A critical look at hadronic $b \longrightarrow s$ penguin modes

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Overview

CP violation in the SM is described by the KM mechanism and currently data is consistent with this scheme.

—But there is still room for New Physics. One way to look for NP is to test the "unitarity triangle"

We focus on angle β and ask whether $\sin(2\beta)$ is universal.

Does S_f in $b \to s$ transitions measure $\sin(2\beta)$?

- $b \to sc\bar{c}$

  Probed in $B \to J/\psi K_S$ and related $c\bar{c}$ modes.

  $S_f = \sin(2\beta) = 0.673 \pm 0.023$ in $B \to J/\psi K_S$ [HFAG, Winter 2009]

  S_f yields $\sin(2\beta)$ as "wrong phase" penguin is $\mathcal{O}(\lambda^2)$ suppressed.

  $\Delta S_{J/\psi K_S} \approx -(2.16 \pm 2.23) \cdot 10^{-4}$ [Boos, Mannel, Reuter, hep-ph/0403085]

- $b \to sq\bar{q}$ $(q \in u, d, s)$

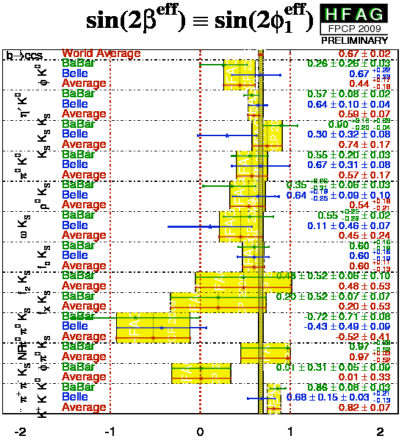
  Penguin modes probed in $B \to (\phi, \eta', \eta, f_0, \pi^0, \rho^0, ...)K_S$.

  Deviations of $-\eta_f S_f$ from $\sin(2\beta)$ possible from new physics.

  [Grossman, Worah, hep-ph/9612269]

- In the SM the charmless hadronic $b \to s$ decays measure $\sin(2\beta)$ up to small corrections. *How large are the corrections?*

- To identify the presence of non-SM physics in CP-violating observables one needs to make and interpret measurements of improved precision.



$B \to f_0 K_S$ and $B \to \phi K_S$ are two theoretically clean modes to test for it.

ΔS_f and C_f

$$A_f(t) = \frac{Br(\bar{B}^0(t) \to f) - Br(B^0(t) \to f)}{Br(\bar{B}^0(t) \to f) + Br(B^0(t) \to f)} \equiv S_f \sin(\Delta M_B\, t) - C_f \cos(\Delta M_B\, t)\,,$$

$$S_f = \frac{2\,\mathrm{Im}(\zeta_f)}{1+|\zeta_f|^2}\,, \qquad C_f = \frac{1-|\zeta_f|^2}{1+|\zeta_f|^2}\,, \qquad \zeta_f = \left(\frac{q}{p}\right)\frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)}$$

For $b \to sq\bar{q}$, the decay amplitude is [M. Beneke, Phys. Lett. B 620, 143 (2005)]

$$A(\bar{B} \to f) = \lambda_c\, a_f^c + \lambda_u\, a_f^u \propto (1 + e^{-i\gamma}\, d_f)\,, \; d_f \equiv |\lambda_u/\lambda_c|(a_f^u/a_f^c)\,, \lambda_q \equiv V_{qb} V_{qs}^*$$

$$\Delta S_f = -\eta_f\, S_f - \sin(2\beta) \equiv \frac{2\,\mathrm{Re}(d_f)\cos(2\beta)\sin\gamma + |d_f|^2\,(\sin(2\beta+2\gamma) - \sin(2\beta))}{1 + 2\,\mathrm{Re}(d_f)\cos\gamma + |d_f|^2}$$

$$C_f = -\frac{2\,\mathrm{Im}(d_f)\sin\gamma}{1 + 2\,\mathrm{Re}(d_f)\cos\gamma + |d_f|^2}$$

We compute d_f using QCD factorization approach.

[Beneke, Buchalla, Neubert, and Sachrajda, 1999, 2001; Beneke, Neubert, 2003; Cheng, Yang, 2006].

$B \to f_0 K_S$ and $B \to \phi K_S$ decays

Topologies — Tree (T), Color suppressed tree (C), Penguin (P^u, P^c), and annihilation (A)

- $d_{f_0 K_S} \propto \frac{P^u}{P^c}$

No "C" contribution because $\langle f_0 | \bar{q}\, \gamma^\mu\, q | 0 \rangle = 0$ due to charge conjugation symmetry [M. Diehl and G. Hiller, 2001].

- $d_{\phi K_S} \propto \frac{C + P^u}{P^c}$

If we assume ϕ to be a pure $s\bar{s}$ state, there would be no C contribution. $\phi - \omega$ mixing introduces C contribution.

Uncertainties

Sources of uncertainties:

- Input parameters such as quark mass, form factors, meson decay constants, and Gegenbauer moments of LCDA.
- Theoretical uncertainties come from the end point divergences associated with hard spectator interaction and annihilation amplitudes.

We perform a random scan over all the theoretical parameter space to gauge the size of the uncertainty on the value of ΔS_f.

