A consistent resolution for possible anomalies in $B \to \phi K_S$ and $B \to \eta' K$ decays

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Introduction

CP asymmetry in $B^0 \to \phi K_S$

- CP violation in B system has been confirmed in measurements of time-dependent CP asymmetries in $B^0 \to J/\Psi K_S$ decay.
  World average (2003): $(\phi_1 \equiv \beta)$ $b \to c\bar{c}s$

$$\sin(2\phi_1)_{J/\Psi K_S} = +0.731 \pm 0.056$$

- Recent measurements in $B^0 \to \phi K_S$ (2003): $b \to s\bar{s}s$

$$\begin{aligned} \sin(2\phi_1)^{Belle}_{\phi K_S} &= -0.96 \pm 0.50^{+0.09}_{-0.11} \ \text{(3.5}\sigma\text{ off)} \ [(2002)\ -0.73 \pm 0.64 \pm 0.22] \\ \sin(2\phi_1)^{BaBar}_{\phi K_S} &= +0.45 \pm 0.43 \pm 0.07 \ [(2002)\ -0.18 \pm 0.51 \pm 0.09] \end{aligned}$$

$\Rightarrow$ Average $= -0.15 \pm 0.33$ (2.7σ off the SM)

$$\begin{aligned} \mathcal{B}(B^0 \to \phi K_S) &= (8.0 \pm 1.3) \times 10^{-6} \\ \mathcal{B}(B^+ \to \phi K^+) &= (10.9 \pm 1.0) \times 10^{-6} \\ \mathcal{A}_{CP}(B^+ \to \phi K^+) &= (3.9 \pm 8.8 \pm 1.1)\% \end{aligned}$$

- Any new physics effects in time-dependent CP asymmetries:
  - $B^0 - \bar{B}^0$ mixing amplitude (universal to all B_d^0 decays) and/or
  - decay amplitude of each mode

  $\Rightarrow$ New physics effect from the decay amplitude of $B^0 \to \phi K_S$.

$\sin(2\tilde{\phi}_1)_{XY}$ **for** $B \to XY$

$$\sin(2\tilde{\phi}_1)_{XY} = -\frac{2\ \mathrm{Im}\lambda_{XY}}{(1 + |\lambda_{XY}|^2)}$$

$$\lambda_{XY} = e^{-2i\phi_1} \frac{\bar{\mathcal{A}}_{XY}}{\mathcal{A}_{XY}} = e^{-i(2\phi_1 + \theta)} \left| \frac{\bar{\mathcal{A}}_{XY}}{\mathcal{A}_{XY}} \right|$$

$$\mathcal{A}_{XY} = \mathcal{A}_{XY}^{SM} + \mathcal{A}_{XY}^{\not{R}_p}$$

$\Rightarrow$ effective CP angle: $\quad 2\tilde{\phi}_1 = 2\phi_1 + \theta$

- What about other decay modes having the same internal quark level process $b \to s\bar{s}s$ (e.g., $B^0 \to \eta' K_S$)?
  $\Rightarrow$ recent data

$$\sin(2\phi_1)^{Belle}_{\eta' K_S} = +0.43 \pm 0.27 \pm 0.05 \quad (\text{hep}-\text{ex}/0308035)$$
$$\sin(2\phi_1)^{BaBar}_{\eta' K_S} = +0.02 \pm 0.34 \pm 0.03 \quad (\text{hep}-\text{ex}/0303046)$$

BR of $B^+ \to \eta' K^+$

- Recent experimental data :

$$\begin{aligned} \mathcal{B}(B^+ \to \eta' K^+) &= (78 \pm 6 \pm 9) \times 10^{-6} \quad [\text{Belle}] \\ &= (76.9 \pm 3.5 \pm 4.4) \times 10^{-6} \quad [\text{BaBar}] \\ &= (80^{+10}_{-9} \pm 7) \times 10^{-6} \quad [\text{CLEO}] \end{aligned}$$

$\Rightarrow$ still larger than that expected within the SM.

The goal

Try to find a *consistent* explanation for the recent data on $B \to \phi K_S$, $\eta' K_S$, and $\eta' K^+$ without disturbing all the other $B \to PP$ and $B \to VP$ decay modes within the framework of $\not{R}_p$ SUSY.

