$B_d \to \phi K_S$ CP asymmetries as a probe of supersymmetry

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in collaboration with

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at

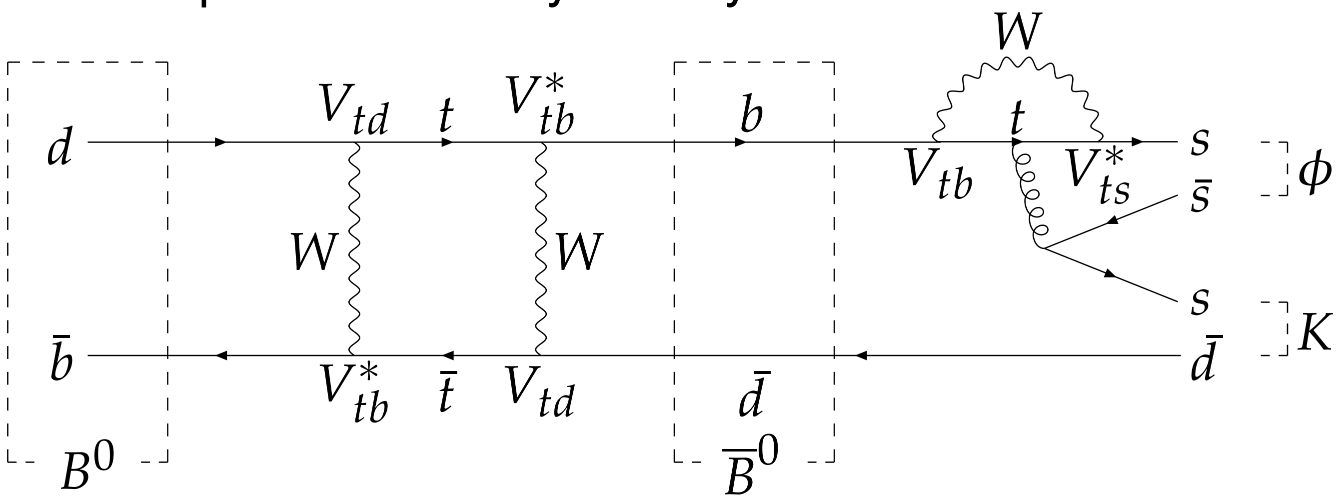
ICFP2003
10Oct2003

Based on

- PRL **90**, 141803 (2003) [hep-ph/0304239]
- hep-ph/0212092, longer version

Overview of CPV in B system

- Time dependent CP asymmetry



$$\mathcal{A}_{\phi K}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to \phi K_S) - \Gamma(B^0(t) \to \phi K_S)}{\Gamma(\overline{B}^0(t) \to \phi K_S) + \Gamma(B^0(t) \to \phi K_S)}$$
$$= -C_{\phi K} \cos(\Delta m_d t) + S_{\phi K} \sin(\Delta m_d t),$$

$$C_{\phi K} = \frac{1 - |\lambda_{\phi K}|^2}{1 + |\lambda_{\phi K}|^2}, \qquad S_{\phi K} = \frac{2\,\mathrm{Im}\lambda_{\phi K}}{1 + |\lambda_{\phi K}|^2},$$

$$\lambda_{\phi K} \equiv -e^{-2i(\beta+\theta_d)} \frac{\overline{A}(\overline{B}^0 \to \phi K_S)}{A(B^0 \to \phi K_S)}$$

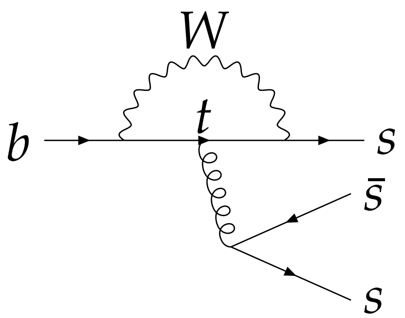
- B^0–$\overline{B}^0$ mixing

$$\langle \overline{B}^0 | H_{\text{eff}}^{\Delta B=2} | B^0 \rangle = \frac{1}{2}\,\Delta m_d\, e^{-i2(\beta+\theta_d)}$$

Assume $\theta_d = 0 \longleftarrow \sin 2\beta_{J/\psi K}$

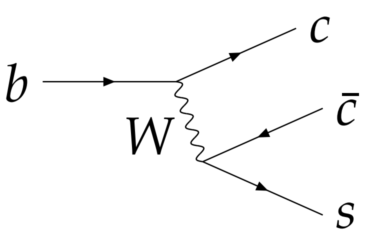
Why $B_d \to \phi K_S$?

- Absence of tree level diagram in the Standard Model $\to$ Sensitive to New Physics.



+ NP at one loop

- Compare $B_d \to J/\psi K_S$:



CPV measurements do not agree with SM very well

- SM prediction

$$\lambda_{\phi K}^{\text{SM}} = -e^{-2i\beta},$$

$$C_{\phi K}^{\text{SM}} = \frac{1 - |\lambda_{\phi K}^{\text{SM}}|^2}{1 + |\lambda_{\phi K}^{\text{SM}}|^2} = 0,$$

$$S_{\phi K}^{\text{SM}} = \frac{2\,\text{Im}\lambda_{\phi K}^{\text{SM}}}{1 + |\lambda_{\phi K}^{\text{SM}}|^2} = \sin 2\beta = 0.734 \pm 0.054$$

- Measurements

	$S_{\phi K}$	$C_{\phi K}$
BaBar*	$+0.45 \pm 0.43 \pm 0.07$	$-0.38 \pm 0.37 \pm 0.12$
Belle†	$-0.96 \pm 0.50^{+0.09}_{-0.11}$	$+0.15 \pm 0.29 \pm 0.07$
Average	-0.15 ± 0.33	-0.05 ± 0.24
Avg. − SM	-2.7σ	-0.2σ

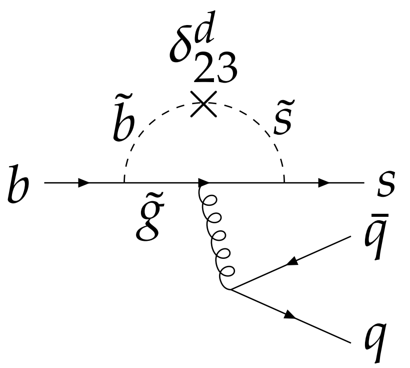
*T. Browder, Talk at LP03

†Belle Collaboration, hep-ex/0308035

Supersymmetry to the rescue

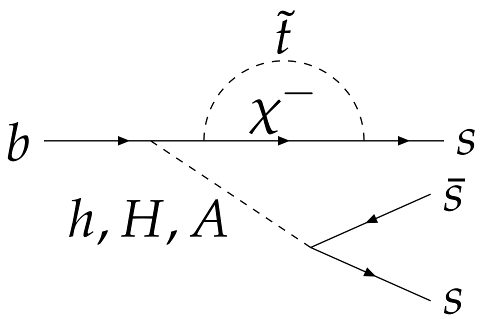
- Modify $\lambda_{\phi K} \equiv -e^{-2i\beta} \frac{\overline{A}(\overline{B}^0 \to \phi K_S)}{A(B^0 \to \phi K_S)}$

- Gluino-squark loops



, $q = u, d, s, c, b$

- Higgs mediated $b \to s s \bar{s}$



$\propto \tan^3 \beta$ for large $\tan \beta$

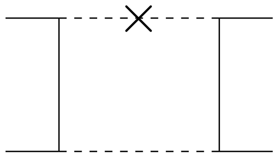
does not affect $b \to s u \bar{u}$ or $b \to s d \bar{d}$
because Yukawa couplings of u and d are small.

Gluino-squark loop contributions to Wilson coefficients

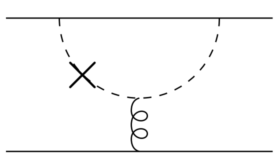
Gabbiani, Gabrielli, Masiero, Silvestrini, NPB**477**(1996)
S. Baek, J. H. Jang, P. Ko, J.-h. Park, NPB**609**(2001)
Beware typos.

