\alpha),\\
O_4 &= (\overline{s}_R b_L)\,(\overline{s}_L b_R),\\
O_5 &= (\overline{s}_R^\alpha b_L^\beta)\,(\overline{s}_L^\beta b_R^\alpha),\\
\widetilde{O}_{i=1,\ldots 3} &= O_{i=1,\ldots 3}|_{L\leftrightarrow R} \cdots
\end{aligned}$$

$$\begin{aligned}
C_1^{\rm MSSM} &= \frac{\alpha_s^2}{4m_{\tilde g}^2} \sin^2 2\theta_L e^{2i\delta_L} \left(f_1(x_{\tilde b_L,\tilde g}, x_{\tilde b_L,\tilde g}) - 2 f_1(x_{\tilde s_L,\tilde g}, x_{\tilde b_L,\tilde g}) + f_1(x_{\tilde s_L,\tilde g}, x_{\tilde s_L,\tilde g}) \right)\\
C_{4(5)}^{\rm MSSM} &= \frac{\alpha_s^2}{4m_{\tilde g}^2} \sin 2\theta_L \sin 2\theta_R e^{i(\delta_L+\delta_R)} \Big(f_{4(5)}(x_{\tilde b_R,\tilde g}, x_{\tilde b_L,\tilde g}) - f_{4(5)}(x_{\tilde b_R,\tilde g}, x_{\tilde s_L,\tilde g})\\
&\quad - f_{4(5)}(x_{\tilde s_R,\tilde g}, x_{\tilde b_L,\tilde g}) + f_{4(5)}(x_{\tilde s_R,\tilde g}, x_{\tilde s_L,\tilde g}) \Big)\,,\\
\widetilde{C}_1^{\rm MSSM} &= C_1^{\rm MSSM}|_{L\leftrightarrow R}\,,
\end{aligned}$$

Sensitive to mass splitting of $\tilde{s}$ and $\tilde{b}$ and their mixing.

Only $C_1^{\rm MSSM}(\tilde{C}_1^{\rm MSSM})$ is generated if only LL(RR) exists.

$$M_{12}^{s} = M_{12}^{s,\mathrm{SM}}(1+R)$$

$$\begin{aligned}\Delta m_s &= 2|M_{12}^{s}| \\ &= \Delta m_s^{\mathrm{SM}}|1+R|.\end{aligned}$$

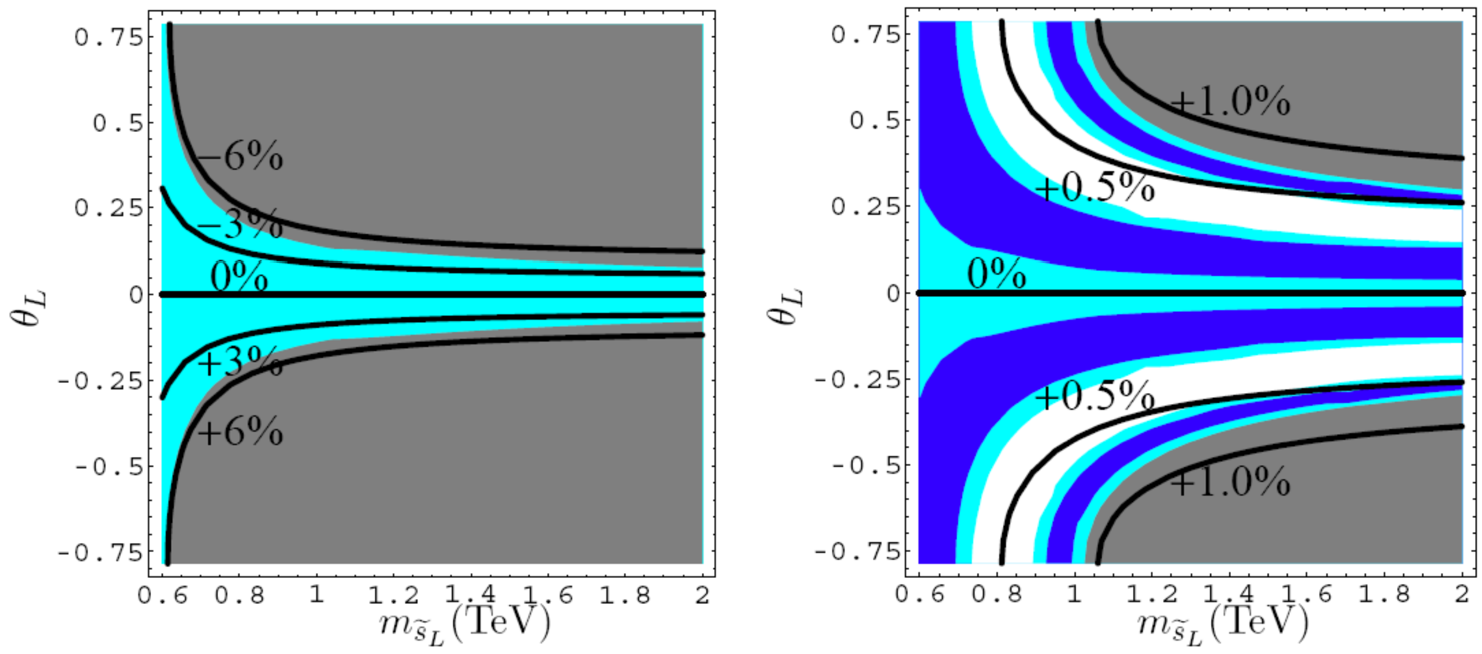
$$|1+R| = 0.77^{+0.02}_{-0.01}(\mathrm{exp}) \pm 0.19(\mathrm{th})$$

