How can we understand $S,C$ for $b \rightarrow s$ penguin decays at $O(0.01)$

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Standard model still in good shape

- Direct and indirect measurements agree very well
- $\beta$ measurements now more restrictive than $V_{ub}$
- $\alpha$ meas. now squeezing more than $\varepsilon_K$ and mixing meas.
- Meas. of $\beta$ from $B \rightarrow \eta'K_S$ now as precise as from $c\bar{c}K^0$
- 2001 observation
sin2\(\beta\) for \(b \to s\) penguin modes

- Typically have a dominant penguin amplitude and a Cabibbo- and color-suppressed tree
  - Penguin has same CKM phase as \(B \to \psi K_S\)
  - Tree \(\propto V_{ub}\) \(\Rightarrow\) additional phase (measures \(\sin 2\alpha\))
- Tree large \(\Rightarrow\) deviations from sin2\(\beta\)
$\sin2\beta$ from $\eta'K_S$

- Plot has cut on $L_{\text{sig}}/(L_{\text{sig}}+L_{\text{BG}})$
  - $N_{\text{sig}} = 819 \pm 38$
  - Purity = 0.57

- $N_{\text{sig}} = 512 \pm 27$
  - Purity = 0.61

- $S = +0.30 \pm 0.14 \pm 0.02$
  - $C = -0.21 \pm 0.10 \pm 0.02$

- $S = +0.65 \pm 0.18 \pm 0.04$
  - $C = +0.19 \pm 0.11 \pm 0.05$
Status of $b \rightarrow s$ penguin modes

<table>
<thead>
<tr>
<th>CP even $(\eta = +1)$</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.43 ± 0.11 2.7σ</td>
<td></td>
</tr>
<tr>
<td>3.7σ</td>
<td></td>
</tr>
</tbody>
</table>
“Model-independent” bounds

• Use SU(3) and measurements of color-suppressed modes to bound S and C

\[ A_f \equiv A(B^0 \to f) = V_{cb}^* V_{cs} \ a_f^c + V_{ub}^* V_{us} \ a_f^u = V_{cb}^* V_{cs} \ a_f^c (1 + \xi_f) \]

\[ \xi_f \equiv \frac{V_{ub}^* V_{us}}{V_{cb}^* V_{cs}} \ a_f^u \ , \ \ \delta_f = \arg \frac{a_f^u}{a_f^c} \]

\[ \Rightarrow -\eta_f S_f - \sin 2\beta = 2 \cos 2\beta \sin \gamma \cos \delta_f |\xi_f| \]

\[ C_f = -2 \sin \gamma \sin \delta_f |\xi_f| \]

\[ C_f^2 + [(\eta_f S_f + \sin 2\beta)/\cos 2\beta]^2 = 4 \sin^2 \gamma |\xi_f|^2 \]

Bounds are ellipses in \( S_f - C_f \) plane; \( C \)'s near 0

Bounds for \( \eta' K_S \) and \( \phi K_S \):


Sign of strong phase not known ⇒ unclear if \( S \) is larger or smaller than \( \sin 2\beta \)

Method is limited to uncertainty \( \sim \lambda^2 = 0.05 \) due to approximations
Other relevant work

• Original idea to measure $\sin 2\beta$ with penguin modes
    $(\Delta S(\eta'K_S) < 0.02)$
• Apply similar technique using $I$ spin to $\pi^0K_S$
• Update $\eta'K_S$
  • Gronau and Rosner, hep-ex/5003131.
Recent bounds for $\eta'K_S$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\pi^0\pi^0$</th>
<th>$\pi^0\eta$</th>
<th>$\pi^0\eta'$</th>
<th>$\eta$</th>
<th>$\eta'\eta'$</th>
<th>$\eta\eta'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>1.45 ± 0.29</td>
<td>2.5</td>
<td>3.7</td>
<td>2.0</td>
<td>10</td>
<td>4.6</td>
</tr>
<tr>
<td>Anticipated</td>
<td>1.8</td>
<td>1.5</td>
<td>1.6</td>
<td>2.0</td>
<td>1.2</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Use predictions from Chiang et al.

$A_{\eta K}$

Updated GLNQ

Neglect spectator amplitudes (GRZ)

SU(3) fits with arbitrary strong phase for CS tree (Chiang et al.)

Experiment (unscaled)
What data is used?

• For $\eta'K_S$:

$$|\xi_{\eta'K_S}| < \left| \frac{V_{us}}{V_{ud}} \right| \left( 0.59 \sqrt{\frac{B(\eta'\pi^0)}{B(\eta'K^0)}} + 0.33 \sqrt{\frac{B(\eta\pi^0)}{B(\eta'K^0)}} + 0.14 \sqrt{\frac{B(\pi^0\pi^0)}{B(\eta'K^0)}} \right)$$

$$+ 0.53 \sqrt{\frac{B(\eta'\eta')}{B(\eta'K^0)}} + 0.38 \sqrt{\frac{B(\eta\eta)}{B(\eta'K^0)}} + 0.96 \sqrt{\frac{B(\eta\eta')}{B(\eta'K^0)}}$$

• GRZ (neglect spectator amplitudes):
  $\eta\pi^0, \eta'\pi^0, \eta'\eta$ only

• GLNQ - use $\eta'K^+$: $\eta\pi^+, \eta'\pi^+, \pi^+\pi^0, K^+K^0$
  • Not much better than GRZ approach (0.08)
  • We now see $\eta'\pi^+$ also and even $K^+K^0$ is beginning to emerge
Which modes (cont.)

