Branching Fractions and CP Violation in $B_d \rightarrow K\bar{K}$ at BaBar

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$B_d \to K^0\bar{K}^0$: Pure $b \to d$ Penguin Amplitude

- Modes dominated by loop (penguin) diagrams are sensitive to New Physics contributions.
- Many New Physics models contribute additional CP-violating phases.
- $B \to K^0\bar{K}^0$ is dominated by the $b \to d$ transition.
- Analogous to $b \to s$ penguins in $\phi K_s$.
  - But new physics might affect $b \to d$ differently than $b \to s$.
- Same penguin as in $B \to \pi^+\pi^-$ and $B \to K^0\bar{K}^+$.
  - Useful for extracting $\alpha$ in the former and the annihilation contribution in the latter.

Penguin modes are suppressed in the standard model.

$b \to d$ further suppressed by $|V_{td}/V_{ts}|^2 = 0.043$ with respect to $b \to s$.

Small branching fractions.
**B_d → K^0\overline{K^0}: Expectations from the Standard Model**

- **Assuming top-quark dominance:**
  - BF ≈ 10^{-6}
  - Decay weak phase exactly cancels mixing phase
    \[ \lambda \equiv \frac{q_A}{p_A} = \left( \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \right) \left( \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \right) = 1 \]

- Expect zero indirect CP violation
  - S(K^0\overline{K^0}) = 0
  - any non-zero value would indicate New Physics

- Expect a small contribution from u- and c-penguins
  - S(K^0\overline{K^0}) < 0.10, sensitive to combination of all three UT angles

**Predictions (using QCD FA):**

\[ 0.02 < S_{KK}(SM) < 0.13 \]
\[ -0.17 < C_{KK}(SM) < -0.15 \]

### Flavor-Changing New Physics in Theory and Experiment

**sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_i^\text{eff})**

<table>
<thead>
<tr>
<th>Process</th>
<th>World Average</th>
<th>BaBar</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to cs$</td>
<td>$0.68 \pm 0.03$</td>
<td>$0.12 \pm 0.31 \pm 0.10$</td>
<td>$0.50 \pm 0.21 \pm 0.06$</td>
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<tr>
<td>$b \to cs$</td>
<td>$0.55 \pm 0.11 \pm 0.02$</td>
<td>$0.64 \pm 0.10 \pm 0.04$</td>
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<tr>
<td>$b \to cs$</td>
<td>$0.66 \pm 0.26 \pm 0.08$</td>
<td>$0.30 \pm 0.32 \pm 0.08$</td>
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<tr>
<td>$b \to cs$</td>
<td>$0.33 \pm 0.26 \pm 0.04$</td>
<td>$0.33 \pm 0.35 \pm 0.08$</td>
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<tr>
<td>$b \to cs$</td>
<td>$0.17 \pm 0.52 \pm 0.26$</td>
<td>$0.62 \pm 0.35 \pm 0.02$</td>
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<tr>
<td>$b \to cs$</td>
<td>$0.11 \pm 0.46 \pm 0.07$</td>
<td>$0.62 \pm 0.23$</td>
<td></td>
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<tr>
<td>$b \to cs$</td>
<td>$0.18 \pm 0.23 \pm 0.11$</td>
<td>$-0.84 \pm 0.71 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>$b \to cs$</td>
<td>$0.41 \pm 0.18 \pm 0.07 \pm 0.11$</td>
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<td></td>
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</tbody>
</table>

**Naïve average**

- $b \to qs\bar{s}$
- $b \to q\bar{q}\bar{q}$

**The experimental program is just beginning:**

- $B \to \rho \gamma$
- $B \to KK$

**Need to explore the $b \to d$ sector and add another constraint**

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**M. Ciuchini and L. Silvestrini,**

**M. Ciuchini et al.,**
hep-ph/0512141
\( B^{\rightarrow} K^0 \bar{K}^0 \): Example of a Potential New Physics Scenario


Predictions for various assumptions on the weak phase \( \theta_{NP} \) and strong phase \( \delta_{NP} \) between NP amplitudes:

\[
\theta_{NP} = \frac{\pi}{4}, \frac{\pi}{3}, \frac{\pi}{2}, \pi
\]

\[0 < \delta_{NP} < 2\pi\]

Note: this scenario does not include all experimental constraints
Evidence for $B_d \rightarrow K^0\overline{K}^0$ (ICHEP 2004)

\[
N(K_S^0K_S^0) = 23.0^{+7.7}_{-6.7}^{+1.9}_{-2.0} \quad (4.5\sigma)
\]

\[
\mathcal{B}(B^0 \rightarrow K^0\overline{K}^0) = (1.19^{+0.40}_{-0.35} \pm 0.13) \times 10^{-6}
\]