Effective Hamiltonian

- The effective Hamiltonian for charmless nonleptonic B decays can be written as

$$\mathcal{H} = \frac{G_F}{\sqrt{2}}\Big[V_{ub}V_{uq}^* \sum_{i=1,2} c_i O_i - V_{tb}V_{tq}^* \sum_{i=3}^{12} c_i O_i\Big] + h.c.$$

- The $\not{R}_p$ part of the superpotential of MSSM

$$\mathcal{W}_{\not{R}_p} = \kappa_i L_i H_2 + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c$$

For $b \longrightarrow s\bar{s}s$ transitions,

the sneutrino mediated diagrams: **Tree level effect!**

$$\frac{\lambda'_{i22}\lambda'^{*}_{i23}}{m^2_{\tilde{\nu}}}(\bar{s}^{\alpha}_{L}b^{\alpha}_{R})(\bar{s}^{\beta}_{R}s^{\beta}_{L})$$

$$\frac{\lambda'_{i32}\lambda'^{*}_{i22}}{m^2_{\tilde{\nu}}}(\bar{s}^{\alpha}_{R}b^{\alpha}_{L})(\bar{s}^{\beta}_{L}s^{\beta}_{R})$$

$\Rightarrow$ after the Fierz rearrangement:

$$\frac{\lambda'_{i22}\lambda'^{*}_{i23}}{8m^2_{\tilde{\nu}}}(\bar{s}^{\alpha}\gamma^{\mu}_{L}s^{\beta})(\bar{s}^{\beta}\gamma_{\mu R}b^{\alpha})$$

$$\frac{\lambda'_{i32}\lambda'^{*}_{i22}}{8m^2_{\tilde{\nu}}}(\bar{s}^{\alpha}\gamma^{\mu}_{R}s^{\beta})(\bar{s}^{\beta}\gamma_{\mu L}b^{\alpha})$$

$$\gamma^{\mu}_{R,L} = \gamma^{\mu}(1 \pm \gamma_5)$$

$$\sum_{i=1}^{3}\frac{\lambda'_{i22}\lambda'^{*}_{i23}}{8m^2_{\tilde{\nu}_{iL}}} \equiv d^{R}_{222}\ , \quad \sum_{i=1}^{3}\frac{\lambda'_{i32}\lambda'^{*}_{i22}}{8m^2_{\tilde{\nu}_{iL}}} \equiv d^{L}_{222}$$

$\not{R}_p$ part

$$H_{eff}^{\lambda'}(b \to \bar{d}_j d_k d_n) = d^R_{jkn}[\bar{d}_{n\alpha}\gamma^\mu_L d_{j\beta}\ \bar{d}_{k\beta}\gamma_{\mu R} b_\alpha] + d^L_{jkn}[\bar{d}_{n\alpha}\gamma^\mu_L b_\beta\ \bar{d}_{k\beta}\gamma_{\mu R} d_{j\alpha}] ,$$

$$H_{eff}^{\lambda'}(b \to \bar{u}_j u_k d_n) = u^R_{jkn}[\bar{u}_{k\alpha}\gamma^\mu_L u_{j\beta}\ \bar{d}_{n\beta}\gamma_{\mu R} b_\alpha] ,$$

$$H_{eff}^{\lambda''}(b \to \bar{d}_j d_k d_n) = \frac{1}{2} d''_{jkn}[\bar{d}_{k\alpha}\gamma^\mu_R d_{j\beta} \cdot \bar{d}_{n\beta}\gamma_{\mu R} b_\alpha - \bar{d}_{k\alpha}\gamma^\mu_R d_{j\alpha} \cdot \bar{d}_{n\beta}\gamma_{\mu R} b_\beta]$$

$$H_{eff}^{\lambda''}(b \to \bar{u}_j u_k d_n) = u''_{jkn}[\bar{u}_{k\alpha}\gamma^\mu_R u_{j\beta} \cdot \bar{d}_{n\beta}\gamma_{\mu R} b_\alpha - \bar{u}_{k\alpha}\gamma^\mu_R u_{j\alpha} \cdot \bar{d}_{n\beta}\gamma_{\mu R} b_\beta]$$

with

$d^R_{jkn} = \sum_{i=1}^3 \frac{\lambda'_{ijk}\lambda'^*_{in3}}{8m^2_{\tilde{\nu}_{iL}}}$

$d^L_{jkn} = \sum_{i=1}^3 \frac{\lambda'_{i3k}\lambda'^*_{inj}}{8m^2_{\tilde{\nu}_{iL}}}$ $(j, k, n = 1, 2)$

$u^R_{jkn} = \sum_{i=1}^3 \frac{\lambda'_{ijn}\lambda'^*_{ik3}}{8m^2_{\tilde{e}_{iL}}}$ $(j, k = 1;\ n = 2)$