$$\begin{aligned}R(\mu_b) &= \xi_1(\mu_b) + \widetilde{\xi}_1(\mu_b) + \frac{3}{4}\frac{B_4(\mu_b)}{B_1(\mu_b)}\left(\frac{M_{B_s}}{m_b(\mu_b)+m_s(\mu_b)}\right)^2 \xi_4 \\ &+ \frac{1}{4}\frac{B_5(\mu_b)}{B_1(\mu_b)}\left(\frac{M_{B_s}}{m_b(\mu_b)+m_s(\mu_b)}\right)^2 \xi_5,\end{aligned}$$

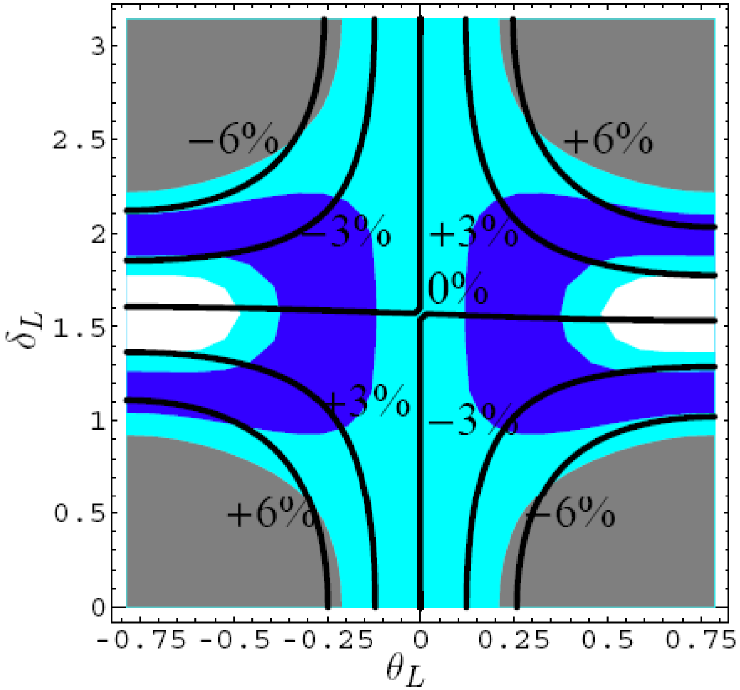
$$\begin{aligned}\xi_i(\mu_b) &\equiv C_i^{\mathrm{SUSY}}(\mu_b)/C_1^{\mathrm{SM}}(\mu_b), \\ \widetilde{\xi}_i(\mu_b) &\equiv \widetilde{C}_i^{\mathrm{SUSY}}(\mu_b)/C_1^{\mathrm{SM}}(\mu_b).\end{aligned}$$

Results for $m_{\tilde{g}} = 0.5$ (TeV), $m_{\tilde{b}_L} = 0.5$ (TeV)

