$B \to \phi K_S$ and $B \to \eta' K$ Decays in R-parity Violating SUSY

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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 $B \to J/\Psi K_S$ decay.
  World average: $(\phi_1 \equiv \beta)$ $b \to c\bar{c}s$

$$\sin(2\phi_1)_{J/\Psi K_S} = 0.734 \pm 0.054$$

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

$$\sin(2\phi_1)^{BaBar}_{\phi K_S} = -0.19^{+0.52}_{-0.50} \pm 0.09$$
$$\sin(2\phi_1)^{Belle}_{\phi K_S} = -0.73 \pm 0.64 \pm 0.22$$

  $\Rightarrow$ both show a tendency of (**small or large**) negative values of $\sin(2\phi_1)$.

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

  $\Rightarrow$ the decay amplitude of $B^0 \to \phi K_S$.

- 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

$$
\begin{aligned}
\sin(2\phi_1)^{Belle}_{\eta' K_S} &= +0.71 \pm 0.37^{+0.05}_{-0.06} \;\; (\mathrm{PRD, hep-ex/0207098}) \\
(&= +0.28 \pm 0.55^{+0.07}_{-0.08} \;\; (\mathrm{hep-ex/0207033})) \\
\sin(2\phi_1)^{BaBar}_{\eta' K_S} &= +0.02 \pm 0.34 \pm 0.03 \;\; (\mathrm{hep-ex/0303046})
\end{aligned}
$$

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

- Recent experimental data :

$$
\begin{aligned}
\mathcal{B}(B^+ \to \eta' K^+) &= (79^{+12}_{-11} \pm 9) \times 10^{-6} \;\; [\mathrm{Belle}] \\
&= (70 \pm 8 \pm 5) \times 10^{-6} \;\; [\mathrm{BaBar}] \\
&= (80^{+10}_{-9} \pm 7) \times 10^{-6} \;\; [\mathrm{CLEO}]
\end{aligned}
$$

$\Rightarrow$ still larger than that expected within the Standard Model (SM).

The goal

Try to find a *consistent* explanation for *all the observed data* in $B \to PP$ and $B \to VP$ decays in the framework of $\not{R}_p$ SUSY.

Effective Hamiltonian

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

the sneutrino mediated diagrams:

$$\frac{\lambda'_{i22}\lambda'^{*}_{i23}}{m^2_{\tilde{\nu}}}(\bar{s}^\alpha_L b^\alpha_R)(\bar{s}^\beta_R s^\beta_L)$$

$$\frac{\lambda'_{i32}\lambda'^{*}_{i22}}{m^2_{\tilde{\nu}}}(\bar{s}^\alpha_R b^\alpha_L)(\bar{s}^\beta_L s^\beta_R)$$

$\Rightarrow$ after the Fierz rearrangement:

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

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

$\not{R}_p$ 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

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

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

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

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

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

α, β: color indices; $\gamma^\mu_{R,L} = \gamma^\mu(1 \pm \gamma_5)$

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

Decay amplitude of $B^- \to \phi K^-$

$$\bar{\mathcal{A}}_{\phi K} = \bar{\mathcal{A}}^{SM}_{\phi K} + \bar{\mathcal{A}}^{\not{R}_p}_{\phi K}$$

$$\bar{\mathcal{A}}^{SM}_{\phi K} = -\frac{G_F}{\sqrt{2}} V_{tb} V^*_{ts} (a_3 + a_4 + a_5 - \frac{1}{2} a_7 - \frac{1}{2} a_9 - \frac{1}{2} a_{10}) A_\phi$$

$$\bar{\mathcal{A}}^{\not{R}_p}_{\phi K} = \left(d^L_{222} + d^R_{222} \right) \, [\xi A_\phi]$$

$A_\phi = \langle K | \bar{s} \gamma^\mu (1 - \gamma_5) b | B \rangle \, \langle \phi | \bar{s} \gamma_\mu s | 0 \rangle$
$a_i = c_i^{eff} + \xi c_{i+1}^{eff}$ ($i =$ odd)
$a_i = c_i^{eff} + \xi c_{i-1}^{eff}$ ($i =$ even)
$\xi \equiv 1/N_c$ (N_c: the effective number of color)