- QCD penguin operators

$$C_{3,\dots,6} = -\frac{\alpha_s^2}{4\widetilde{m}^2}\Bigg($$



$+$

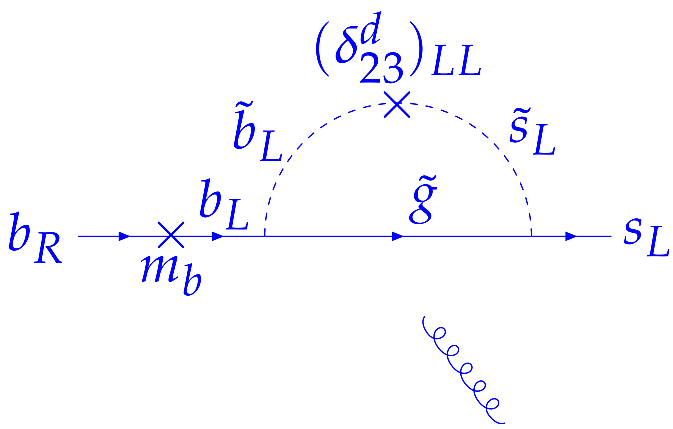


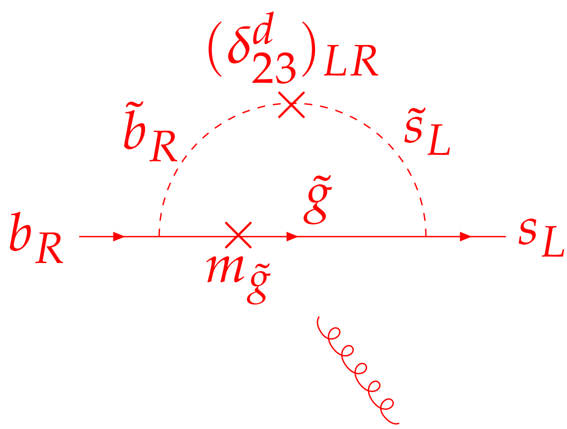
$$\Bigg)(\delta^d_{LL})_{23}$$

- Magnetic operators

$$C_{7\gamma} = -\frac{4\pi Q_b \alpha_s}{3\widetilde{m}^2}\Big[(\delta^d_{23})_{LL} M_4(x) - (\delta^d_{23})_{LR}\left(\frac{m_{\tilde g}}{m_b}\right) 4B_1(x)\Big],$$

$$C_{8g} = -\frac{\pi\alpha_s}{\widetilde{m}^2}\Big[(\delta^d_{23})_{LL}\left(\frac{3}{2}M_3(x) - \frac{1}{6}M_4(x)\right) + (\delta^d_{23})_{LR}\left(\frac{m_{\tilde g}}{m_b}\right)\frac{1}{6}\left(4B_1(x) - 9x^{-1}B_2(x)\right)\Big]$$





Analysis of gluino-squark loops

- Numerical analysis
  - Mass insertion approximation with $m_{\tilde{g}} = \widetilde{m} = 400$ GeV
  - BBNS approach for hadronic matrix elements

Beneke, Buchalla, Neubert, Sachrajda, PRL**83**(1999); NPB**591**(2000); NPB**606**(2001)

  - Scan over one of δ^d_{23}'s such that

$$2.0 \times 10^{-4} < B(B \to X_s\gamma) < 4.5 \times 10^{-4},$$

$$\Delta M_s > 14.9 \text{ ps}^{-1}$$

A. Stocchi, hep-ph/0010222

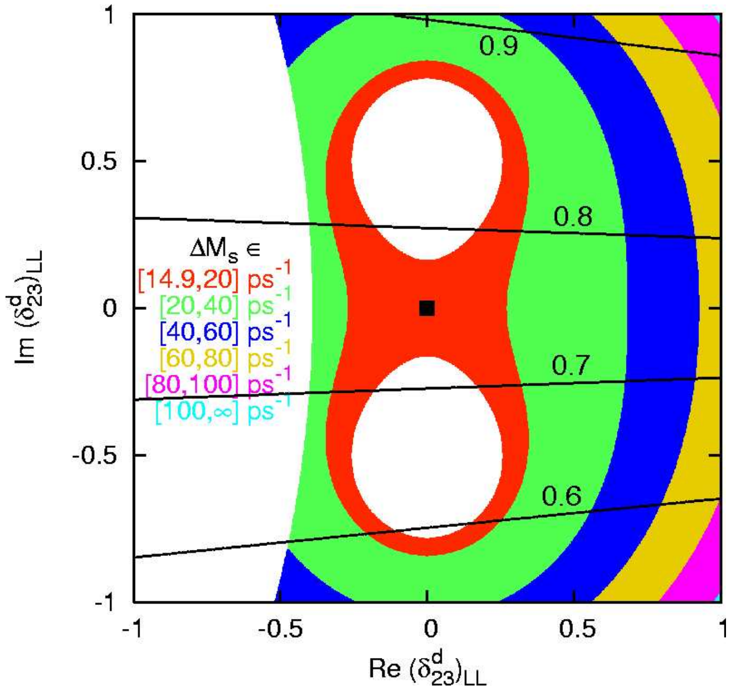
- Consider five cases:
  - Single $(\delta^d_{23})_{LL}$ or $(\delta^d_{23})_{RR}$ insertion
  - Single $(\delta^d_{23})_{LR}$ or $(\delta^d_{23})_{RL}$ insertion
  - Single $(\delta^d_{23})_{RL}$ insertion with $C_{7\gamma}(m_b) = C_{8g}(m_b) = 0$ $\to RL$ dominance scenario

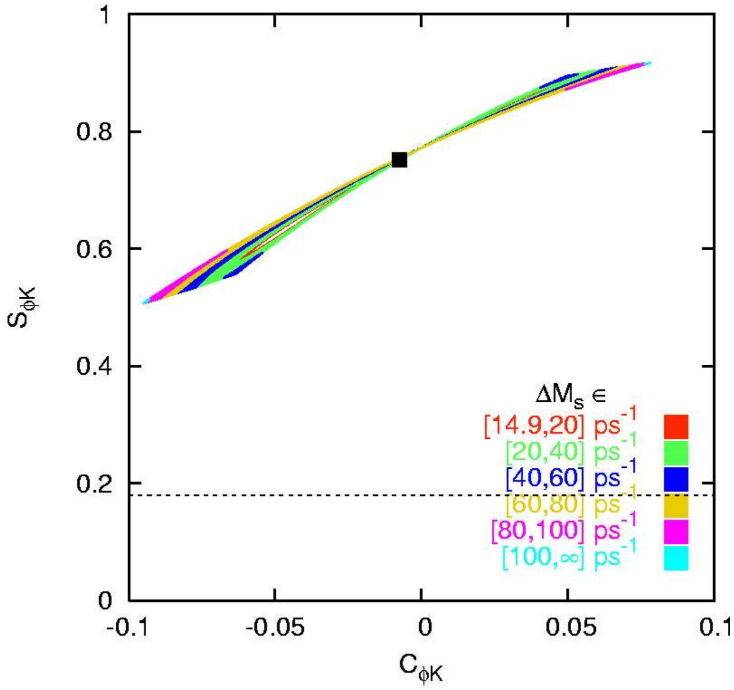
Everett, Kane, Rigolin, L. T. Wang, T. T. Wang, JHEP**0201**(2002)

In this case, $B \to X_s\gamma$ is given by $\widetilde{C}_{7\gamma}$ which is $C_{7\gamma}$ with $L \leftrightarrow R$.

LL bad for $S_{\phi K} < 0$

- Plots for $m_{\tilde{g}} = \tilde{m} = 400$ GeV

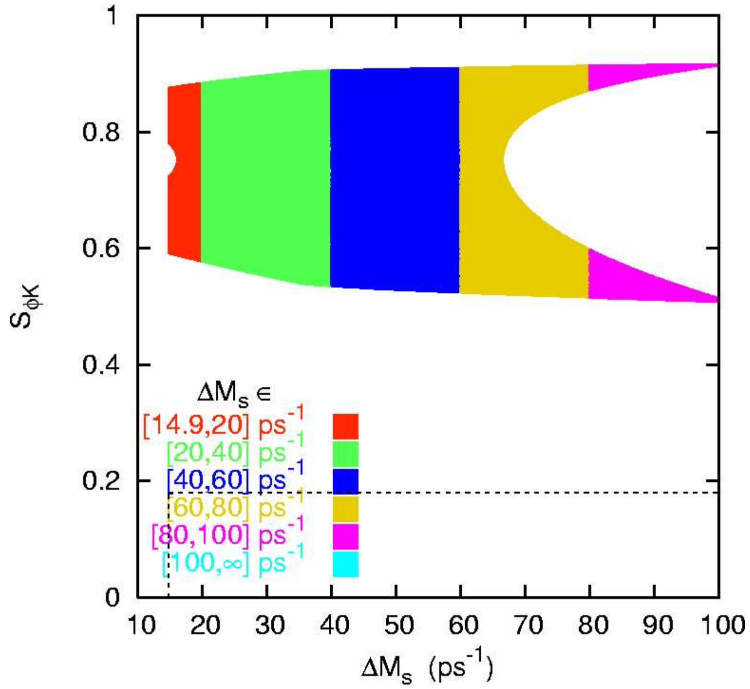


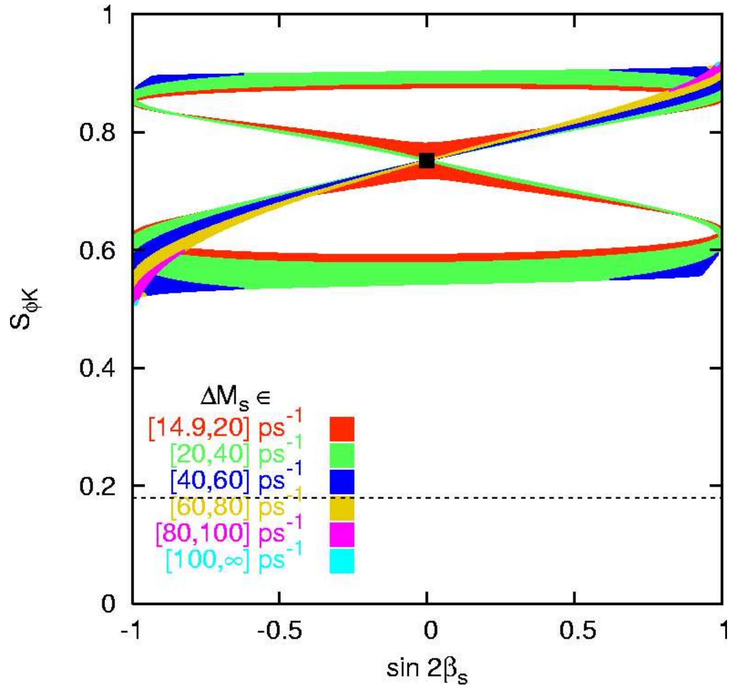


- $(\delta^d_{23})_{LL}$ can not significantly lower $S_{\phi K}$.