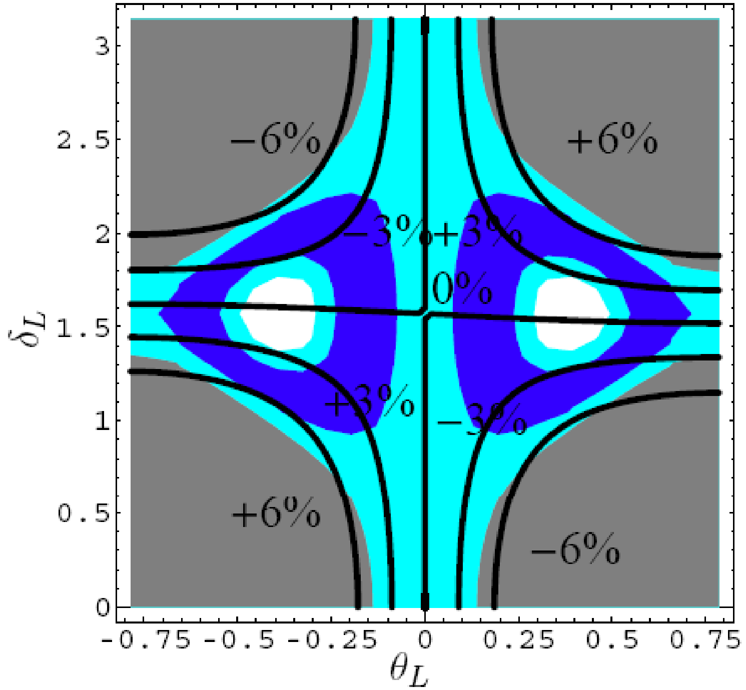
$\delta_L = 0$ $\delta_L = \pi/2$



$B \to X_S\gamma$ constraint $BR^{\rm exp}(B \to X_s\gamma)/BR^{\rm SM}(B \to X_s\gamma) = 1.06 \pm 0.13$



(a)



(b)

Figure 2: Contour plots for $|1+R|$ in (θ_L,δ_L) plane. (a) $m_{\tilde{s}_L} = 0.8$ (TeV), (b) $m_{\tilde{s}_L} = 1.0$ (TeV).