PRL 95: 221801, 2005 (227 million BB pairs)

\[
N(K_S^0K_S^0) = 15.6 \pm 5.8^{+1.1}_{-0.6} \quad (3.5\sigma)
\]

\[
\mathcal{B}(B^0 \rightarrow K^0\overline{K}^0) = (0.8 \pm 0.3 \pm 0.1) \times 10^{-6}
\]

PRL 95: 231802, 2005 (275 million BB pairs)

Next Step for BaBar: Observe the mode and measure CP asymmetries with
\sim 350 million BB pairs
Measuring $S_{KK}$ at BaBar

Challenge: Need to vertex a decay with no primary tracks from the $e^+e^-$ interaction point

Solution: Exploit precise knowledge of the interaction point and fit the entire $\Upsilon(4S)$ decay chain using beam-spot constraints.

Method developed by BaBar, described in PRL 93: 131805, 2004 and PRD 71: 111102, 2005

1. Constrain $B_{rec}$ decay to beam-spot in $x$-$y$
2. Use a neural-net algorithm to determine the $B_{tag}$ flavor
3. Determine the proper-time difference $\Delta t$ between $B_{rec}$ and $B_{tag}$ decay vertices
Use $K_S$’s that decay in the Silicon Vertex Tracker

Classes of $K_S$ decays:

- **35%** Class I - both pions have hits in inner layers
- **25%** Class II - not Class I, both pions have hits in SVT
- **40%** Class III and IV: not used for time-dependent measurement

Have two $K_S$’s but need only one to vertex the signal B

Class I $B^0$’s: 58%
Class II $B^0$’s: 26%
The data sample consists of 347 million $\Upsilon(4S) \rightarrow B\bar{B}$ pairs (316 fb$^{-1}$) collected with the BaBar detector.

- $B \rightarrow K^0\bar{K}^0$ reconstructed in $K^0\bar{K}^0 \rightarrow K_S K_S$ and $K_S \rightarrow \pi^+\pi^-$
- Efficiency: 8.5 ± 0.3% (including secondary branching fractions)
- Unbinned Maximum-likelihood fit
  - Four variables: $m_{ES}, \Delta E, \text{Fisher}, \Delta t$
  - Extract signal yield, background yield, and the time-dependent CP-violating asymmetry parameters $S$ and $C$

\[
m_{ES} = \sqrt{E_{\text{beam}}^* - p_B^*}^2
\]

\[
\Delta E = E_B^* - E_{\text{beam}}^*
\]
Unbinned Maximum Likelihood Fit and Discriminating Variables

\[ \mathcal{L} = \exp \left( - \sum_{i} n_i \right) \prod_{j=1}^{N} \left[ \sum_{i} n_i P_i \right] \]

- \( n_i \) = candidate category, signal or background
- \( P_i \) = probability density for category \( i \)
- \( N \) = number of events

**Kinematic**

**Event-shape**

**Distributions from the final fit model**

- Solid histogram = Signal
- Dashed histogram = Background
Fit result closely tracks the generated CP-violating structure

Resolution function characterizes the data well
Results: Branching Fraction

$N(K_s^0 K_s^0) = 32 \pm 8 \pm 3 \ (7.3\sigma)$

$B(B^0 \rightarrow K^0 \overline{K}^0) = (1.08 \pm 0.28 \pm 0.11) \times 10^{-6}$

Dominant systematic uncertainties:
→ Fitter bias
→ Uncertainty in PDF shapes in the fit

M. Pivk and F. R. Le Diberder,
“sPlot: A Statistical Tool to Unfold Data Distributions,”
Results: CP Violation

Projection Plots

BABAR

$S(K^0_s K^0_s) = -1.28^{+0.80}_{-0.73}^{+0.11}_{-0.16}$

$C(K^0_s K^0_s) = -0.40 \pm 0.41 \pm 0.06$

PRL 97: 171805, 2006
$B^+ \rightarrow \bar{K}^0 K^+$
Penguin + Annihilation Amplitudes

- Same penguin amplitude as in $B^0 \rightarrow K^0 \bar{K}^0$
- Annihilation contribution may affect branching fraction
- Need comparison with $B^0 \rightarrow K^0 \bar{K}^0$ to estimate the size of this effect
Analysis Overview