$d''_{jkn} = \sum_{i=1}^3 \frac{\lambda''_{ij3}\lambda''^*_{ikn}}{4m^2_{\tilde{u}_{iR}}}$

$u''_{jkn} = \sum_{i=1}^2 \frac{\lambda''_{ji3}\lambda''^*_{kin}}{4m^2_{\tilde{d}_{iR}}}$ $(j = 1, 2;\ k = 1;\ n = 2)$

α, β: color indices

QCD Factorization

Beneke, Buchalla, Neubert, Sachrajda

- allows calculations of non-factorizable contributions (dominated by hard gluon exchange)
- Decay amplitude

$$\mathcal{A}(B \to PV) = \mathcal{A}^f(B \to PV) + \mathcal{A}^a(B \to PV) \ ,$$

where

$$\mathcal{A}^f(B \to PV) = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \sum_{i=1}^{10} V_{pb} V_{pq}^* \ a_i^p \langle PV | O_i | B \rangle_{\rm NF} \ ,$$

$$(q = d, \ s)$$

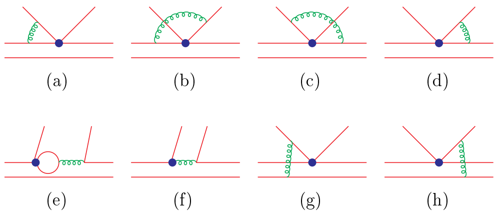
including vertex corrections, penguin corrections, and hard spectator scattering contributions.

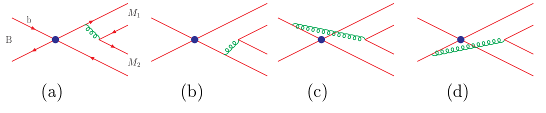
$$\mathcal{A}^a(B \to PV) \propto f_B f_P f_V \sum V_{pb} V_{pq}^* \ b_i \ ,$$

including weak annihilation contributions

Order of α_s corrections

vertex, penguin, hard spectator scattering, and weak annihilation





$B \to \phi K$ *and* $B \to \eta^{(\prime)} K$

Decay amplitude of $B \to \phi K$

$$\mathcal{A}(B \to \phi K) \equiv \mathcal{A}_{\phi K} = \mathcal{A}_{\phi K}^{SM} + \mathcal{A}_{\phi K}^{\not R_p} \ ,$$

$$\mathcal{A}_{\phi K}^{SM} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V_{pb} V_{pq}^* \left(a_3 + a_4^p + a_5 - \frac{1}{2} a_7 - \frac{1}{2} a_9 - \frac{1}{2} a_{10}^p \right) A_\phi + \mathcal{A}_{\phi K}^a$$

$$\mathcal{A}_{\phi K}^{\not R_p} \propto \left(d_{222}^L + d_{222}^R \right) A_\phi \qquad \left(d_{222}^L \sim \frac{\lambda'_{323} \lambda'^*_{322}}{8 m_{\tilde{\nu}}^2} \right)$$

$$A_\phi = \langle K | \bar{s} \gamma^\mu (1 - \gamma_5) b | B \rangle \langle \phi | \bar{s} \gamma_\mu s | 0 \rangle \ , \qquad a_i = a_i^L + a_i^V + a_i^P + a_i^H$$

Decay amplitude of $B \to \eta' K$

$$\mathcal{A}_{\eta' K}^{\not R_p} \sim \left(d_{222}^L - d_{222}^R \right) \left[\frac{\bar{m}}{m_s} \left(A_{\eta'}^s - A_{\eta'}^u \right) \left(\tilde{a}_6 + \frac{f_{\eta'}^u}{f_{\eta'}^s} \tilde{a}'_6 \right) + A_{\eta'}^s (\tilde{a}_4 - \tilde{a}_5) + A_{\eta'}^u \tilde{a}_4 \right]$$

$$\bar{m} \equiv m_{\eta'}^2 / (m_b - m_s), \qquad A_{\eta'}^{u(s)} = f_{\eta'}^{u(s)} F^{B \to K} (m_B^2 - m_K^2)$$

- $\eta - \eta'$ mixing :

$$|\eta\rangle = \cos\theta_8 |\eta_8\rangle - \sin\theta_0 |\eta_0\rangle$$
$$|\eta'\rangle = \sin\theta_8 |\eta_8\rangle + \cos\theta_0 |\eta_0\rangle \quad (\theta_8 \approx -22.2^0, \ \theta_0 \approx -9.1^0)$$