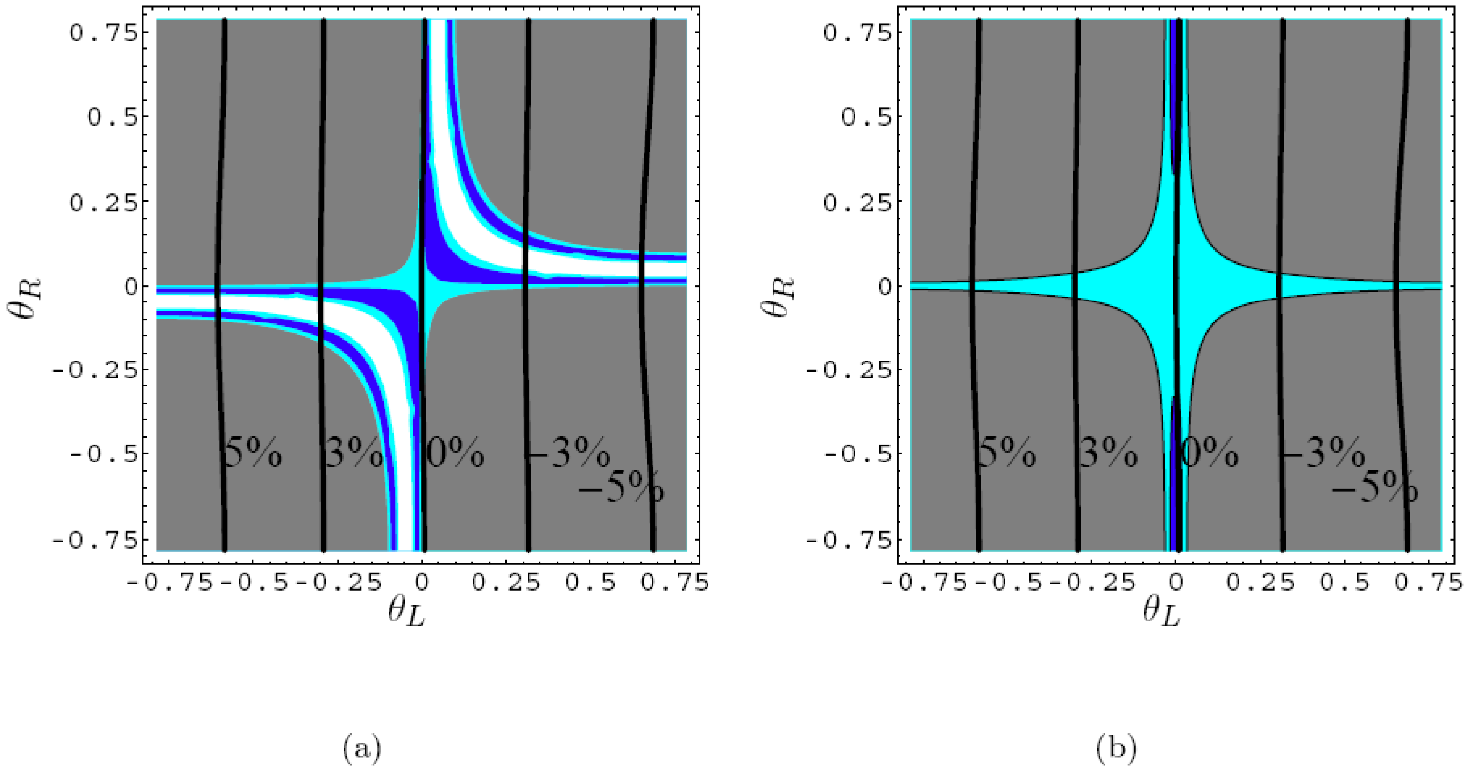


Figure 3: Contour plots for $|1+R|$ in (θ_L,θ_R) plane. $m_{\tilde{s}_L} = m_{\tilde{s}_R} = 0.6$ (TeV). (a) $\delta_L = \delta_R = 0$ (b) $\delta_L = 0, \delta_R = \pi/2$. We assume both LL and RR mixing exist. The rest is the same with figure 1.

B_s ® $K^+ K^-$ and B_s ® $K^0 \overline{K}^0$

In the SM,

$$
\begin{aligned}
\mathcal{A}(B_s^0 \to K^+ K^-) &\simeq V_{ub}^* V_{us}[T' + (P'_u - P'_t)] + V_{cb}^* V_{cs}(P'_c - P'_t) \\
&\equiv V_{ub}^* V_{us} T^{s\pm} + V_{cb}^* V_{cs} P^{s\pm}\,,
\end{aligned}
$$

$$
\mathcal{A}(B_s^0 \to K^0 \bar{K}^0) \simeq V_{ub}^* V_{us} T^{s0} + V_{cb}^* V_{cs} P^{s0}
$$

- The SM amplitudes are fixed by $B \to KK$ modes by flavor-SU(3) symmetry, including factorizable SU(3)-breaking effect

- $\mathcal{A}(B_d^0 \to K^0 \bar{K}^0) \simeq V_{ub}^* V_{ud} T^{d0} + V_{cb}^* V_{cd} P^{d0}$
  1. $BR(B_d^0 \to K^0 \bar{K}^0) = (0.96 \pm 0.25) \times 10^{-6}$
  2. $\Delta_d \equiv T^{d0} - P^{d0}$: QCDf, free of IR divergence and

$$\Delta_d = (1.09 \pm 0.43) \times 10^{-7} + i(-3.02 \pm 0.97) \times 10^{-7} \text{ GeV}$$