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

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

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

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

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

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

$$
\begin{aligned}
\bar{\mathcal{A}}^{R\!\!\!/_p}_{\eta' K} &= \left(d^R_{121} - d^L_{112}\right)\xi A^u_{\eta'} \\
&+ \left(d^L_{121} - d^R_{112}\right)\frac{\bar{m}}{m_d} A^u_{\eta'} \\
&+ \left(d^L_{222} - d^R_{222}\right)\left[\frac{\bar{m}}{m_s}\left(A^s_{\eta'} - A^u_{\eta'}\right) - \xi A^s_{\eta'}\right] \\
&+ u^R_{112}\left[\xi A^u_{\eta'} - \frac{2m_K^2 A_K}{(m_s+m_u)(m_b-m_u)}\right]
\end{aligned}
$$

$\bar{m} \equiv m^2_{\eta'}/(m_b - m_s)$
$A^{u(s)}_{\eta'} = f^{u(s)}_{\eta'} F^{B\to K}(m_B^2 - m_K^2)$
$A_K = f_K F^{B\to\eta'}(m_B^2 - m^2_{\eta'})$

- For $B^\pm \to \eta K^\pm$: $\eta \leftrightarrow \eta'$

NOTE

$$
\begin{aligned}
& d^R_{222}[\bar{s}_\alpha\gamma^\mu(1-\gamma_5)s_\beta][\bar{s}_\beta\gamma_\mu(1+\gamma_5)b_\alpha] \\
& + d^L_{222}[\bar{s}_\alpha\gamma^\mu(1+\gamma_5)s_\beta][\bar{s}_\beta\gamma_\mu(1-\gamma_5)b_\alpha]
\end{aligned}
$$

$$
\begin{aligned}
\Rightarrow\ & d^R_{222}\xi\langle\phi(\eta')|\bar{s}_\alpha\gamma^\mu(1-\gamma_5)s_\alpha|0\rangle\langle K|\bar{s}_\beta\gamma_\mu(1+\gamma_5)b_\beta|B\rangle \\
& + d^L_{222}\xi\langle\phi(\eta')|\bar{s}_\alpha\gamma^\mu(1+\gamma_5)s_\alpha|0\rangle\langle K|\bar{s}_\beta\gamma_\mu(1-\gamma_5)b_\beta|B\rangle
\end{aligned}
$$

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 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 $\sin(2\phi_1)_{\phi K_S}$,
  but do not affect $\sin(2\phi_1)_{\eta' K_S}$ [Belle] ?, OR, do affect $\sin(2\phi_1)_{\eta' K_S}$ [BaBar] ?

- From now on, concentrate on d^L_{222} and d^R_{222} :
  less constained & $\underline{b \to s\bar{s}s}$ 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
  $\bar{\mathcal{A}}^{\not R_p}_{\eta' K} \;\propto\; (d^L_{222} - d^R_{222})$

- Three cases
  Case 1 : generate a **small** value of $\sin(2\phi_1)_{\phi K_S}$ & $\sin(2\phi_1)^{Belle}_{\eta' K_S}$
  Case 2 : generate a **large negative** $\sin(2\phi_1)_{\phi K_S}$ & $\sin(2\phi_1)^{Belle}_{\eta' K_S}$
  Case 3 : generate a **small** value of $\sin(2\phi_1)_{\phi K_S}$ & $\sin(2\phi_1)^{BaBar}_{\eta' K_S}$

Solutions for Case 1 & 2

$$\text{Set} \qquad \underline{d^L_{222} = -ke^{-i\theta'}}, \quad \underline{d^R_{222} = ke^{i\theta'}}$$
$$k = |d^L_{222}| = |d^R_{222}|$$
$$d^L_{222} \propto |\lambda'_{i32}\lambda'^*_{i22}|e^{-i\theta'}, \quad d^R_{222} \propto |\lambda'_{i22}\lambda'^*_{i23}|e^{i\theta'}$$
$$\Rightarrow \qquad (d^L_{222} + d^R_{222}) = i2k\sin\theta', \qquad (d^L_{222} - d^R_{222}) = -2k\cos\theta'$$

$\Rightarrow \bar{\mathcal{A}}^{\not R_p}_{\phi K}$: purely imaginary

$\rightarrow$ introduce a new weak phase to $\bar{A}(B \to \phi K)$

$\rightarrow$ can cause non-zero *direct* CP asymmetries, different from the SM prediction