• For $\phi K_S$:

\[
a(\phi K^0) = \frac{1}{2} \left[ b(K^{*0}K^0) - b(K^{*0}\bar{K}^0) \right] + \frac{1}{2} \sqrt{\frac{3}{2}} \left[ cb(\phi\eta) - sb(\phi\eta') \right] \\
+ \frac{\sqrt{3}}{4} \left[ cb(\omega\eta) - sb(\omega\eta') \right] - \frac{\sqrt{3}}{4} \left[ cb(\rho^0\eta) - sb(\rho^0\eta') \right] \\
+ \frac{1}{4} b(\rho^0\pi^0) - \frac{1}{4} b(\omega\pi^0) - \frac{1}{2\sqrt{2}} b(\phi\pi^0)
\]

• Use $\phi K^+$: $\phi\pi^+, K^{*0}K^+ \Rightarrow \Delta S < 0.23$

  (this method was pointed out by Grossman and Worah in '97!)

• Bottom line is that the model-independent approach isn’t good enough for Belle/BABAR era never mind SuperB
Specific calculations

- **QCD Factorization**
  

  Quantities in square brackets are positive!

  \[
  \begin{align*}
  \pi K_S & : \hat{d}_f \sim \frac{[-P^u] + [C]}{[-P^c]} & \rho K_S & : \hat{d}_f \sim \frac{[P^u] - [C]}{[P^c]} \\
  \eta' K_S & : \hat{d}_f \sim \frac{[-P^u] - [C]}{[-P^c]} & \phi K_S & : \hat{d}_f \sim \frac{[-P^u]}{[-P^c]} \\
  \eta K_S & : \hat{d}_f \sim \frac{[P^u] + [C]}{[P^c]} & \omega K_S & : \hat{d}_f \sim \frac{[P^u] + [C]}{[P^c]} 
  \end{align*}
  \]

  Beneke CKM2005

  Color-sup. tree

  u penguin

  *Range is from scan of random input parameters which satisfy exp. BRs within 3σ

<table>
<thead>
<tr>
<th>Mode</th>
<th>Theory $\delta \sin(2\beta)_f$</th>
<th>[Range]$^*$</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi K_S$</td>
<td>$0.07^{+0.05}_{-0.04}$</td>
<td>$[+0.02, 0.13]$</td>
<td>$-0.39^{+0.27}_{-0.29}$</td>
</tr>
<tr>
<td>$\rho K_S$</td>
<td>$-0.08^{+0.08}_{-0.12}$</td>
<td>$[-0.24, 0.02]$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\eta' K_S$</td>
<td>$0.01^{+0.01}_{-0.01}$</td>
<td>$[-0.01, 0.03]$</td>
<td>$-0.32 \pm 0.11$</td>
</tr>
<tr>
<td>$\eta K_S$</td>
<td>$0.10^{+0.11}_{-0.07}$</td>
<td>$[-1.45, 0.27]$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\phi K_S$</td>
<td>$0.02^{+0.01}_{-0.01}$</td>
<td>$[+0.01, 0.04]$</td>
<td>$-0.39 \pm 0.20$</td>
</tr>
<tr>
<td>$\omega K_S$</td>
<td>$0.13^{+0.08}_{-0.08}$</td>
<td>$[+0.03, 0.19]$</td>
<td>$0.02 \pm 0.64^{+0.13}_{-0.16}$</td>
</tr>
</tbody>
</table>
More QCDF

- Account for specific FSI final states
  Cheng, Chua, and Soni, hep-ph/0502235
  - Mode \( \eta'K_S \), \( \phi K_S \), \( \pi^0 K_S \), \( \omega K_S \), \( f_0 K_S \)
  - \( \Delta S \) = 0.006, 0.029, 0.048, 0.008, 0.021
  - Good agreement with Beneke for main modes
  - Also predict C: generally small but \( C(\omega K_S) = 0.15 \pm 0.02 \)
    (2.6\( \sigma \) away from data: \(-0.48 \pm 0.25\))

- Another recent QCDF calculation
  - Quite close agreement with Beneke (v2 with error fixed to be posted soon)
Fits to data

- SU(3) fits to PP data
- Experimental inputs:
  - BR, $A_{\text{ch}}$: $\pi^+\pi^0$, $\eta\pi^+$, $\eta'\pi^+$, $K^+\pi^-$, $K^+\pi^0$, $K^0\pi^+$, $\eta K^+$, $\eta' K^+$
  - BR, S, C: $\pi^+\pi^-$, $K^0\pi^0$, $\eta' K^0$
  - BR, C: $\pi^0\pi^0$
  - BR Limits: $K^+K^0$, $K^+K^-$, $K^0K^0$, $\eta K^0$, $\eta\pi^0$, $\eta'\pi^0$, $\eta\eta$, $\eta'\eta$, $\eta'\eta'$
  - A total of 36 measurements! ($C(\pi^0\pi^0)$ and $A_{\text{ch}}(\eta'\pi^+)$ were not available for the ’04 paper. Limit are not used in the fit.
Theory parameters

Parameters: 6 amplitudes, 5 strong phases and $\gamma$

- Result $\gamma = 52 \pm 9^\circ$, $\Delta S(\eta'K^0) = 0.01 \pm 0.01$
### $b \rightarrow s$ penguin comparisons

- **Rankings (3=Gold, 2=Silver, 1=Bronze):**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Naïve theory</th>
<th>QCD Fact.</th>
<th>QCD Fact.+FSI</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta'K_S$</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$\phi K^0$</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>$\pi^0 K_S$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\omega K_S$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$f_0 K_S$</td>
<td>2?</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$K^+ K^- K_S$</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>2.5</td>
</tr>
<tr>
<td>$K_S K_S K_S$</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
</tbody>
</table>

- **Reason $\eta'K_S$ is Gold is same for theory and experiment**
  - Penguin amplitude is 2-3× larger than any other mode

- **Million dollar question:**

  What can we believe when SM is at stake?