  3. $-0.2 \leq A_{\rm dir}^{d0} \leq 0.2$

cf. $A_{dir}(B^+ \to K^+ \bar{K}^0) = -0.12^{+0.18}_{-0.17}$

S. Descotes-Genon, J. Matias, J. Virto (06)

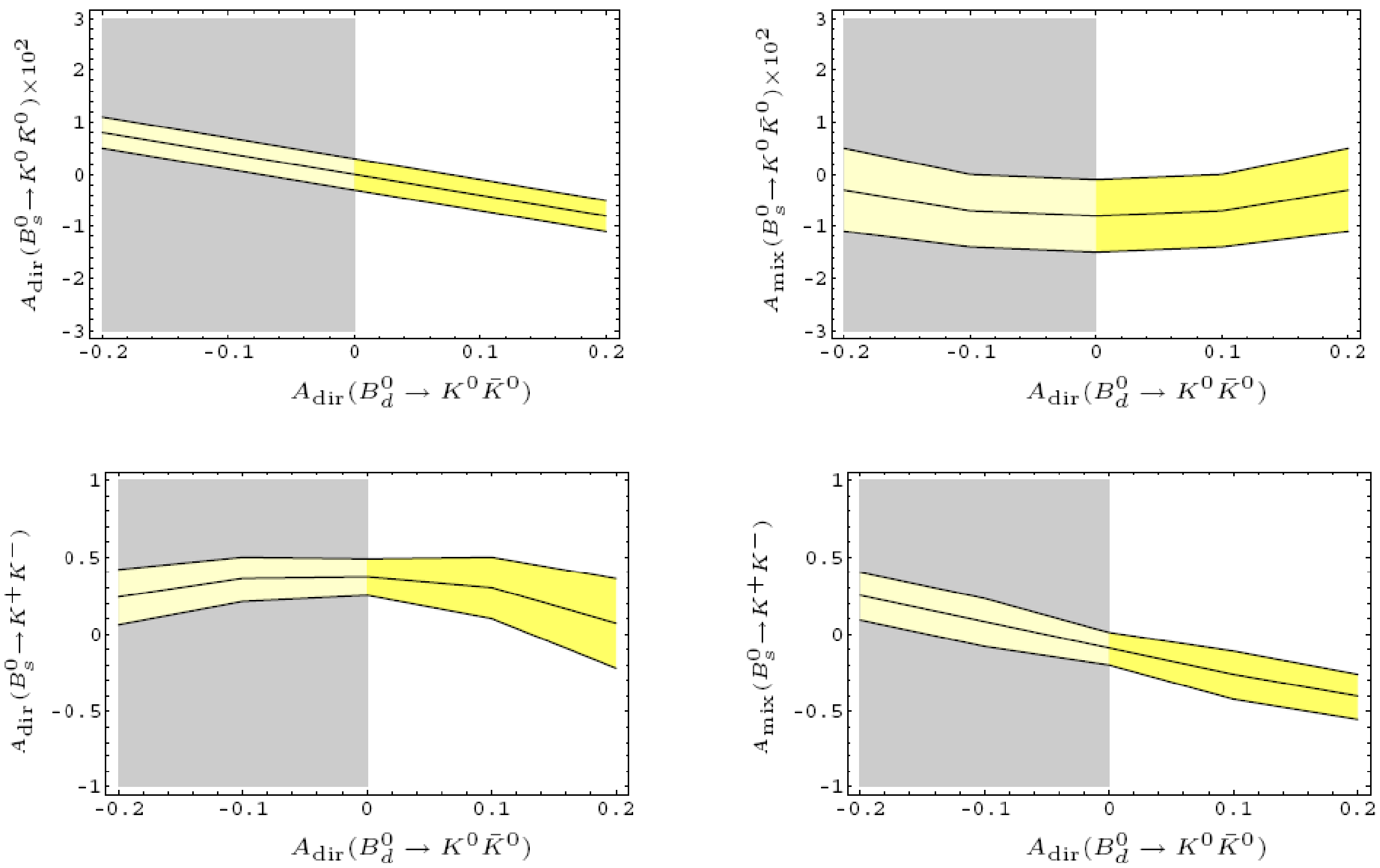


Figure 1: SM predictions for the CP asymmetries in $B_s^0 \to K^0\bar{K}^0$ (up) and $B_s^0 \to K^+K^-$ (down) as a function of $A_{\rm dir}(B_d^0 \to K^0\bar{K}^0)$. As explained in the text, the preferred range is the non-shadowed half of the plots $[A_{\rm dir}(B_d^0 \to K^0\bar{K}^0) \geq 0]$.

- $m_{\tilde{u}_L} = m_{\tilde{d}_{L,R}} = m_{\tilde{b}_{L,R}} = m_{\tilde{g}} = 250 \text{ GeV}$
- $250 \text{ GeV} < m_{\tilde{u}_R}, m_{\tilde{s}_{R,L}} < 1000 \text{ GeV}$
- $-\pi < \delta_{L,R} < \pi$
- $-\pi/4 < \theta_{L,R} < \pi/4$