$$S_{\phi K} \gtrsim 0.05 \quad \text{for} \quad m_{\tilde{g}} = \tilde{m} = 250 \text{ GeV}$$

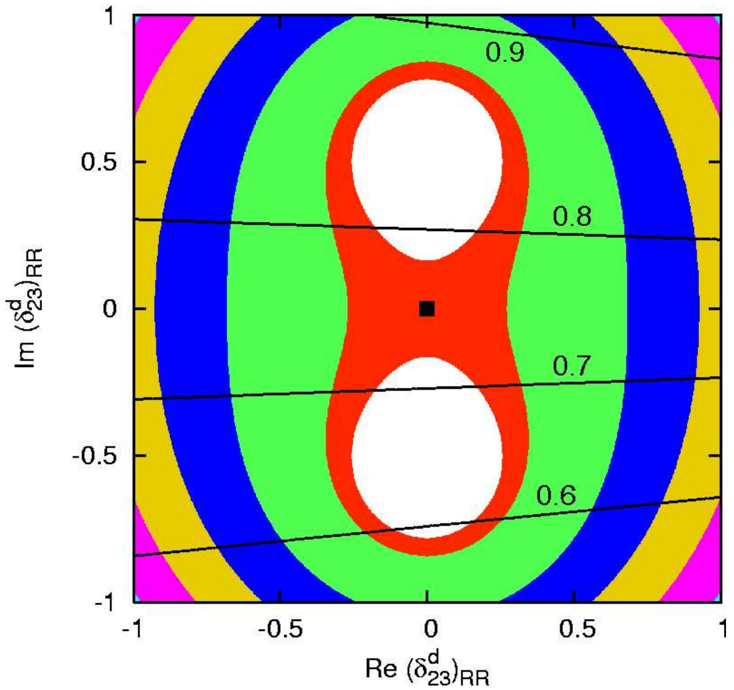
- But large effects possible in B_s–$\overline{B}_s$ mixing

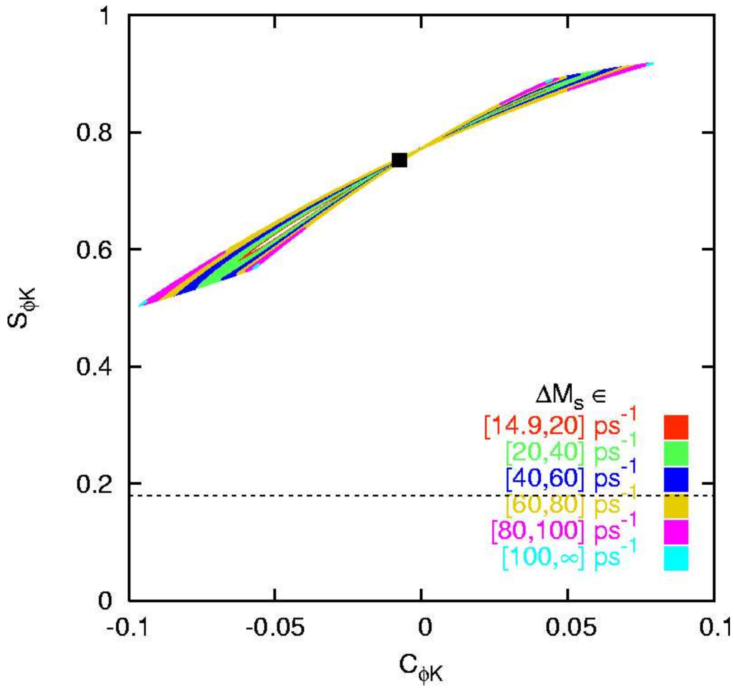




RR similar to LL

- Plots for $m_{\tilde{g}} = \tilde{m} = 400$ GeV





- The only difference from LL insertion is $B \to X_s\gamma$.
  - LL insertion

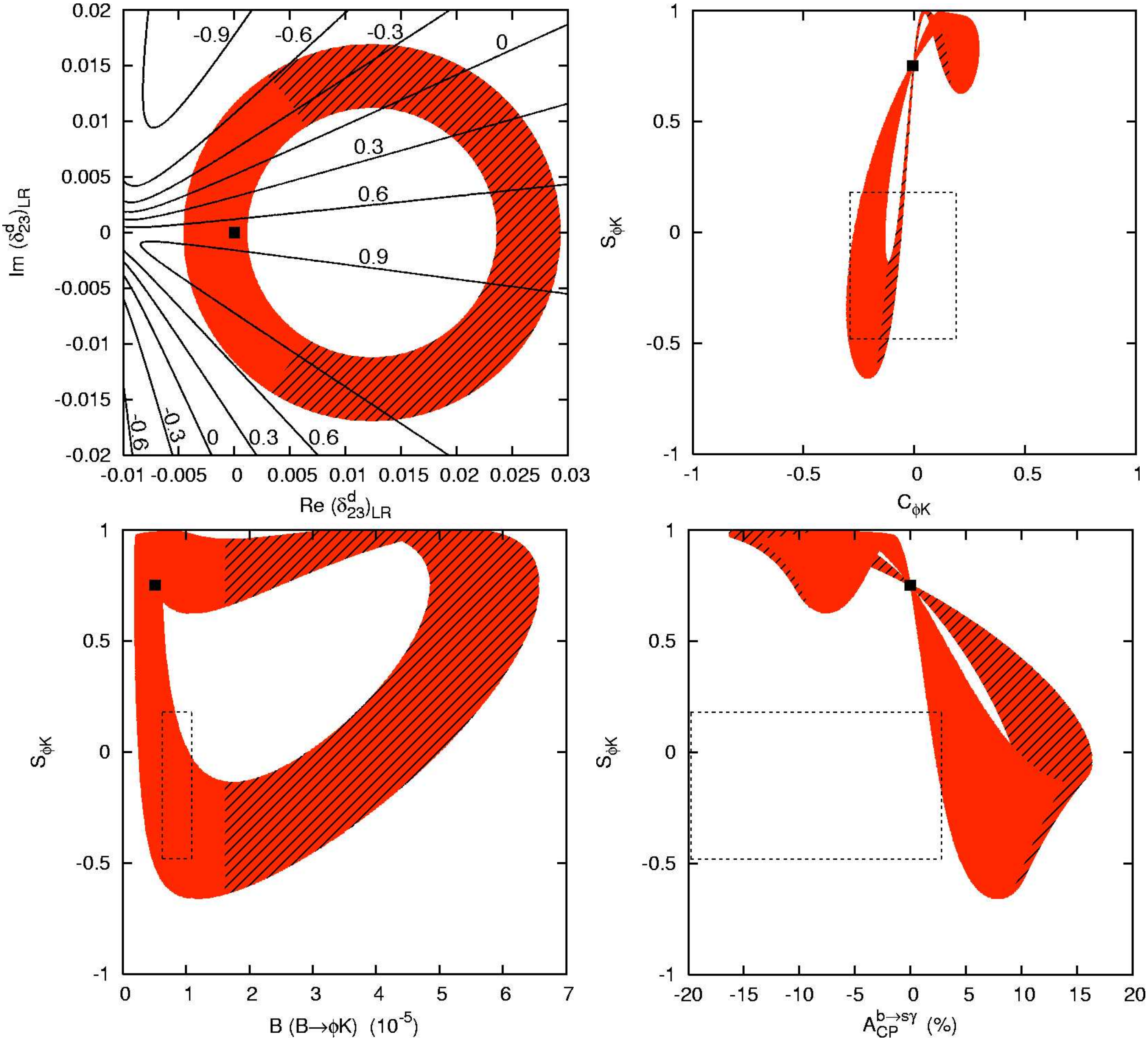
$$B(B \to X_s\gamma) \propto \left| C_{7\gamma}^{\text{SM}} + C_{7\gamma}^{\text{SUSY}} \right|^2$$