$\bar{\mathcal{A}}^{\not R_p}_{\eta' K}$: no new phase & *constructive* contribution to $\bar{\mathcal{A}}^{SM}_{\eta' K}$

Case 1 : $|\lambda'_{322}| = |\lambda'_{332}| = |\lambda'_{323}| = 0.055, \quad \tan\theta' = 0.52$:
solution at $\xi \equiv \frac{1}{N_c} = 0.45$

Case 2 : $|\lambda'_{322}| = |\lambda'_{332}| = |\lambda'_{323}| = 0.069, \quad \tan\theta' = 2.8$:
solution at $\xi \equiv \frac{1}{N_c} = 0.25$

Solution for Case 3 : d^L_{222} and/or d^R_{222}

$|\lambda'_{322}| = |\lambda'_{332}| = |\lambda'_{323}| = 0.077, \quad \tan\theta' = 1.13$:
solution at $\xi \equiv \frac{1}{N_c} = 0.25$

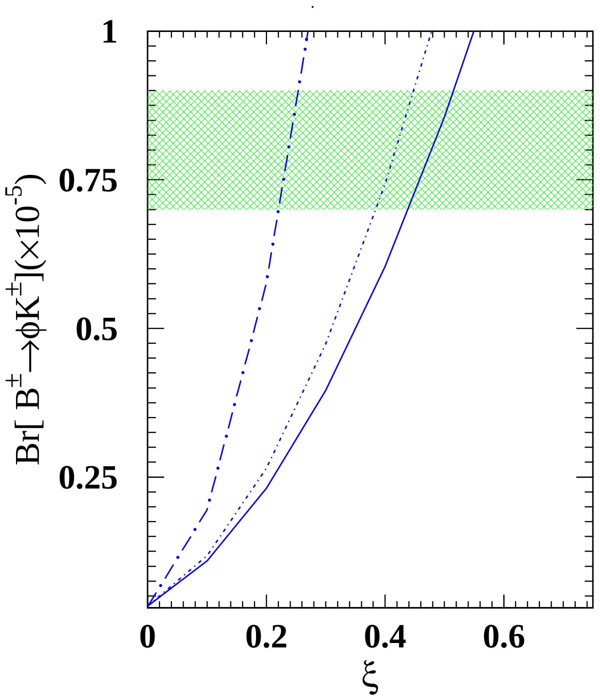


Figure 1: BR vs ξ. The dotted and dot-dashed lines correspond to Case 1 and Case 2 respectively. The solid line corresponds to the SM (The SM BR is same for both cases). The shaded region is allowed by the experimental data.

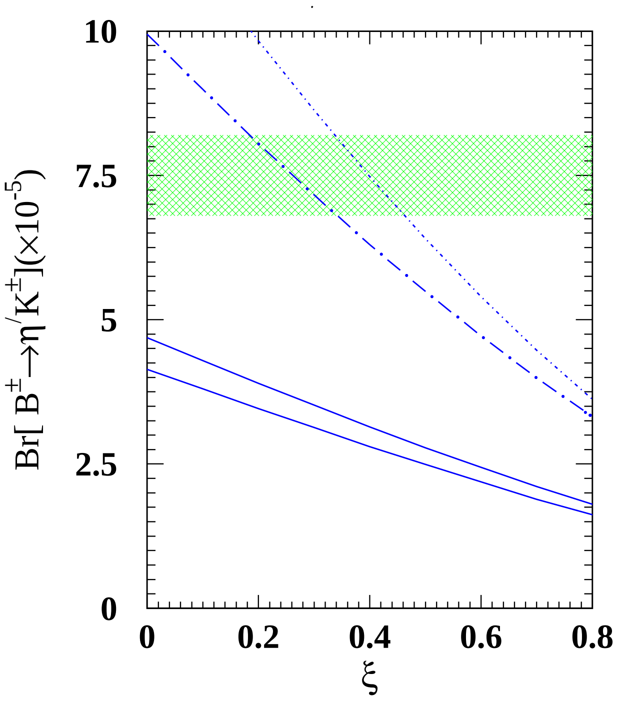


Figure 2: BR vs ξ. The dotted and dot-dashed lines correspond to Case 1 and Case 2 respectively. The solid lines correspond to the SM. The upper solid line is for Case 1 and the lower solid line is for Case 2. The shaded region is allowed by the experimental data.

