Measurement of time dependent CP violation in $B \rightarrow \phi K_s$
**b → sss Decays**

- **CP violation from interference of decay amplitudes into CP eigenstate:**
  \[ B^0 \rightarrow \phi K_s \quad \text{and} \quad B^0 \rightarrow B^0 - \bar{b} \rightarrow s \phi \]

- Decays dominantly through penguin amplitudes (gluonic & EW), tree small:

- Decay exclusively through penguin:

  \[ | \sin 2\beta(\phi K_s) - \sin 2\beta(J/\psi K_s) | < 4\% \]

- Estimate hadronic pollution (rescattering) using flavor SU(3) relations (30% breaking) between (measured) decay rates of charmless quasi-two-body decays:

  e.g. [Grossman, Ligeti, Nir, Quinn, hep-ph/0303171] **worst case scenario today:**

  \[ | \sin 2\beta(\phi K_s) - \sin 2\beta(J/\psi K_s) | < 25\% \]

  With more data, smaller bounds: 1 ab\(^{-1}\) expect ~10%
BaBar Detector

1.5T Magnet

DCH

EMC

SVT

DIRC

110 fb⁻¹

PEP-II Delivered 139.05 fb⁻¹
BABAR Recorded 132.69 fb⁻¹
BABAR off-peak 12.50 fb⁻¹

Delivered Luminosity
Recorded Luminosity
Off Peak
Measuring $\sin(2\beta)$ at the Asymmetric B-Factor

$e^- : 9$ GeV $\rightarrow B_{tag}^+$

$\mu^+, e^+, K^+$

$B_{tag} : Xl^+, XK^+, X\pi_-$

(B flavor sample)

$e^+ 3$ GeV

$B_{CP}$

$\Delta t \approx \Delta z/c \langle \beta \gamma \rangle_{\gamma(4S)}$

$\langle \beta \gamma \rangle_{\gamma(4S)} = 0.56$

Time dependent asymmetry:

$$a_r(t) = \frac{R - \overline{R}}{R + \overline{R}}(t) = -C_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t)$$
Event Variables

Energy-substituted mass:
\[ M_{ES} = \frac{s}{2} + p_Y p_B^2 / E_Y^2 - p_B^2 \]^{1/2}

Energy difference:
\[ \Delta E = E_B^* - s^{0.5}/2 \]

(E_Y, p_Y), (E_B, p_B) 4 momenta of Υ(4S) and B in laboratory frame,
E_B^* reconstructed B energy in center of mass frame

Number of signal events is consistent with published branching fraction.

signal events : 70 ± 9.0
purity : 61 ± 0.1%
Event Variables

Helicity angle:
- angle(K, B) in φ-rest frame

Fisher discriminant:
linear combination of
- $\cos \theta_T$ (thrust angle*)
- $\cos \theta_B$ (emission angle* w.r.t. z-axis)
- momentum-weighted Legendre polynomials

\[ F = a_0 \cos \theta_T + a_1 \cos \theta_B + a_2 \sum p_i L_0(\theta_i) + a_3 \sum p_i L_2(\theta_i) \]

*Y(4S) rest frame
Tagging

- Tagging performance evaluated from data using B flavor sample
- Tags grouped into 4 mutually exclusive categories:

\[
\sigma(S) \sim \frac{1}{\sqrt{NQ}}
\]

\[
Q = \Sigma \varepsilon(1-2\omega)^2
\]

<table>
<thead>
<tr>
<th>Category</th>
<th>(\varepsilon) (%)</th>
<th>(\omega) (%)</th>
<th>(\Delta \omega) (%)</th>
<th>(Q) (%)</th>
<th>(\phi)Ks signal events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton</td>
<td>9.5</td>
<td>3.9</td>
<td>0.8</td>
<td>8.1</td>
<td>6.8</td>
</tr>
<tr>
<td>Kaon I</td>
<td>16.3</td>
<td>9.6</td>
<td>1.1</td>
<td>10.7</td>
<td>11.7</td>
</tr>
<tr>
<td>Kaon II</td>
<td>19.4</td>
<td>19.3</td>
<td>3.4</td>
<td>7.3</td>
<td>13.9</td>
</tr>
<tr>
<td>Inclusive</td>
<td>20.5</td>
<td>31.8</td>
<td>4.0</td>
<td>2.7</td>
<td>14.6</td>
</tr>
<tr>
<td>Total</td>
<td>65.7</td>
<td></td>
<td></td>
<td>28.7 ± 0.7</td>
<td></td>
</tr>
</tbody>
</table>

Tagging optimized for maximal value of \(Q\)
Vertexing ($\Phi K \% J/\Psi K$)