  - RR insertion

$$B(B \to X_s\gamma) \propto \left| C_{7\gamma}^{\text{SM}} \right|^2 + \left| \widetilde{C}_{7\gamma}^{\text{SUSY}} \right|^2$$

LR good for $S_{\phi K} < 0$

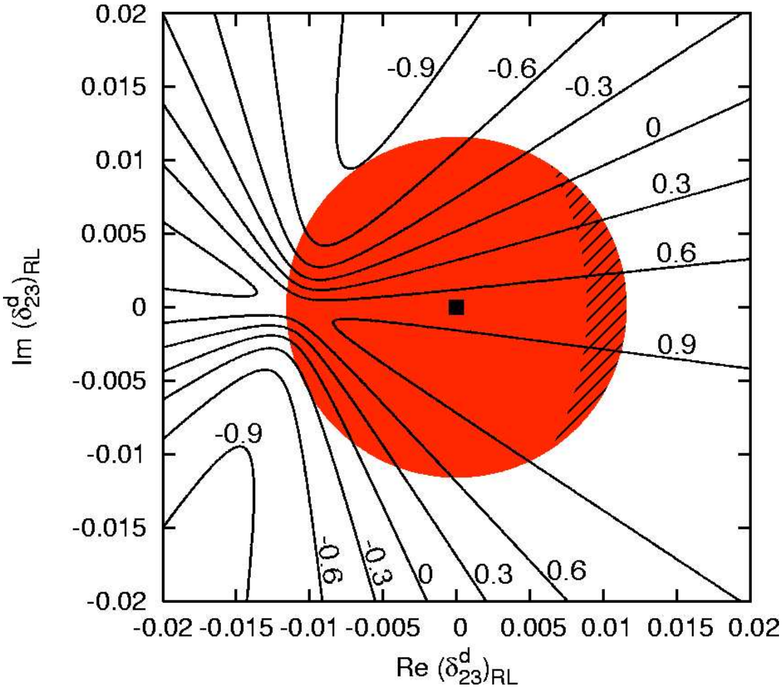
- Plots for $m_{\tilde{g}} = \tilde{m} = 400$ GeV

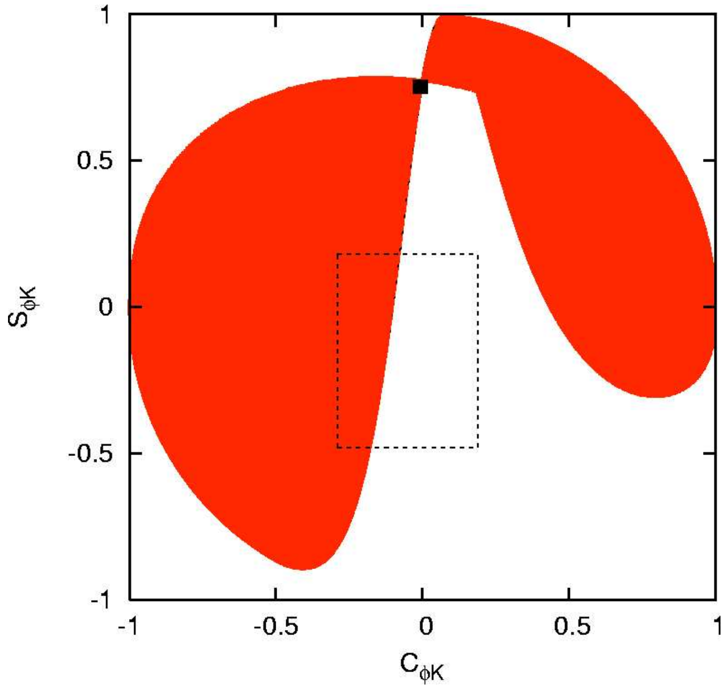


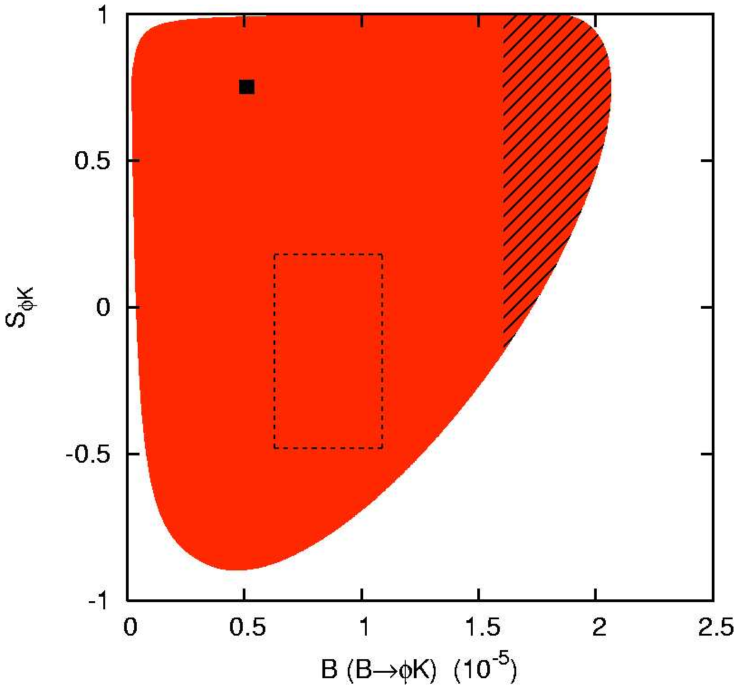
- $-0.6 < S_{\phi K} < 1$ for $|(\delta^d_{23})_{LR}| \sim 10^{-2}$.
  Correlations between $S_{\phi K}$ and $C_{\phi K}$, $S_{\phi K}$ and $A_{\rm CP}^{b\to s\gamma}$.
  Hatched region for $B(B \to \phi K) > 1.6 \times 10^{-5}$.
  Not much effect on B_s–$\overline{B}_s$ mixing.

RL good for $S_{\phi K} < 0$ (with $C_{7\gamma} = C_{7\gamma}^{\text{SM}},\ C_{8g} = C_{8g}^{\text{SM}}$)