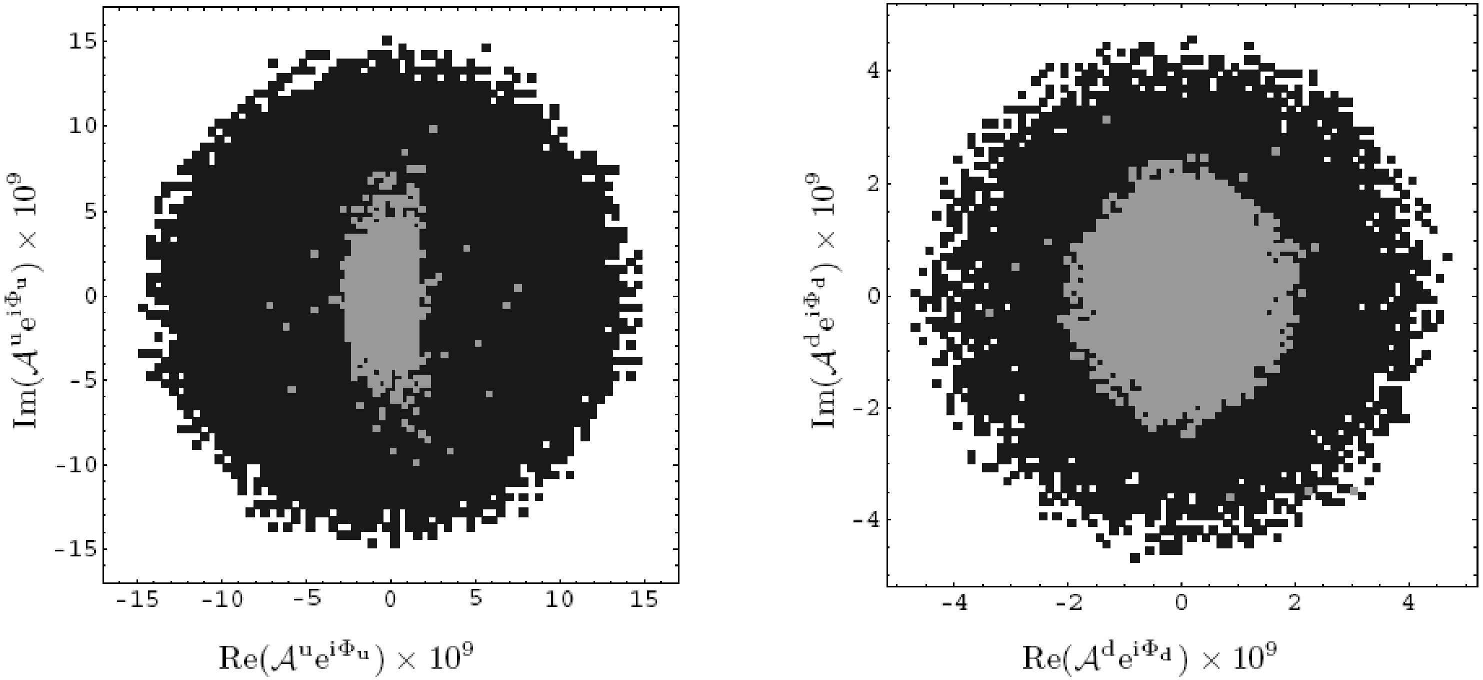


Figure 2: SUSY contribution to the NP amplitudes $\mathcal{A}^u e^{i\Phi_u}$ (left) and $\mathcal{A}^d e^{i\Phi_d}$ (right) in the scenario with simultaneous LL and RR mixings. The dark regions correspond to the variation of the SUSY parameters over the considered parameter space. The light regions satisfy the experimental bounds, including the recent measurement of ΔM_s.

Isobreaking terms: P_{EW}

$$-A(B_s \to K^+K^-) = P' + T' + \frac{2}{3}P'^{C}_{EW} + E' + PA'$$
$$= A\left[a_5^{QCD} - a_4^{QCD} - \chi a_2^{QCD} - \lambda_u a_2 + \frac{2}{3}\left(a_5^{EW} - a_4^{EW} - \chi a_2^{EW}\right)\right] \quad (9)$$
$$A(B_s \to K^0\overline{K^0}) = P' - \frac{1}{3}P'^{C}_{EW} + PA'$$
$$= A\left[a_5^{QCD} - a_4^{QCD} - \chi a_2^{QCD} - \frac{1}{3}\left(a_5^{EW} - a_4^{EW} - \chi a_2^{EW}\right)\right], \quad (10)$$