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

$\sin(2\tilde{\phi}_1)$	Case 1	Case 2	Case 3	experimental data
$\sin(2\tilde{\phi}_1)_{\phi K_S}$	0	-0.82	0.1	$-0.19^{+0.52}_{-0.50} \pm 0.09$ [BaBar] $-0.73 \pm 0.64 \pm 0.22$ [Belle]
$\sin(2\tilde{\phi}_1)_{\eta' K_S}$	0.73	0.72	-0.1	$+0.71 \pm 0.37^{+0.05}_{-0.06}$ [Belle] $+0.02 \pm 0.34 \pm 0.03$ [BaBar]

$\mathcal{A}_{CP}(B^\pm \to \phi K^\pm) = 0.039 \pm 0.086 \pm 0.011$ [BaBar]

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

mode	Case 1 $\mathcal{B} \times 10^6$	Case 1 $\mathcal{A}_{CP}$	Case 2 $\mathcal{B} \times 10^6$	Case 2 $\mathcal{A}_{CP}$
$B^+ \to \eta' K^+$	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

QCD Factorization

Beneke, Buchalla, Neubert, Sachrajda

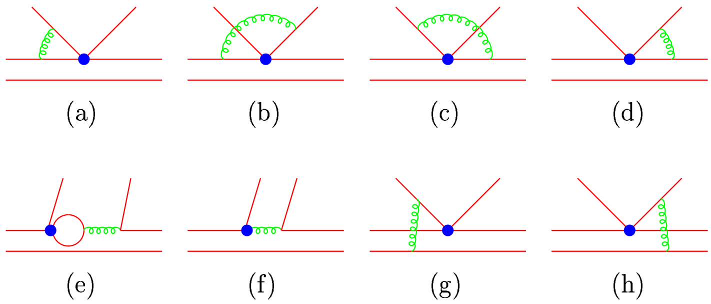
$$\mathcal{A}(B\to PV) = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \sum_{i=1}^{10} V_{pb} V_{pq}^* \; a_i^p \langle PV | O_i | B \rangle_{\rm NF}$$

$(q = d, \; s)$

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


(a)
(b)
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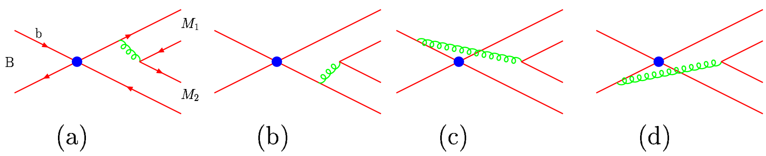
(e)
(f)
(g)
(h)


b
B
M_1
M_2
(a)
(b)
(c)
(d)

- **A preliminary result**

$$\text{Set} \quad d^L_{222} = -ke^{-i\theta'}, \; d^R_{222} = ke^{i\theta'}$$

$\Rightarrow$ We find a solution for $|\lambda'_{322}| = |\lambda'_{332}| = |\lambda'_{323}| = 0.065, \quad \tan\theta' = 0.52$:

$$\begin{aligned} \sin(2\tilde{\phi}_1)_{\phi K_S} &= -0.53 \\ \mathcal{B}(B^0 \to \phi K^0) &= 7.67 \times 10^{-6} \\ \mathcal{B}(B^+ \to \phi K^+) &= 8.22 \times 10^{-6} \\ \mathcal{A}_{CP}(B^+ \to \phi K^+) &= 0.16 \end{aligned}$$

- Need to check the process $B \to \eta' K_S$.

Summary

- In R_p violating SUSY, possible to consistently understand:
  the *anomalous* $\sin(2\phi_1)_{\phi K_S}$ as well as the *normal/anomalous* $\sin(2\phi_1)_{\phi K_S}$
  & the large $\mathcal{B}(B \to \eta' K)$.
- All the observed data can be accommodated for certain values of $R\!\!\!/_p$ couplings.
- in progress:
  in QCD improved factorization approach
  &
  in perturbative QCD approach
  e.g., $\mathcal{A}_{CP}(B \to \phi K)$
- future measurement:
  - $b \to s\bar{q}q$ penguin processes ($q = s, u, d$): $B \to \phi K$, $\eta' K$, $K^+ K^- K$
    time-dependent CP asymmetries & direct CP asymmetries
    (also $B_s \to \phi\phi$, $\mu\mu$)
  - ηK decay channels: small BR