- Plots for $m_{\tilde{g}} = \tilde{m} = 400$ GeV



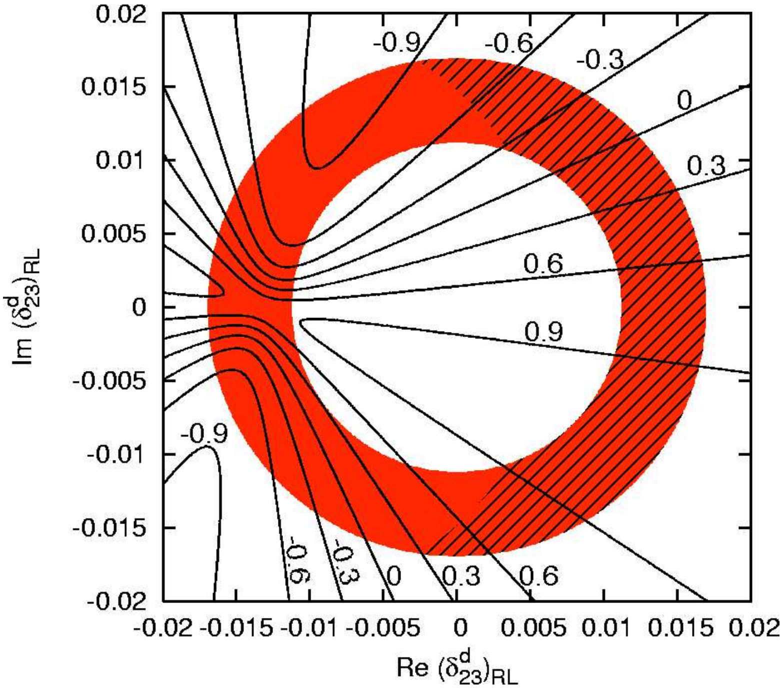


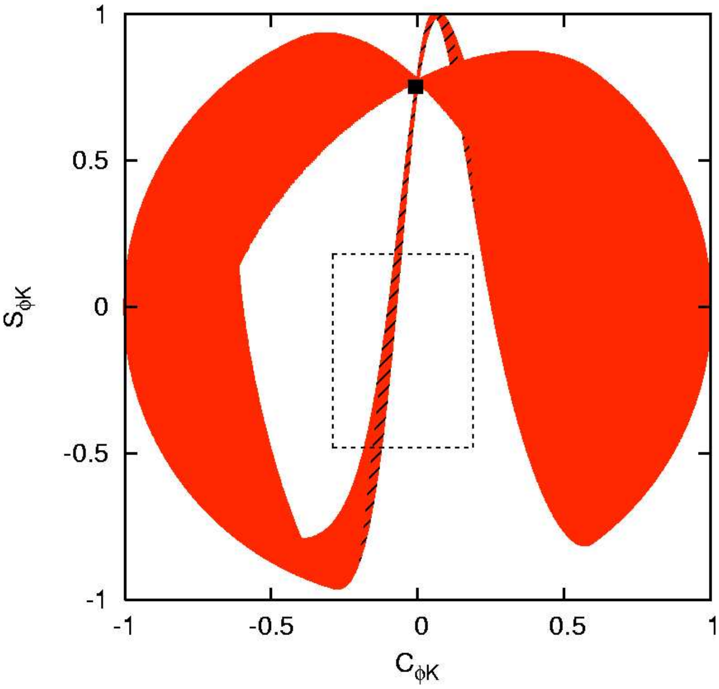


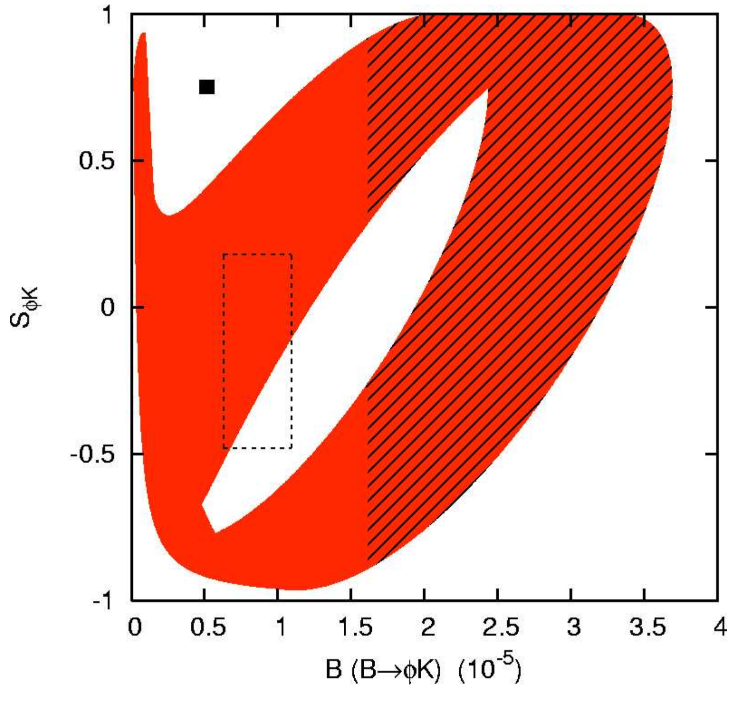
- $-1 < S_{\phi K} < 1$ for $|(\delta^d_{23})_{RL}| \sim 10^{-2}$.
  $A_{\text{CP}}^{b\to s\gamma} = 0$ for single $(\delta^d_{23})_{RL}$, but it can arise if $(\delta^d_{23})_{RR} \neq 0$ as well.
  Not much effect on B_s–$\overline{B}_s$ mixing.

RL dominance good for $S_{\phi K} < 0$ $\left(C_{7\gamma}(m_b) = C_{8g}(m_b) = 0\right)$

- Plots for $m_{\tilde{g}} = \tilde{m} = 400$ GeV





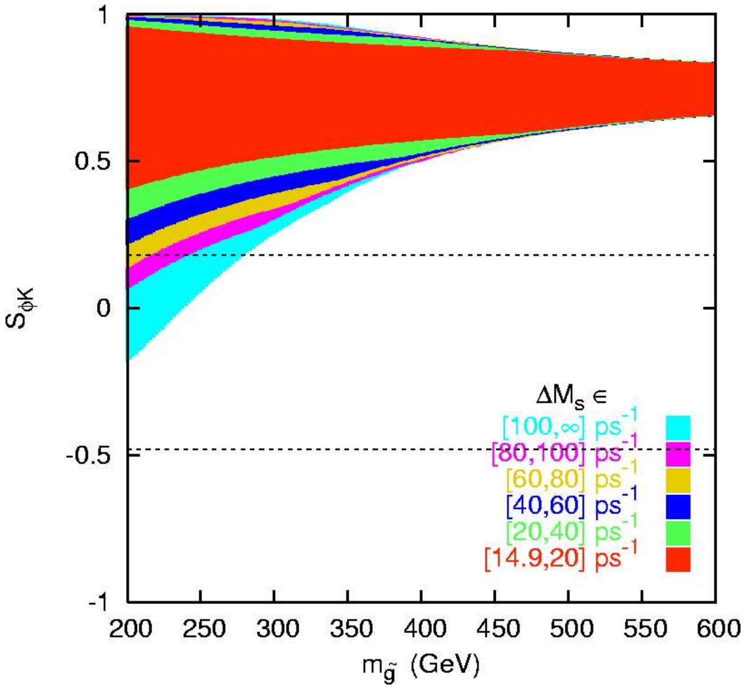


- $-1 < S_{\phi K} < 1$ for $|(\delta^d_{23})_{RL}| \sim 10^{-2}$.
  $C_{\phi K} < -0.2$ or $C_{\phi K} > 0.2$ for $S_{\phi K} < 0$.
  $A_{\rm CP}^{b\to s\gamma} = 0$ for single $(\delta^d_{23})_{RL}$, but it can arise if $(\delta^d_{23})_{RR} \neq 0$ as well. Not much effect on B_s–$\overline{B}_s$ mixing.

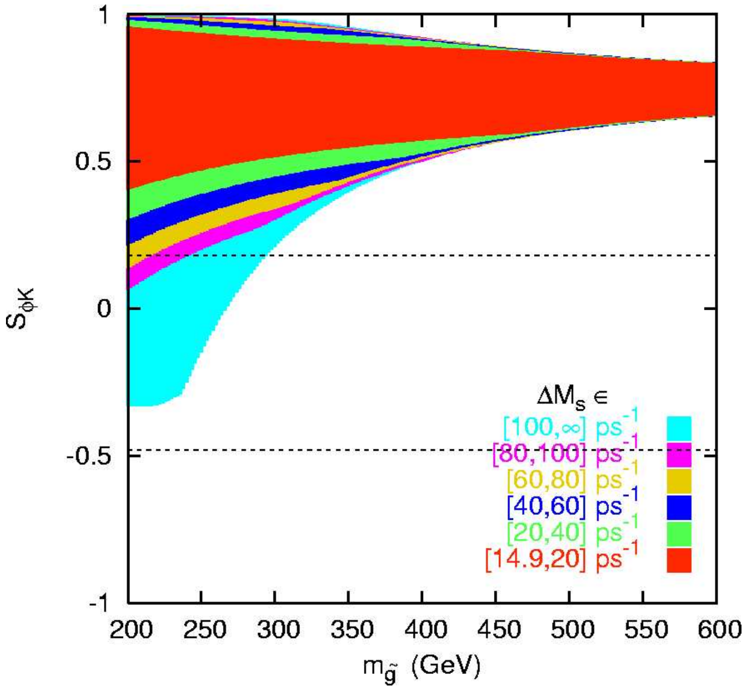
SUSY particle mass dependence

- Allow $|\delta^d_{23}| < 1$ consistent with $B(B \to X_s \gamma)$. Fix $\frac{m^2_{\tilde{g}}}{\tilde{m}^2} = 1$.