ΔS in $b \to s$ penguin modes

Theory (QCDF) [Beneke, 2005] vs. Experiment [HFAG winter 2009]:

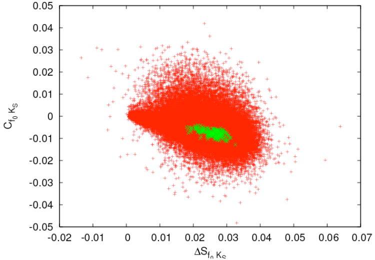
Mode	ΔS_f	ΔS_f[Range]	$\sin(2\beta^{eff})$ (Expt.)
$\pi^0 K_S$	$0.07^{+0.05}_{-0.04}$	$[+0.02, 0.15]$	0.57 ± 0.17
$\rho^0 K_S$	$-0.08^{+0.08}_{-0.12}$	$[-0.29, 0.02]$	$0.54^{+0.18}_{-0.21}$
$\eta' K_S$	$0.01^{+0.01}_{-0.01}$	$[+0.00, 0.03]$	0.59 ± 0.07
ηK_S	$0.10^{+0.11}_{-0.07}$	$[-1.67, 0.27]$	—
ϕK_S	$0.02^{+0.01}_{-0.01}$	$[+0.01, 0.05]$	$0.44^{+0.17}_{-0.18}$
ωK_S	$0.13^{+0.08}_{-0.08}$	$[+0.01, 0.21]$	0.45 ± 0.24

If there is color suppressed tree (C) contribution, there is more freedom for ΔS_f to be large.

Parameter scan— $B \to f_0 K_S$ decay

We have large excursions in $\Delta S_{f_0 K_S}$ over small regions of parameter space. However, once we impose the branching ratio constraint the range is found to be small.

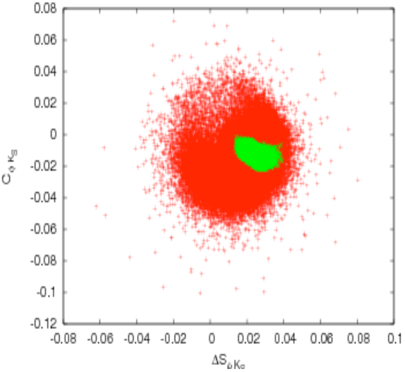
$$\Delta S_{f_0 K_S} = [0.018, 0.033] \text{ for } 1\sigma \text{ and } [-0.019, 0.064] \text{ for } 3\sigma \text{ scan.}$$



Parameter scan — $B \to \phi K_S$ decay

First we consider ideal mixing, i.e, ϕ is a pure $s\bar{s}$ state.

$$\Delta S_{\phi K_S} = [0.014, 0.039] \text{ for } 1\sigma \text{ and } [-0.062, 0.080] \text{ for } 3\sigma \text{ scan.}$$

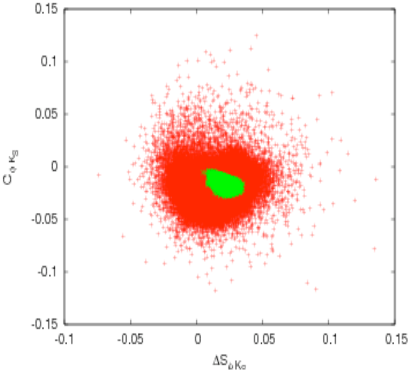


	$\Delta S_{\phi K_S}$	Range
[Grossman *et al.*]	–	$\lvert S_{\phi K_S} \rvert < 0.4$
[Beneke]	0.020	$[0.01, 0.05]$
[Cheng *et al.*]	$0.020^{+0.000}_{-0.040}$	–
[Virto]	–	$[0.03, 0.06]$
[Silvestrini *et al.*]	0.0 ± 0.09	–

Parameter scan — $B \to \phi K_S$ decay

We vary θ in the range $[2, 4]^\circ$ for 1σ scan and $[0, 6]^\circ$ for 3σ scan.

$\Delta S_{\phi K_S} = [0.0048, 0.035]$ for 1σ and $[-0.074, 0.14]$ for 3σ scan.



Summary

We have investigated the size of ΔS_f in the SM using QCD factorization approach.

- The largest excursion in ΔS_f comes from the first inverse moment of the B meson distribution amplitude, λ_B.
- large negative values of ΔS_f come from the uncertainties associated with λ_B and the end point divergences associated with the power corrections.

> These large excursions are controlled once we impose branching ratio constraint.

- $\Delta S_{f_0 K_S}$ is not sensitive to the $B \to f_0$ form factor and the f_0 scalar decay constant as the $B \to f_0 K_S$ decay amplitude is driven by strange quark component of f_0.
- The slightly larger range in $\Delta S_{\phi K_S}$ is due to the $\phi - \omega$ mixing, which introduces a color suppressed tree contribution to the $B \to \phi K_S$ decay amplitude.

Outlook

The pattern of CP violation in nature can be described by a single phase in the quark mixing (CKM) matrix to the $\mathcal{O}(10\%)$ level. No new source of CP violation beyond the Standard Model has been found yet.

We achieve sufficient theoretical control to interpret experimental results of much higher precision.

There is still a lot to learn from future experiments. We look forward to LHCb and SuperB for more answers and more questions.

$\phi - \omega$ mixing angle

	θ
[Kucukarslan *et al.*]	3.39
[Urech]	3.26
[Connell *et al.*]	2.82
[Coon *et al.*]	3.41
[Bernicha *et al.*]	3.01
[Bernicha *et al.*]	3.47
[Bernicha *et al.*]	3.21
[GMO mass formula]	3.75