NOTE

$$d_{222}^R\ [\bar{s}_\alpha \gamma^\mu (1-\gamma_5) s_\beta][\bar{s}_\beta \gamma_\mu (1+\gamma_5) b_\alpha]$$
$$+d_{222}^L\ [\bar{s}_\alpha \gamma^\mu (1+\gamma_5) s_\beta][\bar{s}_\beta \gamma_\mu (1-\gamma_5) b_\alpha]$$

$$\Rightarrow\ d_{222}^R\ \langle \phi(\eta') | \bar{s}_\alpha \gamma^\mu (1-\gamma_5) s_\alpha | 0 \rangle \langle K | \bar{s}_\beta \gamma_\mu (1+\gamma_5) b_\beta | B \rangle$$
$$+d_{222}^L\ \langle \phi(\eta') | \bar{s}_\alpha \gamma^\mu (1+\gamma_5) s_\alpha | 0 \rangle \langle K | \bar{s}_\beta \gamma_\mu (1-\gamma_5) b_\beta | B \rangle$$

SM & QCD Factorization

New parameters

- End point divergent integrals in hard spectator scattering & weak annihilation contributions
  $\Rightarrow$ phenomenological parameters (8 new parameters for $B \to PP$ & PV)

$$X_{H,A} \equiv \int_0^1 \frac{dx}{x} = \left(1 + \rho_{H,A} e^{i\phi_{H,A}}\right) \ln \frac{m_B}{\Lambda_h}$$

$$\rho_{H,A} \le 1 \,, \quad 0^0 \le \phi_{H,A} \le 360^0 \,, \quad \Lambda_h = 0.5 \text{ GeV}$$

Global fit for $B \to PP$ & $B \to PV$: to determine $\rho_{H,A}$ & $\phi_{H,A}$ (Du, Gong, Sun, Yang, Zhu)

(12 modes: $B \to \pi\pi$, πK , $\pi\rho$, $K\rho$, ..., except $B \to \phi K$, $\eta^{(\prime)} X$)

- Large X_A & X_H case (unphysical)
  $\rho_H = \rho_A = 1$, $\phi_H^{PP} = -22^0$, $\phi_H^{PV} = 198^0$, $\phi_A^{PP} = 54^0$, $\phi_A^{PV} = -55^0$
  $\Rightarrow$ BR for $B \to \phi K$ and $B \to \eta' K$: fit the exp. data ($\chi^2 = 7.6$)
  $\Rightarrow$ No solution for $\sin(2\phi_1)_{\phi K_S}$

- Small X_A & X_H case
  $\rho_A^{PP} = 0$, $\rho_A^{PV} = 0.5$, $\rho_H^{PP} = 1$, $\rho_H^{PV} = 0.746$,
  $\phi_H^{PP} = \phi_H^{PV} = 180^0$, $\phi_A^{PV} = -6^0$ ($\chi^2 = 18.3$)
  $\Rightarrow \mathcal{B}(B^+ \to \phi K^+) = 7.35 \times 10^{-6}$ somewhat small
  $\mathcal{B}(B^+ \to \eta' K^+) = 48.5 \times 10^{-6}$ quite small

Analysis & Results

Strategy for finding possible solutions

- Need new amplitude(s) to explain the large $\mathcal{B}(B^{\pm} \to \eta' K^{\pm})$,
  but do not affect (much) the BRs of $B^{\pm(0)} \to \phi K^{\pm(0)}$, $B \to \pi\pi$, $K\pi$, $\rho\pi$, etc.

- Need new phase(s) to understand $\sin(2\phi_1)_{\phi K_S}$ [Belle, or Average of Belle & BaBar],
  but do not affect $\sin(2\phi_1)_{\eta' K_S}$ [Belle, or Average of Belle & BaBar]

- Concentrate on d^L_{222} and d^R_{222} :
  less constrained & $\underline{b \to s\bar{s}s}$ only!
  $\Rightarrow$ No contribution to most $B \to PP$ and
  $B \to PV$ modes (e.g., $B \to \pi\pi$, $K\pi$, ρK, etc),
  except $B \to \eta^{(\prime)} K$, $B \to \eta^{(\prime)} K^*$, $B \to \phi K$

- $\bar{\mathcal{A}}^{\not R_p}_{\phi K} \propto (d^L_{222} + d^R_{222})$ only
  $\bar{\mathcal{A}}^{\not R_p}_{\eta' K} \propto (d^L_{222} - d^R_{222})$