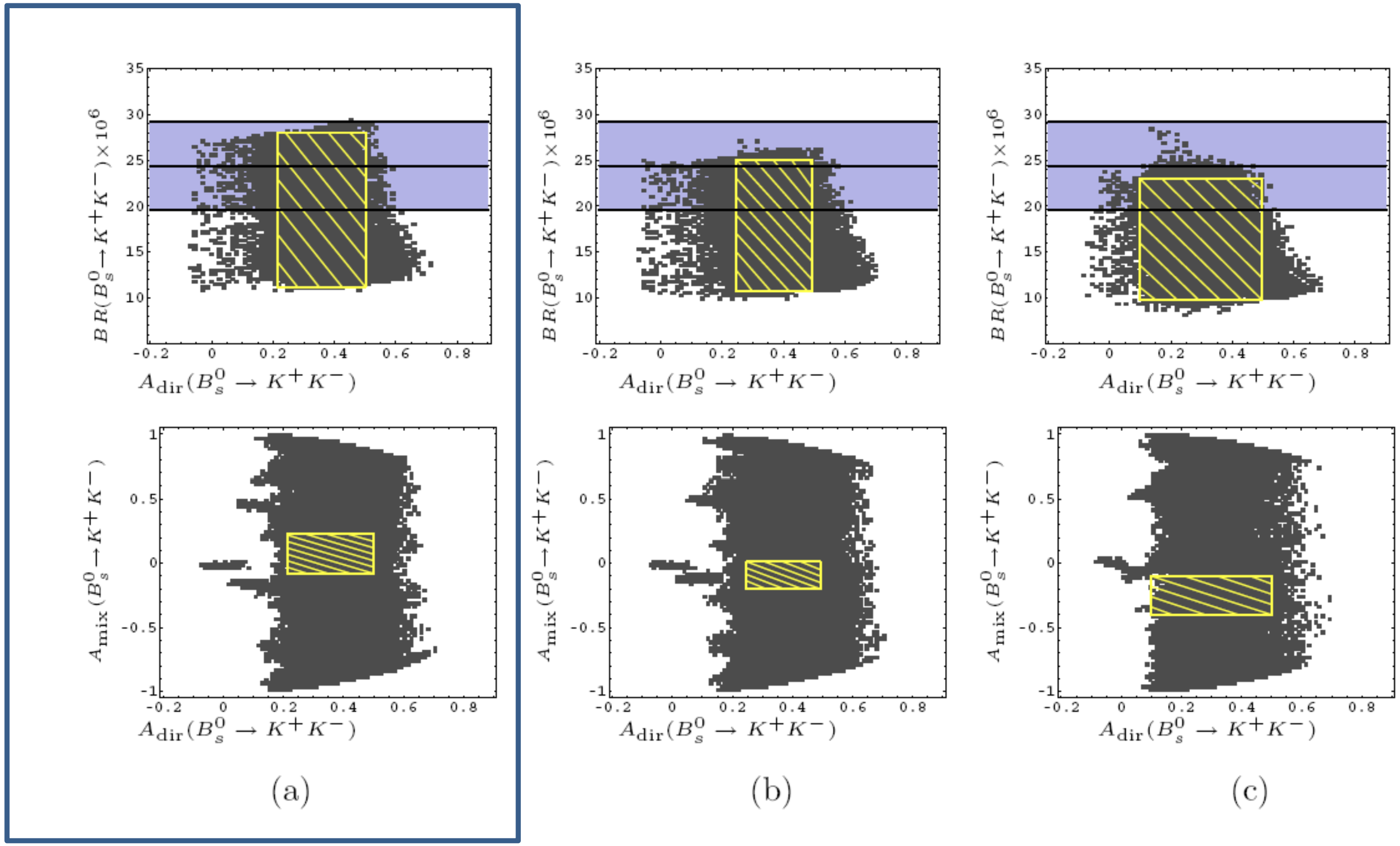


Figure 3: Predictions, in the form of scatter plots, for the correlations between $BR(B_s^0 \to K^+K^-) - A_{\rm dir}(B_s^0 \to K^+K^-)$ (up) and $A_{\rm mix}(B_s^0 \to K^+K^-) - A_{\rm dir}(B_s^0 \to K^+K^-)$ (down) in the presence of SUSY, for a) $A_{\rm dir}^{d0} = -0.1$, (b) $A_{\rm dir}^{d0} = 0$ and (c) $A_{\rm dir}^{d0} = 0.1$. The dashed rectangles correspond to the SM predictions. The horizontal band shows the experimental value for $BR(B_s^0 \to K^+K^-)$ at 1σ.

