Measurements of the CKM angle $\phi_1/\beta$ at the B factories

(Includes new Belle result on $\sin 2\phi_1$)

Himansu Sahoo
University of Hawaii
On Behalf of Belle & BaBar

Flavor Physics and CP Violation 2011
Quark Mixing in SM

Standard Model quark mixing:

\[
\begin{pmatrix}
d' \\
s' \\
b'
\end{pmatrix} =
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub}' \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
d \\
s \\
b
\end{pmatrix}
\]

Cabibbo-Kobayashi-Maskawa (CKM) matrix \( (V_{\text{CKM}}) \)

\[V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\]

CP violation enters the SM through the complex phase in the CKM matrix

Unitarity relation \( (V_{\text{CKM}} V_{\text{CKM}}^+ = 1) \)

\[V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\]
Time-dependent CP Asymmetry

Interference between $B^0 \rightarrow f_{CP}$ and $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$

- $B^0-\bar{B}^0$ mixing: A neutral $B$ meson can transform into its own anti-particle
- Both the $B^0$ and its anti-particle $\bar{B}^0$ can decay to the same state final state.
- CP violation arises from interference between mixing and decay amplitudes.

Time dependent CP asymmetry

$$A(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t)\rightarrow f_{CP}) - \Gamma(B^0(\Delta t)\rightarrow f_{CP})}{\Gamma(\bar{B}^0(\Delta t)\rightarrow f_{CP}) + \Gamma(B^0(\Delta t)\rightarrow f_{CP})}$$

$$= \frac{2Im\lambda}{1+|\lambda|^2} \sin(\Delta m \cdot \Delta t) - \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m \cdot \Delta t)$$

$\chi = \frac{q}{p} \frac{A(\bar{B}^0 \rightarrow f)}{A(B^0 \rightarrow f)}$

Mixing-induced CPV  Direct CPV
Two asymmetric B factories: Belle at KEK-B and BaBar at PEP-II

9 GeV $e^-$ on 3.1 GeV $e^+$ boost $\beta\gamma=0.56$

8 GeV $e^-$ on 3.5 GeV $e^+$ boost $\beta\gamma=0.43$

Peak luminosity: $1.2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

Peak luminosity: $2.1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

World Record
Datasets from B factories

- The B factories have collected > 1.5 ab$^{-1}$ in 10 years
- This corresponds to ~1200 M B$\bar{B}$ pairs at the Y(4S) resonance
CPV Analysis Technique at B factories

$\Delta t$ is determined from decay vertex positions of the B mesons

$\Delta t \approx \Delta z / (\beta \gamma c)$

Boost $\beta \gamma = 0.43$

9 GeV e- on 3.1 GeV e+ boost $\beta \gamma = 0.56$

$\Delta z = 200 \mu m$ (Belle), 250 $\mu m$ (BaBar)

Decay rate

$P(q = \pm 1, \Delta t) = \frac{1}{4 \tau_B} e^{-\frac{|\Delta t|}{\tau_B}} [1 + (S \sin \Delta m \Delta t + A \cos \Delta m \Delta t)] \bar{R}$

$R$ : detector resolution
$w$ : wrong tag fraction
(misidentification of flavor)
2010 picture of SM

- Independent measurements overlap at the apex of the triangle => consistent with CKM picture.
- $\sin 2\phi_1$ is a model independent measurement and the most precise constraint on the apex of the triangle.