- LL or RR insertion

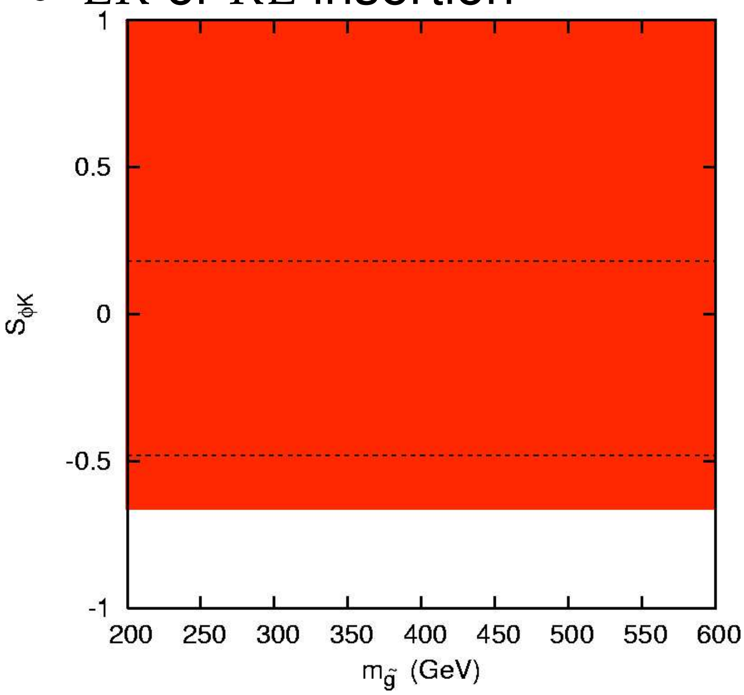


LL

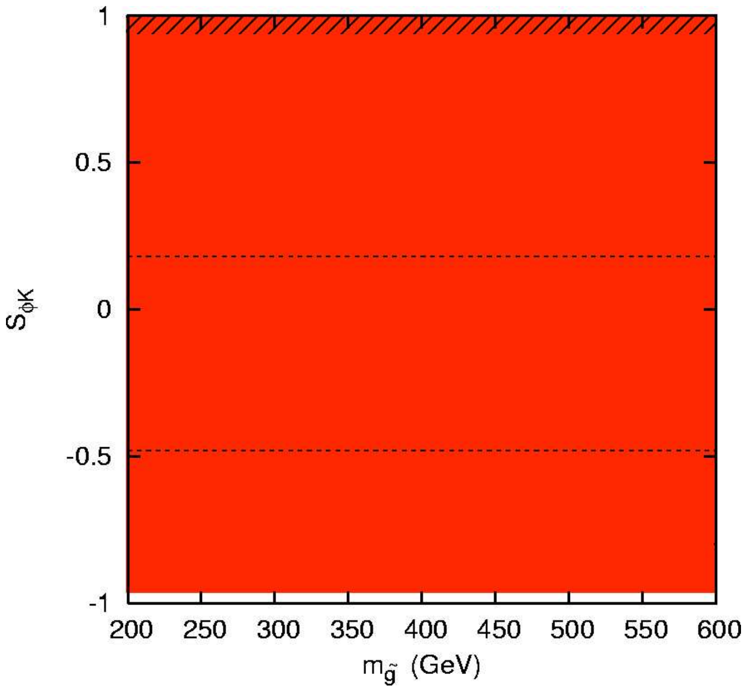


RR

- LR or RL insertion



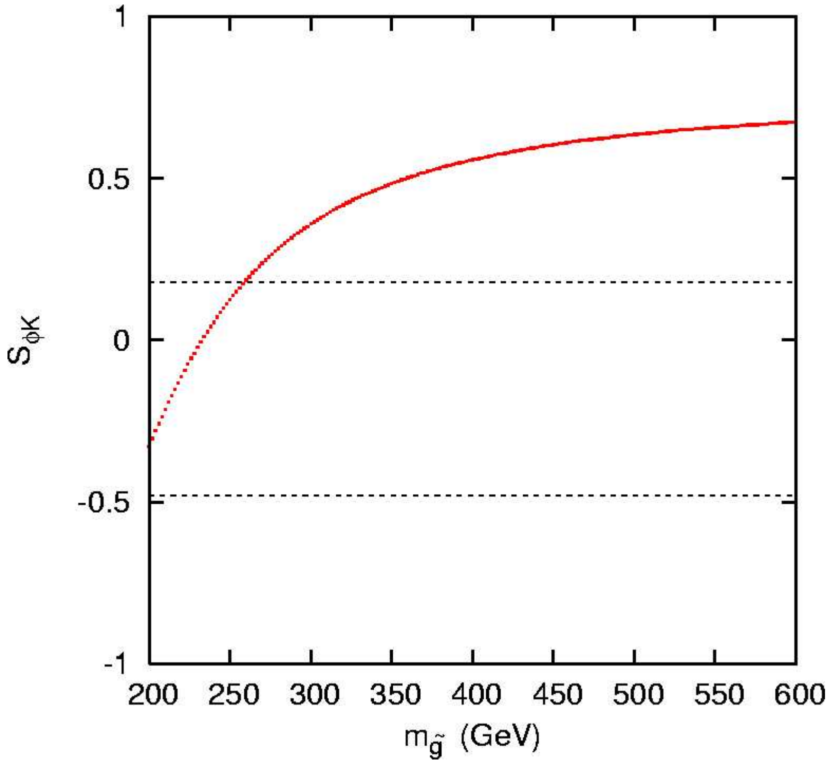
LR



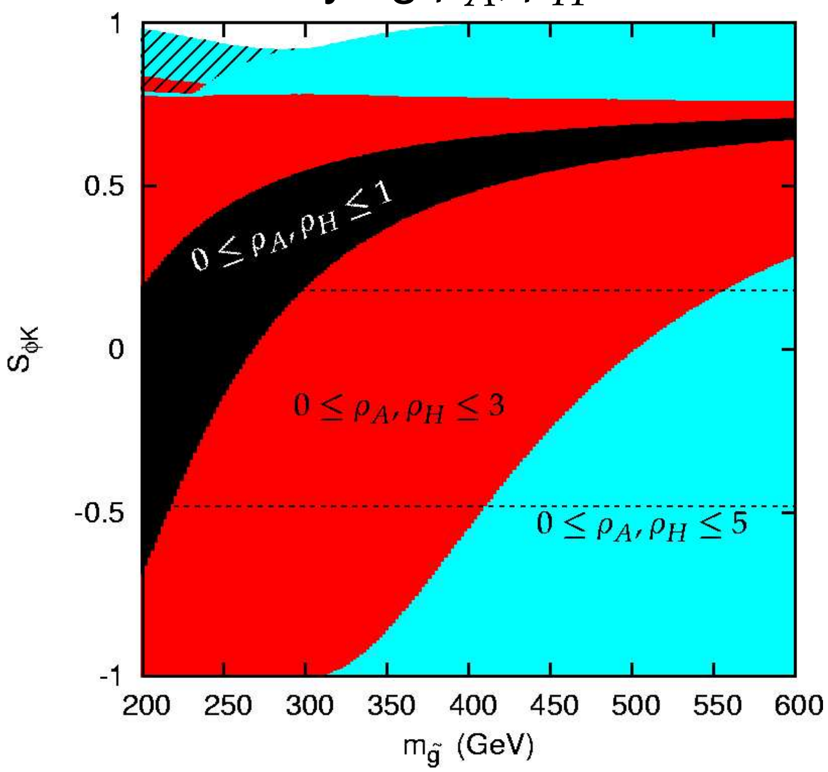
RL dominance

Theoretical uncertainties: what range of ρ_A?

- Plot with $(\delta^d_{23})_{RR} = 0.534 - 0.856i$ which minimizes $S_{\phi K}$ at $m_{\tilde{g}} = \tilde{m} = 200$ GeV



- Plots with varying ρ_A, ρ_H



- BBNS recommend $0 \leq \rho_A, \rho_H \leq 1$.

Are these values plausible?

- LL or RR mixing at large $\tan\beta$
  - $(\delta^d_{23})_{LL} \sim 10^{-2}$ possible from RG running from universal boundary condition. But $(\delta^d_{23})_{LL}$ is real in this case.
  - $(\delta^d_{23})_{RR} \sim 10^{-2}$ possible from SUSY GUT + large mixing in neutrino sector.

    Moroi, PLB**493**(2000); D. Chang, Masiero, Murayama, PRD**67**(2003); Causse, hep-ph/0207070; Harnik, Larson, Murayama, Pierce, hep-ph/0212180

  - Both possible from remnant misalignment in alignment mechanisms

    Leurer, Nir, Seiberg, NPB**398**(1993); Nir, Seiberg, PLB**309**(1993); Barbieri, Dvali, Hall, PLB**377**(1996); Hall, Murayama, PRL**75**(1995); Carone, Hall, Murayama, PRD**54**(1996)

    or decoupling.

    Pomarol, Tommasini, NPB**466**(1996); Cohen, Kaplan, Lepeintre, Nelson, PRL**78**(1997)

  - $(\delta^d_{23})^{\rm ind}_{LR,RL} = (\delta^d_{23})_{LL,RR} \times \frac{m_b(A_b - \mu\tan\beta)}{\tilde{m}^2} \sim 10^{-2}$ for large $\tan\beta$.

    Kaon version (for ϵ_K & ϵ'/ϵ_K): S. Baek, J. H. Jang, P. Ko, J.-h. Park, PRD**62**(2000)

- Intersecting D5 branes

  Kane, P. Ko, H. b. Wang, Kolda, J.-h. Park, L. T. Wang, hep-ph/0212092

Concerning other decay modes

- QCD penguin also affects other decays such as

$$B \longrightarrow \eta' K_S, \quad \pi K, \quad K^+ K^- K_S$$

- There are other 4-quark operators that contribute to these decays. So it may be that only $B \to \phi K_S$ is significantly modified.

- Parity invariance allows us to control $B \to VP$ and $B \to PP$ modes independently.