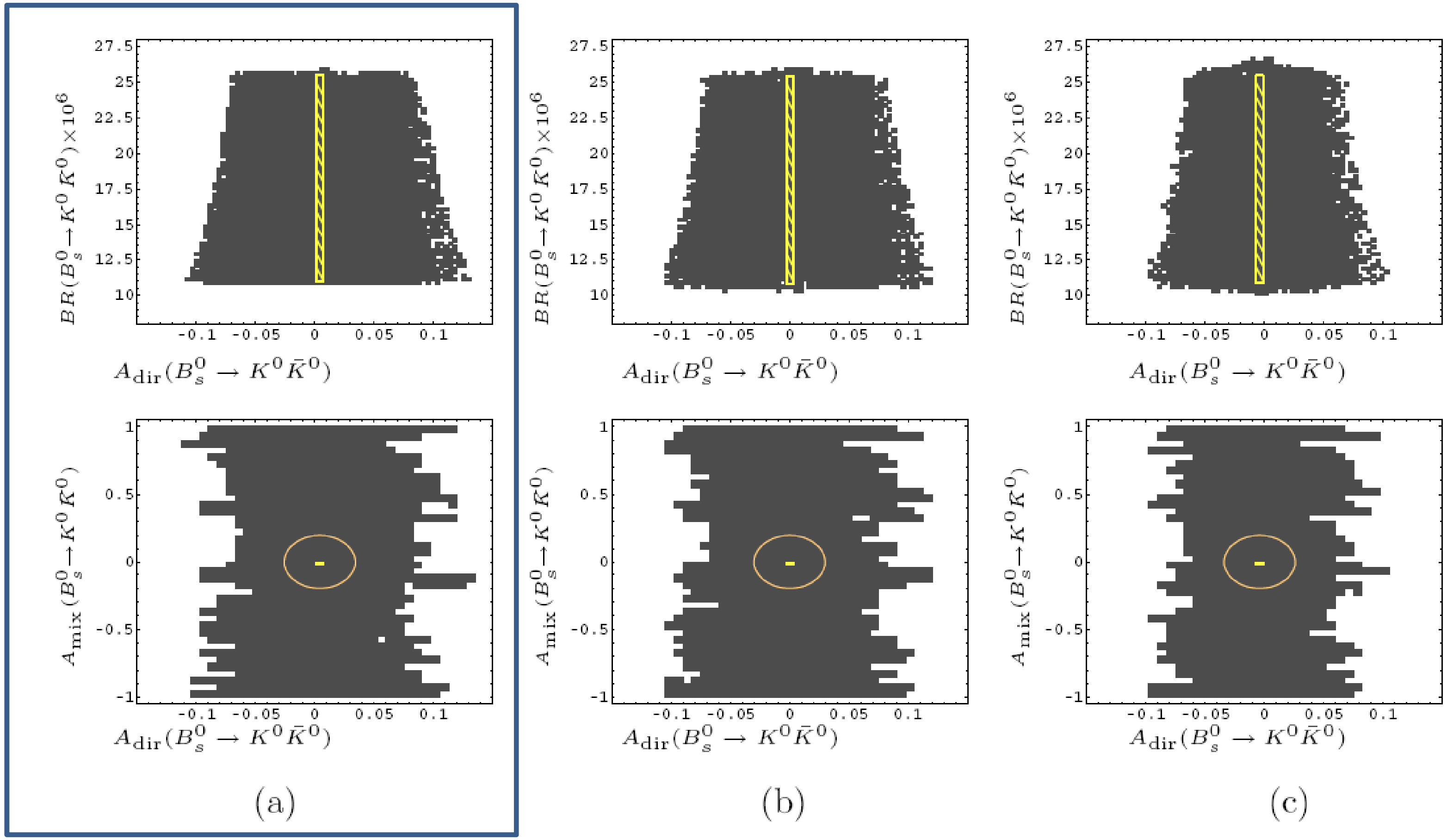


Figure 4: Predictions, in the form of scatter plots, for the correlations between $BR(B_s^0 \to K^0\bar{K}^0)$–$A_{\rm dir}(B_s^0 \to K^0\bar{K}^0)$ (up) and $A_{\rm mix}(B_s^0 \to K^0\bar{K}^0)$ – $A_{\rm dir}(B_s^0 \to K^0\bar{K}^0)$ (down) in the presence of SUSY, for (a) $A_{\rm dir}^{d0} = -0.1$, (b) $A_{\rm dir}^{d0} = 0$ and (c) $A_{\rm dir}^{d0} = 0.1$. The dashed rectangles correspond to the SM predictions. These are quite small in the three lower plots, so they are indicated by a circle.

Conclusions

- NP in the EW-penguin sector of $B \to \pi K$ is a promising possibility.
- GNK scenario can give large enhancement to EW penguins in SUSY.
- Δm_s gives a strong constraint.
- Large CPVs are possible in $B_s \to K^+ K^-$ and/or $B_s \to K^0 K^0$. The differences between the two modes signal NP in the EW-penguin.