Solution

In QCD factorization,
δ': possible strong phase from $O(\Lambda_{QCD}/m_b) \quad \sim O(\alpha_s)$

For $\delta' = 0 \Rightarrow$ unlikely to find a solution
For $\delta' = 30^0 \Rightarrow$ Solution !!

$$d^L_{222} \propto |\lambda'_{i32}\lambda'^*_{i22}|e^{i\theta_L} \ , \quad d^R_{222} \propto |\lambda'_{i22}\lambda'^*_{i23}|e^{i\theta_R}$$

$$|\lambda'_{322}| = 0.086 \ , \ |\lambda'_{332}| = 0.089 \ , \ |\lambda'_{323}| = 0.030 \ ,$$
$$\theta_L = 0.66 \ , \ \theta_R = -2.25 \ , \quad m_{\rm SUSY} = 200 \ {\rm GeV}$$

In Generalized Factorization

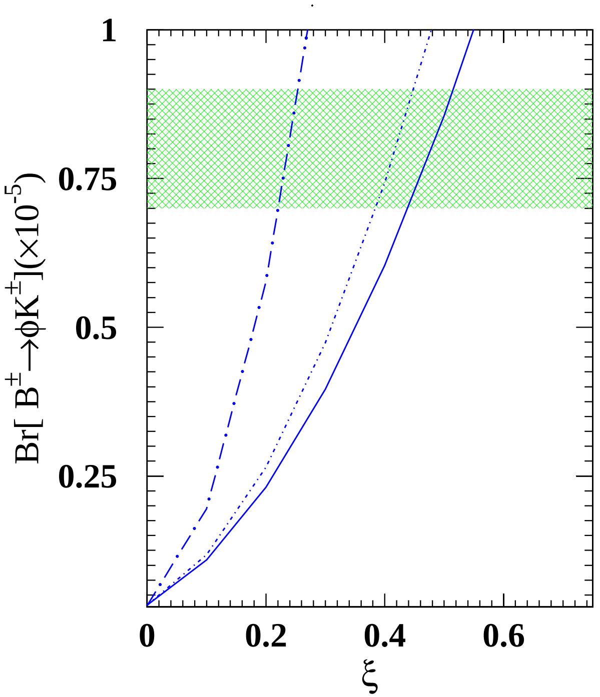


Figure 1: BR vs ξ. The dotted and dot-dashed lines correspond to Case 1 and Case 2 respectively. The solid line corresponds to the SM (The SM BR is same for both cases). The shaded region is allowed by the experimental data. $\left(\xi \equiv \frac{1}{N_c}\right)$

In Generalized Factorization

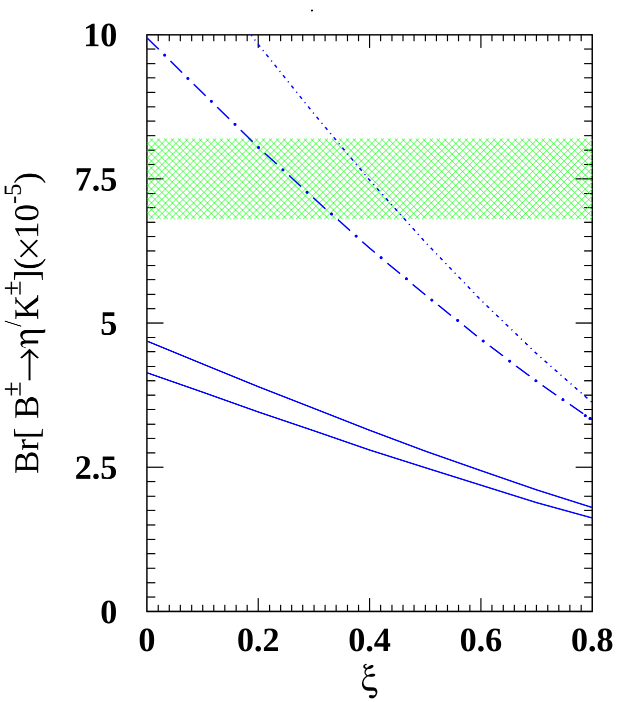


Figure 2: BR vs ξ. The dotted and dot-dashed lines correspond to Case 1 and Case 2 respectively. The solid lines correspond to the SM. The upper solid line is for Case 1 and the lower solid line is for Case 2. The shaded region is allowed by the experimental data.