Kagan, Talk at BCP2 (8Jun2002)
Dutta, C. S. Kim, S. Oh, PRL**90**, 011801(2003)
Khalil, E. Kou, hep-ph/0303214

$$\langle VP | H_{\rm eff}^{\rm NP} | B \rangle = \sum_i (C_i^{\rm NP} + \widetilde{C}_i^{\rm NP}) \, \#_i \propto (\delta_{23}^d)_{LL(LR)} + (\delta_{23}^d)_{RR(RL)}$$

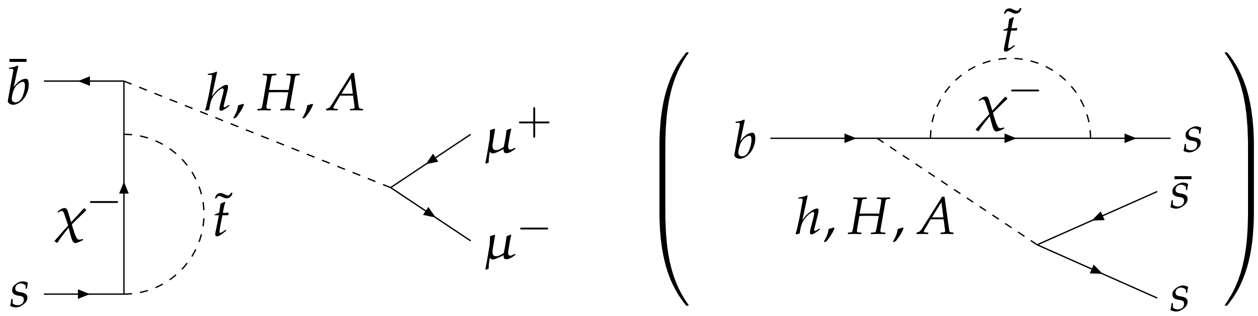
$$\langle PP | H_{\rm eff}^{\rm NP} | B \rangle = \sum_i (C_i^{\rm NP} - \widetilde{C}_i^{\rm NP}) \, \#_i \propto (\delta_{23}^d)_{LL(LR)} - (\delta_{23}^d)_{RR(RL)}$$

Higgs exchange can not explain $S_{\phi K} < 0$ in MFV

For non-minimal flavor violation,
see J. F. Cheng, C. S. Huang, X. h. Wu, hep-ph/0306086

- Higgs mediated FCNC also gives $B_s \to \mu^+\mu^-$

Babu, Kolda, PRL**84**(2000)



- Once we impose the CDF limit

$$B(B_s \to \mu^+\mu^-) < 2.6 \times 10^{-6},$$

CDF Collaboration, PRD**57**(1998)

we find

$$S_{\phi K} > 0.71.$$

Summary

	Gluino-squark			Higgs exchange
	LL or RR	LR	RL or RL dom.	
$S_{\phi K} < 0$	No	Yes	Yes	No
$A_{\rm CP}^{b\to s\gamma}$	$\pm 3\%$	$\pm 15\%$	0	
ΔM_s	Big	$\approx$SM	$\approx$SM	

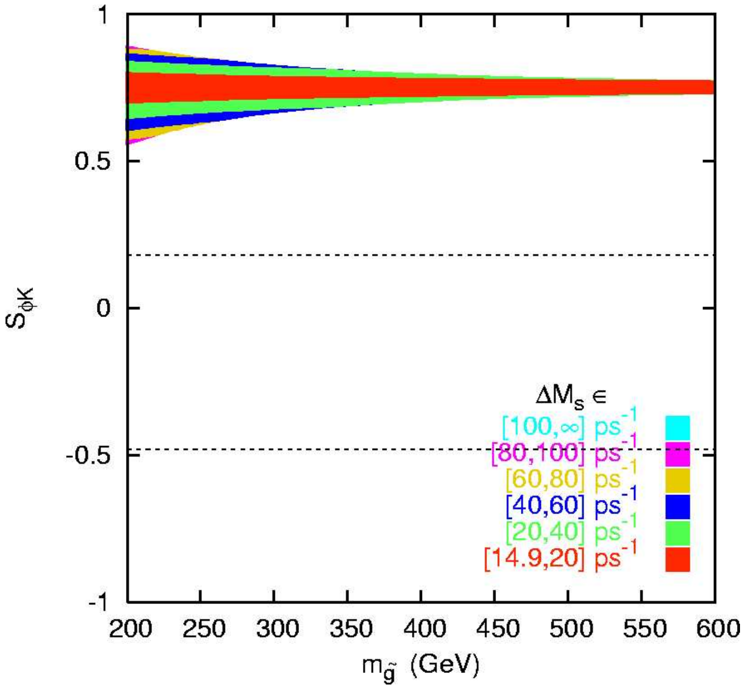
- Correlations among $S_{\phi K}, C_{\phi K}, A_{\rm CP}^{b\to s\gamma}$ may enable experimental discrimination.

- Constraint from $B_d \to \phi K_S$ comparable to that from $B \to X_s\gamma$.

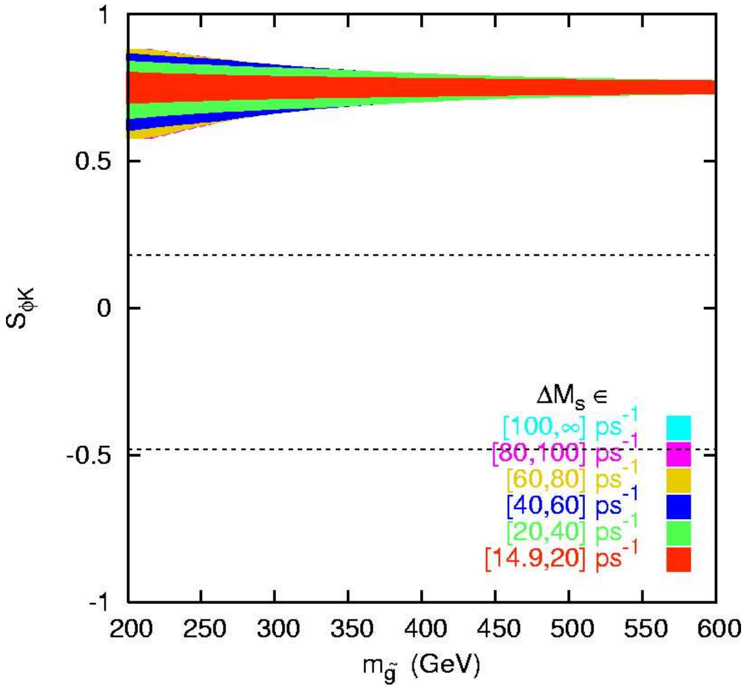
- $(\delta^d_{23})_{LR,RL} \sim 10^{-2}$ natural in SUSY flavor models at large $\tan\beta$ and in a string-inspired model.