Opening angles quite different:

- $\phi \rightarrow K^+K^-$
- $J/\psi \rightarrow l^+l^-$

$B \rightarrow \phi K$:
- Large Q-value
- Helicity angle $\sim \cos^2\theta$

$B$ vertex $z$ resolutions:
- $B_{cp} \sim 50 \mu m$
- $B_{tag} \sim 170 \mu m$

Resolution dominated by the tag side
\( \Delta t \) Resolution

- Comparable \( \sigma(\Delta t) \) distributions in \( J/\psi \) \( K_s \) and \( \phi \) \( K_s \)

- Background Resolution Function:
  \[
  R(\Delta t) = [G_{\text{core}}(\text{bias, scale } (\sigma_i(\Delta t)); \Delta t) + G_{\text{outlier}}(0 \text{ ps}, 8 \text{ ps}; \Delta t)] \\
  \otimes \{f \bullet \text{Exp}(\Delta t / \tau_B) + (1 - f) \bullet \delta(\Delta t)\}
  \]

- Signal Resolution Function:
  \[
  R(\Delta t) = (1 - f_{\text{tail}} - f_{\text{outlier}})G_{\text{core}}(\text{bias}_{\text{tag}}, \text{scale } (\sigma_i(\Delta t)); \Delta t) \\
  + f_{\text{tail}}G_{\text{tail}}(\text{bias, 3 ps}) + f_{\text{outlier}}G_{\text{outlier}}(0 \text{ ps}, 8 \text{ ps}; \Delta t)
  \]

- Established by extensive test with Monte Carlo (MC) events
- Final parameters obtained from B flavor data in simultaneous fit with CP data
CP Fit Strategy

- Use 86200 B-flavor, 2138 $\phi K_s(\pi^+\pi^-)$
- Maximum likelihood fit:
  \[ L = L(M_{ES}) \times L(\Delta E) \times L(F) \times L(\cos \theta_H) \times L(\Delta t) \]
- **Fix** parameters (yields) that depend exclusively on CP sample
- **Float** parameters that depend on B flavor sample
- Total 40 parameters:

<table>
<thead>
<tr>
<th>CP</th>
<th>$S$ and $C$</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t$</td>
<td>Sig. Resolution</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Bkg. Resolution</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Bkg. time evolution.</td>
<td>6</td>
</tr>
<tr>
<td>Tag</td>
<td>Fractions</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Sig. Dilution</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Sig. dilution asym.</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Bkg. Dilution</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Bkg. dilution asym.</td>
<td>4</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>

Tested with $J/\psi Ks$ data, MC data mockfit and Toy MC.
Time Dependent CP Fit for φKs

Zoom into the signal region ($m_{ES} > 5.27\text{GeV}$, $|\Delta E| < 0.06\text{ GeV}$)

\[ S = 0.45 \pm 0.43 \]
\[ C = -0.38 \pm 0.37 \]

statistical error only

Raw asymmetry:

WA

\[ S = 0.736 \]

http://www.slac.stanford.edu/xorg/hfag
Time Dependent CP Fit for $\phi K^+$

Use $\phi K^+$ as control sample

- Standard Model: expect $S=0$ and $C=0$

$B_{\text{ABAR}}$ preliminary

signal events : 252
purity : $76 \pm 0.1\%$

$B_{\text{ABAR}}$ preliminary

$S = 0.23 \pm 0.24$
$C = -0.14 \pm 0.18$

Mahalaxmi Krishnamurthy  Beauty 2003
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainty due to</th>
<th>$S$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit bias</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Event yield</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Parametrization of $\Delta t$ resolution</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Background composition/$CP$ asymmetry</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>$m_{ES}$ background parameterization</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Uncertainties in the SVT alignment</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Beamspot position</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>PDFs for the event yield in signal and background</td>
<td>0.004</td>
<td>0.04</td>
</tr>
<tr>
<td>Potential S-wave contamination</td>
<td>0.002</td>
<td>0.015</td>
</tr>
<tr>
<td>$B^0/\bar{B}^0$ efficiency difference</td>
<td>0.002</td>
<td>0.02</td>
</tr>
<tr>
<td>Doubly-Cabibbo-suppressed decays</td>
<td>0.009</td>
<td>0.027</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.07</td>
<td>0.12</td>
</tr>
</tbody>
</table>
The move .......