Table 1: CP asymmetries in $B^0 \to \phi K_S$ and $B^0 \to \eta' K_S$.

$\sin(2\tilde{\phi}_1)$	Our result	experimental data
$\sin(2\tilde{\phi}_1)_{\phi K_S}$	-0.64	$-0.96 \pm 0.50^{+0.09}_{-0.11}$ [Belle]
		$+0.45 \pm 0.43 \pm 0.07$ [BaBar]
$\sin(2\tilde{\phi}_1)_{\eta' K_S}$	$+0.55$	$+0.43 \pm 0.27 \pm 0.05$ [Belle]
		$+0.02 \pm 0.34 \pm 0.03$ [BaBar]

Table 2: The BRs ($\mathcal{B}$) and CP rate asymmetries ($\mathcal{A}_{CP}$) for $B \to \eta' K$ and $B \to \phi K$.

	Our result		Exp. data	
mode	$\mathcal{B} \times 10^6$	$\mathcal{A}_{CP}$	$\mathcal{B} \times 10^6$	$\mathcal{A}_{CP}$
$B^- \to \phi K^-$	10.5	-4%	(10.9 ± 1.0)	$(3.9 \pm 8.8 \pm 1.1)\%$
$B^0 \to \phi K_S$	9.8	-2%	(8.0 ± 1.3)	$(-19 \pm 30)\%$
$B^- \to \eta' K^-$	71.1	8%	(77.6 ± 4.6)	$(2 \pm 4)\%$
$B^0 \to \eta' K_S$	65.9	8%	(60.6 ± 7.0)	$(8 \pm 18)\%$

In Generalized Factorization

Table 3: CP asymmetries in $B^0 \to \phi K_S$ and $B^0 \to \eta' K_S$.

$\sin(2\tilde{\phi}_1)$	Case 1 ($N_c \approx 2$)	Case 2 ($N_c \approx 4$)	experimental data
$\sin(2\tilde{\phi}_1)_{\phi K_S}$	0	-0.82	$-0.73 \pm 0.64 \pm 0.22$ [(NEW) $-0.96 \pm 0.50^{+0.09}_{-0.11}$] [Belle] $-0.19^{+0.52}_{-0.50} \pm 0.09$ [(NEW) $+0.45 \pm 0.43 \pm 0.07$] [BaBar]
$\sin(2\tilde{\phi}_1)_{\eta' K_S}$	0.73	0.72	$+0.71 \pm 0.37^{+0.05}_{-0.06}$ [(NEW) $+0.43 \pm 0.27 \pm 0.05$] [Belle] $+0.02 \pm 0.34 \pm 0.03$ [BaBar]

Table 4: The BRs ($\mathcal{B}$) and CP rate asymmetries ($\mathcal{A}_{CP}$) for $B \to \eta^{(\prime)} K^{(*)}$ and $B \to \phi K$.

	Case 1		Case 2	
mode	$\mathcal{B} \times 10^6$	$\mathcal{A}_{CP}$	$\mathcal{B} \times 10^6$	$\mathcal{A}_{CP}$
$B^+ \to \eta' K^+$	69.3	0.01	76.1	0.01
$B^+ \to \eta K^{*+}$	27.9	0.04	35.2	0.03
$B^0 \to \eta' K^0$	107.4	0.00	98.9	0.00
$B^0 \to \eta K^{*0}$	20.5	-0.71	11.7	-0.15
$B^+ \to \phi K^+$	8.99	0.21	8.52	0.25

Summary

- In R_p violating SUSY & QCDF, possible to consistently understand: the *anomalous* $\sin(2\phi_1)_{\phi K_S}$ as well as the *normal* $\sin(2\phi_1)_{\eta' K_S}$ $\&$ the large $\mathcal{B}(B \to \eta' K)$.
  $\Rightarrow$ Need a sizable strong phase from $O(\Lambda_{QCD}/m_b)$ contributions.
- All the observed data can be accommodated for certain values of $\not{R}_p$ couplings.

- RPV with (QCDF vs. pQCD) would be interesting

- future measurement:
  - $b \to s\bar{q}q$ penguin processes $(q = s, u, d)$:
    precise measurement of direct CP asymmetries for $B \to \phi K$, $\eta' K$
  - ηK decay channels: small BR

- R_p conserving SUSY
  (minimal extension of mSUGRA : non-universal soft breaking A terms)
  $\Rightarrow$ interesting solutions (coming soon) Arnowitt, Dutta, Hu
  Khalil, Kou