- The data sample consists of 347 million $\Upsilon(4S) \rightarrow \bar{B}B$ pairs (316 fb$^{-1}$)
- $B^{+} \rightarrow K^{0}h^{+}$ reconstructed in $K_{S} \rightarrow \pi^{+}\pi^{-}$, no vertexing
- Use the Detector of Internally Reflected Cherenkov light to separate pion and kaon bachelor tracks
  - DIRC model is the same as in the $B \rightarrow K^{+}\pi^{-}/\pi^{+}\pi^{-}$ analysis
    (see previous talk by Xuanzhong Li)
  - Pion mass is assumed for the track
  - Additional PID from $\Delta E$, where the $K_{S}K^{+}$ peak is displaced -45 MeV relative to the $K_{S}\pi^{+}$ peak
- Efficiency: $12.9 \pm 0.4$ % $K_{S}\pi^{+}$, $12.6 \pm 0.4$ % $K_{S}K^{+}$
- Fit simultaneously for $K_{S}\pi^{+}$ and $K_{S}K^{+}$ using $m_{ES}$, $\Delta E$, Fisher, DIRC
- Extract two signal and two background yields and the corresponding charge asymmetries
Results

\[ N_{K_S^0\pi^+} = 1072 \pm 46^{+32}_{-37} \]
\[ N_{K_S^0K^+} = 71 \pm 19 \pm 4 \ (5.3\sigma) \]
\[ B(B^+ \rightarrow K^0\pi^+) = (23.9 \pm 1.1 \pm 1.0) \times 10^{-6} \]
\[ B(B^+ \rightarrow \bar{K}^0K^+) = (1.61 \pm 0.44 \pm 0.09) \times 10^{-6} \]
\[ A_{K_S^0\pi^+} = -0.029 \pm 0.039 \pm 0.010 \]
\[ A_{K_S^0K^+} = 0.10 \pm 0.26 \pm 0.03 \]
Results

**BABAR sPlots**

- **(a)** $K_S\pi^+$
- **(b)** $K_S\pi^+$
- **(c)** $K_SK^+$
- **(d)** $K_SK^+$
- **(e)** $K_SK_S$

PRL 97: 171805, 2006
$B^0 \rightarrow K^+ K^-$
**W Exchange Amplitude**

- $B(B^0 \rightarrow K^+K^-) \sim (0.7-8) \times 10^{-8}$ in the standard model
- Rescattering or new physics could enhance the branching fraction
- Yield extracted from the $B^0 \rightarrow K^+\pi^- / \pi^+\pi^-$ fit (see previous talk by Xuanzhong Li)
  - Use DIRC and $\Delta E$ to separate from the other two components
  - $K^+K^-$ peak in $\Delta E$ lies on the low tail of the large $K^+\pi^-$ peak
  - Difficult to measure
Results

- 227 million BB pairs
- $3 \pm 13 \pm 7$ events
- $\mathcal{B}(B^0 \rightarrow K^+K^-) < 0.40 \times 10^{-6}$ (90% confidence level)
- Submitted to PRD
Summary

- Observation of $B^0 \rightarrow K^0 \bar{K}^0$ and $B^+ \rightarrow \bar{K}^0 K^+$, dominated by the $b \rightarrow d g$ penguin amplitude
  - With Belle, first observations of $B_d \rightarrow K K$
  - Confirms standard model expectation of branching fractions
  - Branching fraction of $B^+ \rightarrow \bar{K}^0 K^+$ larger than $B^0 \rightarrow K^0 \bar{K}^0$ when combined with Belle’s result
- First time-dependent CP measurement in a $b \rightarrow d$ penguin
  - Method is feasible at BaBar
  - Large positive values of $S$ are disfavored
  - More data is needed to make stronger constraints
- Both modes published in PRL 97: 171805, 2006 for BaBar
- Non-observation of $B^0 \rightarrow K^+ K^-$ is so far consistent with the standard model
  - Submitted to PRD
  - The only twobody charmless mode left to be observed
Backup Slides
Vertexing Results

![Graphs and plots showing vertexing results for different classes (Class I and Class II). The plots include distributions of signal MC, mean of dt residual, and width of dt residual against σd̃.](image)
KsKs PDFs

Background Parameters Floated
K_{sh}^+ PDFs

Cruijff

double Gaussian

bifurcated Gaussian

Argus

1-degree polynomial

double Gaussian
New-Physics Predictions for TDCP

- Predictions for various assumptions on the weak phase $\theta_{NP}$ and strong phase $\delta_{NP}$ between NP amplitudes
  - Depending on the NP phase, $S_{KK}$ (NP) could be large
- Current BF measurement consistent with NP scenario


$\theta_{NP} = \frac{\pi}{4}, \frac{\pi}{3}, \frac{\pi}{2}, \pi$

$0 < \delta_{NP} < 2\pi$

- New physics in $b \rightarrow d$ penguins is highly constrained assuming three-generation unitarity
- But there’s still room for NP
  - Measure TDCP in $b \rightarrow d$ penguins for the first time and add another constraint