Old result: Fit to $\phi Ks$, $Ks \rightarrow \pi^+\pi^-$ and $Ks \rightarrow \pi^0\pi^0$ sample combined (80 $fb^{-1}$)

$$S = -0.18 \pm 0.51$$
$$C = -0.80 \pm 0.38$$

Old $Ks \rightarrow \pi^+\pi^-$ only:

$$S = -0.12 \pm 0.52$$
$$C = -0.77 \pm 0.41$$

Overlap between reprocessed (new) Run1+2 and old $Ks \rightarrow \pi^+\pi^-$
(80% overlap)

Old $Ks \rightarrow \pi^+\pi^-$:

$$S = 0.02 \pm 0.55$$
$$C = -0.57 \pm 0.44$$

New $Ks \rightarrow \pi^+\pi^-$:

$$S = 0.05 \pm 0.51$$
$$C = -0.25 \pm 0.48$$

New+Run3 $Ks \rightarrow \pi^+\pi^-$:

$$S = 0.45 \pm 0.43$$
$$C = -0.38 \pm 0.37$$
% change in tag due to reprocessing : ~ 8%

→ ~ 3 events flip tag around $\Delta t = 0$

\[ A_{cp} = \frac{F_+ - F_-}{F_+ + F_-} = \frac{-C \cdot \langle D \rangle}{1 + (\Delta m \cdot \tau)^2} \]

old sample : $F_+ - F_- = 5$ events

new sample : if all 3 flip events are $B^0$ or $\bar{B}^0$ tags ($F_+ - F_- = 2$ or 8 )

$\Delta C \sim \pm 0.3$
$\Delta S \sim 0.0$

- swap of the samples confirms the effect

=> change of result covered by statistical error.

Low statistics channels are prone to fluctuations!
More results

\[ B (B^0 \to \phi K^0) = (8.4^{+1.5}_{-1.3} \pm 0.3) \times 10^{-6} \]

\[ B (B^+ \to \phi K^+) = (10.0^{+0.9}_{-0.8} \pm 0.5) \times 10^{-6} \]

\[ B (B^+ \to \phi \pi^+) < 0.41 \times 10^{-6} \]

\[ A_{cp}(B^+ \to \phi K^+) = 0.04 \pm 0.09 \pm 0.01 \]

⇒ the two independent methods give the same result of \( A_{cp} \) in \( \phi K^+ \)

\[ C (B^0 \to \phi K_s) = -0.38 \pm 0.37 \quad \Rightarrow \quad A_{cp} = 0.14 \pm 0.14 \]

\[ \text{in 110 fb}^{-1} \]

\[ C (B^+ \to \phi K^+) = -0.14 \pm 0.18 \quad \Rightarrow \quad A_{cp} = 0.05 \pm 0.07 \]

\[ \text{in 80 fb}^{-1} \]

\[ \text{hep-ex/0309025} \]
Summary / Outlook

- Measured time dependent asymmetry in $B^0 \rightarrow \phi K_s(\pi^+\pi^-)$.

- More CP events are needed by increase of luminosity and by including other channels e.g. $\phi K l$, $\phi K_s(\pi^0\pi^0)$.

- Expectation for the error in 300 fb$^{-1}$:
  
  $\sigma (S) = 0.26$
  
  $\sigma (C) = 0.17$

Stay tuned ...
Current status of $S$

<table>
<thead>
<tr>
<th>Charmonium Modes</th>
<th>OPAL 98</th>
<th>ALEPH 00</th>
<th>CDF 00</th>
<th>BABAR 02</th>
<th>Belle 03</th>
<th>Average (charmonium)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$3.2^{+1.8}_{-2.0} \pm 0.5$</td>
<td>$0.84^{+0.92}_{-1.04} \pm 0.16$</td>
<td>$0.79^{+0.41}_{-0.44}$</td>
<td>$0.741 \pm 0.067 \pm 0.034$</td>
<td>$0.733 \pm 0.057 \pm 0.028$</td>
<td>$0.738 \pm 0.049$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\phi K_S$</th>
<th>BABAR 03</th>
<th>Belle 03</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.45 \pm 0.43 \pm 0.07$</td>
<td>$-0.98 \pm 0.5 \pm 0.09$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\eta K_S$</th>
<th>BABAR 03</th>
<th>Belle 03</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$0.02 \pm 0.34 \pm 0.03$</td>
<td>$0.43 \pm 0.27 \pm 0.05$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$K K K \bar{K}$</th>
<th>Belle 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.51 \pm 0.26 \pm 0.04$</td>
<td></td>
</tr>
</tbody>
</table>

Average (s penguin) $0.24 \pm 0.15$

Average (All) $0.695 \pm 0.047$

$sin(2\beta_{(eff)})$
Time Dependent CP Fit for $\phi K_s$

$S = 0.45 \pm 0.43$

$C = -0.38 \pm 0.37$

• 15% correlation