[Backup] SUSY particle mass dependence with $m_{\tilde{g}}^2/\tilde{m}^2 \neq 1$

- $m_{\tilde{g}}^2/\tilde{m}^2 = 3$

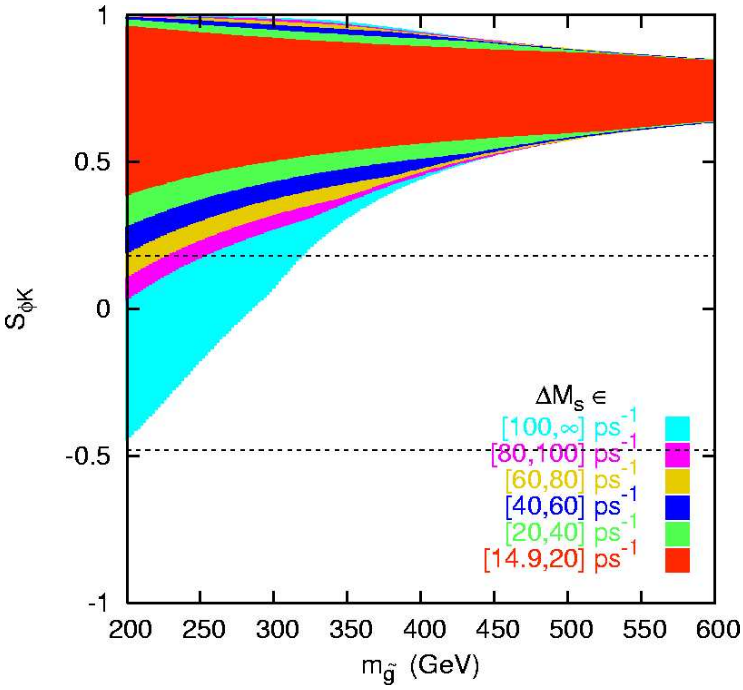


LL

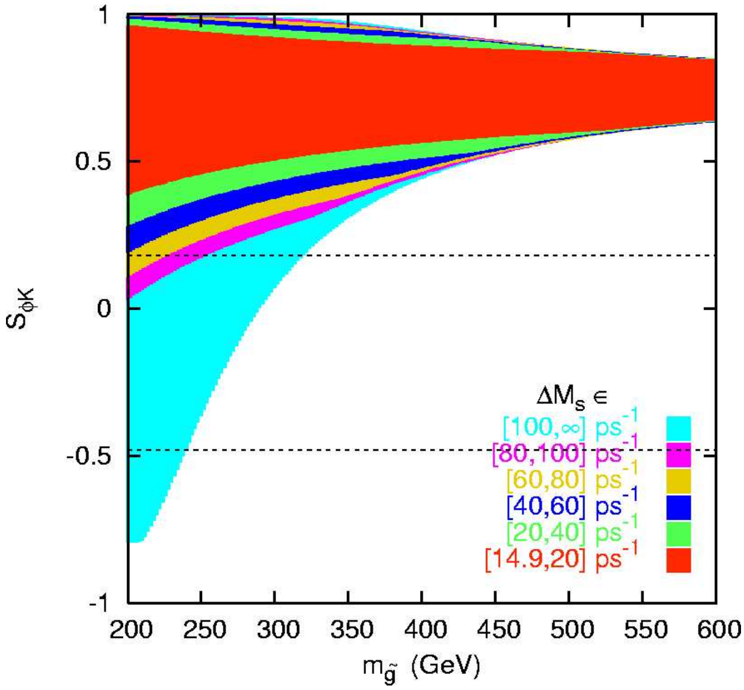


RR

- $m_{\tilde{g}}^2/\tilde{m}^2 = 0.5$



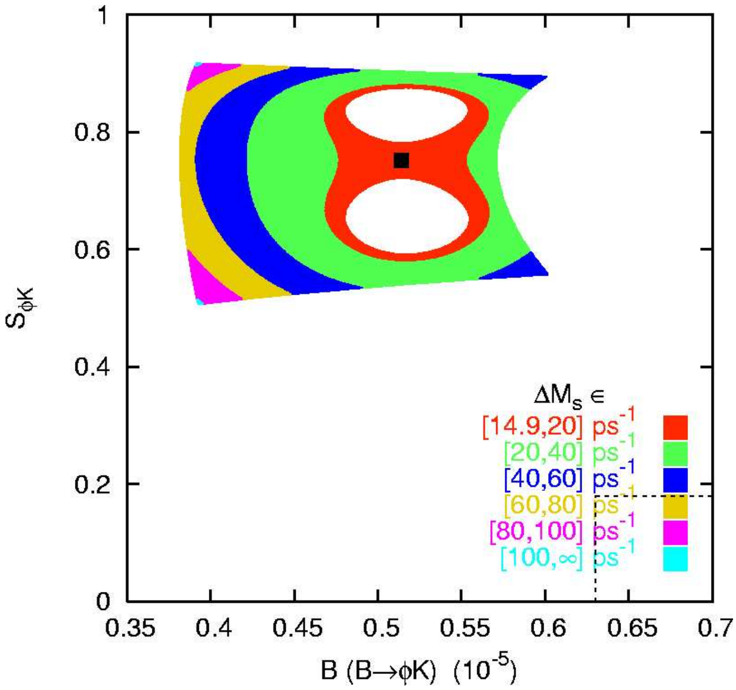
LL

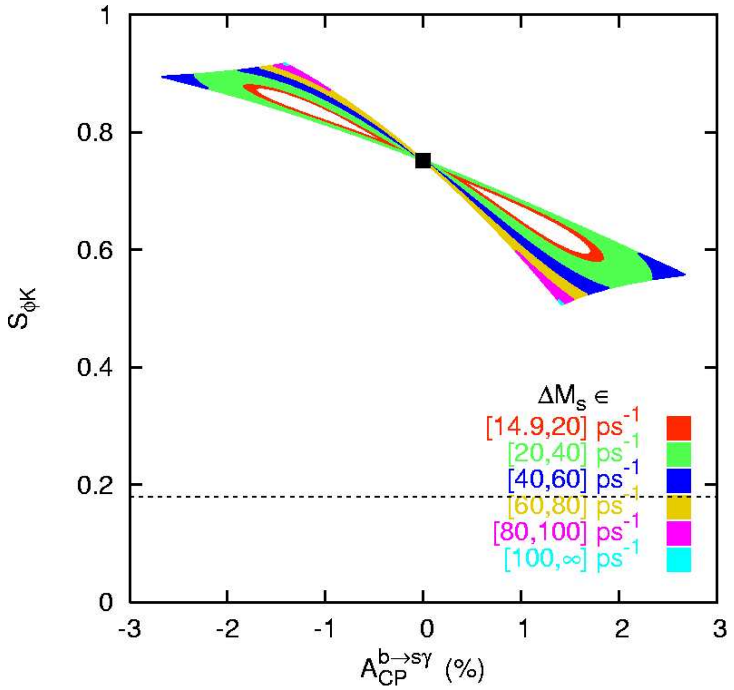


RR

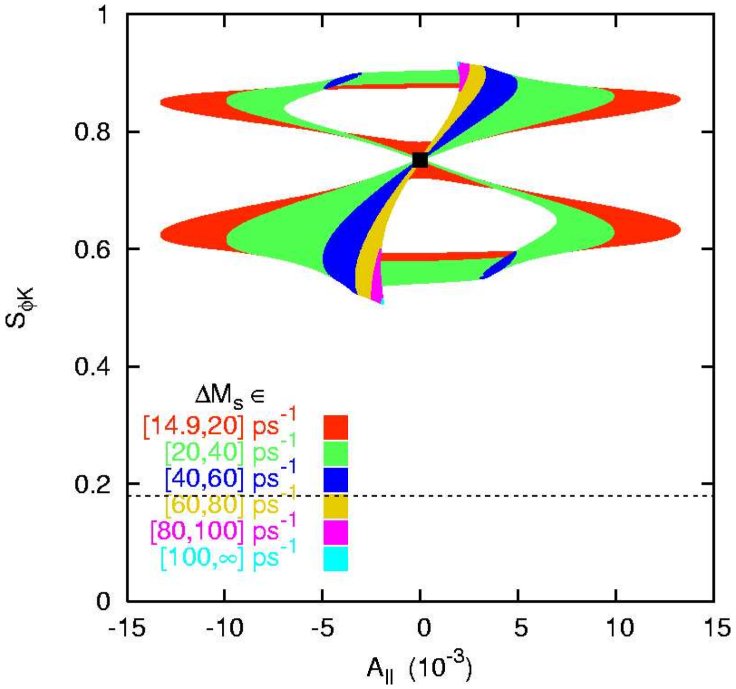
[Backup] Other plots for LL

- $\Delta B = 1$



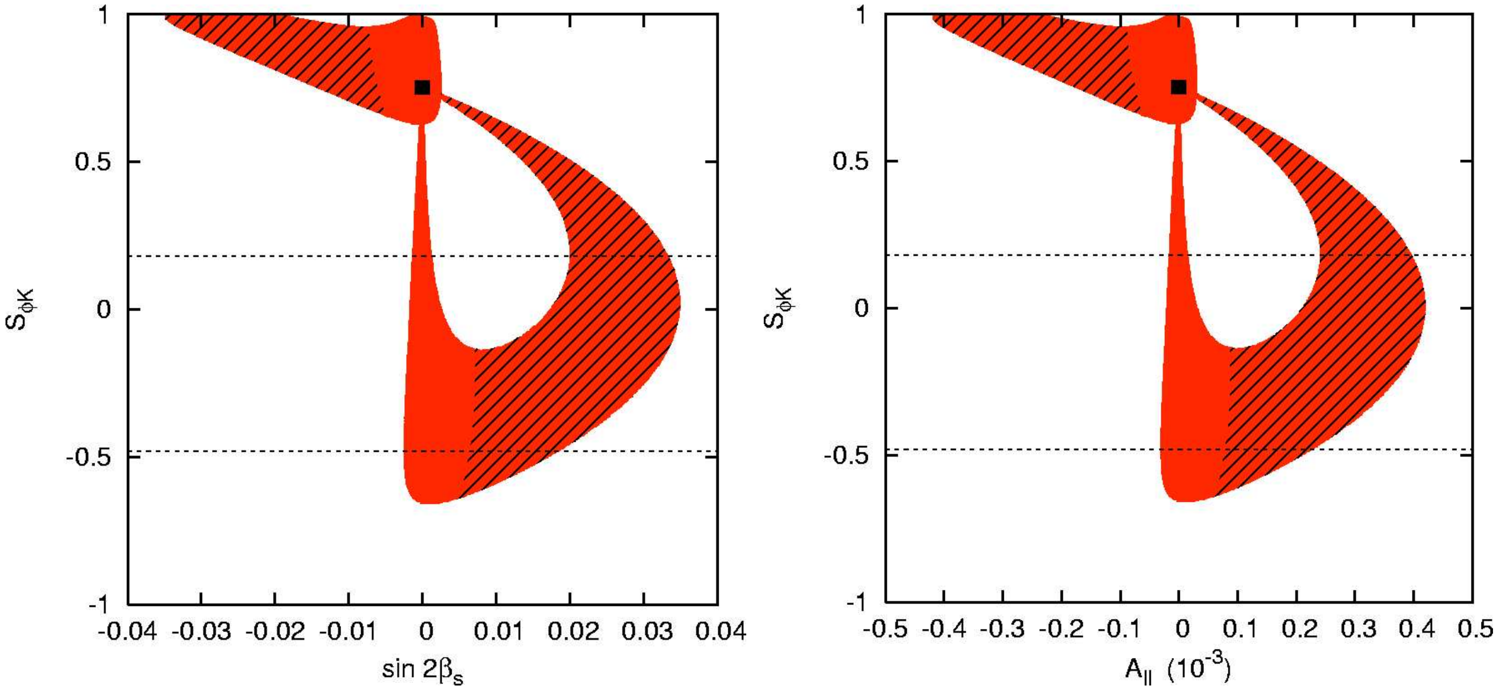


- $\Delta B = 2$



[Backup] Other plots for LR or RL

- $\Delta B = 2$ for LR



- $\Delta B = 2$ for RL dominance