$\sim 2.8\sigma$ difference between $\mathcal{B}(B \to \tau \nu)$ measurement and value predicted from other observables excluding $\mathcal{B}(B \to \tau \nu)$
$B \rightarrow (c\bar{c})K^0$ decay modes

$B \rightarrow$ Charmonium $K^0$: Golden modes for CP Violation measurements

- Clean Experimental Signature
  - Many accessible modes with (relatively) Large BFs
  - Low Background Levels, high efficiency
- Clean Extraction of CKM angle
  - Dominated by tree diagram
  - Leading penguin diagram has the same weak phase as tree

$B^0 \rightarrow J/\psi K_0 \sim 8.7 \times 10^{-4}$
$B^0 \rightarrow \psi' K^0 \sim 6.2 \times 10^{-4}$
$B^0 \rightarrow \chi_{c1} K^0 \sim 3.9 \times 10^{-4}$
$B^0 \rightarrow \eta_c K^0 \sim 8.9 \times 10^{-4}$

B$^0 \overline{B}^0$ Mixing

$B^0$ $\overline{B}^0$ Mixing

Tree Diagram

$B^0$ $\rightarrow$ $J/\psi K^0$

$A \propto V_{cb}^* V_{cs}$

SM expectation

$\chi = \frac{q}{p} \frac{A}{\overline{A}} = \eta_{cp} e^{-i2\phi_1}$

$S = -\eta_{cp} \sin 2\phi_1$

$A(-C) = 0$

$A(\Delta t) = -\eta_{cp} \sin 2\phi_1 \sin(\Delta m \cdot \Delta t)$

Sensitive to the angle $\phi_1$ of the CKM triangle
**B \to (c\bar{c}) K^0 signals**

- Belle’s new result with full data sample (772 M BB).
- More data and improved tracking ⇒ nearly 50% more statistics.

\[
\Delta E \equiv E_B^* - E_{\text{beam}}^* \quad M_{bc} \equiv \sqrt{(E_{\text{beam}}^*)^2 - (p_B^*)^2}
\]

$P_B^*$ for $K_L$ : only $K_L$ direction is measured; missing momentum is calculated using known B energy and $K_L$ direction.

### Decay Modes and Signal Yield

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Signal Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to J/\psi K_S$</td>
<td>12681±114</td>
</tr>
<tr>
<td>$B^0 \to \psi' K_S$</td>
<td>1981±46</td>
</tr>
<tr>
<td>$B^0 \to \chi_{c1} K_S$</td>
<td>943±33</td>
</tr>
<tr>
<td>$B^0 \to J/\psi K_L$</td>
<td>10041±154</td>
</tr>
</tbody>
</table>

Preliminary!
$\sin 2\phi_1$ in $B \to (c\bar{c})K^0$ decays

Background subtracted, good tagged only

$B^0 \rightarrow J/\psi K_S$

$S = 0.671 \pm 0.029$

$A = -0.014 \pm 0.021$

$B^0 \rightarrow J/\psi K_L$

$S = -0.641 \pm 0.047$

$A = 0.019 \pm 0.026$

$B^0 \rightarrow \psi'K_S$

$S = 0.739 \pm 0.079$

$A = 0.103 \pm 0.055$

$B^0 \rightarrow \chi_{c1} K_S$

$S = 0.636 \pm 0.117$

$A = -0.023 \pm 0.083$

(stat errors only)

CP Violation is observed in all modes
Charmonium $K^0$ Systematics

- Significant improvement in systematics:
  $0.017 \rightarrow 0.013$
- Better model for resolution function
  (decay mode independent)

### Systematic errors:

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta S$</th>
<th>$\Delta A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertexing</td>
<td>$+0.008$</td>
<td>$-0.009$</td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>$+0.004$</td>
<td>$-0.003$</td>
</tr>
<tr>
<td>Resolution function</td>
<td>$\pm 0.007$</td>
<td>$\pm 0.001$</td>
</tr>
<tr>
<td>Physics parameters</td>
<td>$\pm 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Fit bias</td>
<td>$\pm 0.004$</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>$J/\psi K_S^0$ signal fraction</td>
<td>$\pm 0.002$</td>
<td>$\pm 0.001$</td>
</tr>
<tr>
<td>$J/\psi K_L^0$ signal fraction</td>
<td>$\pm 0.004$</td>
<td>$+0.000$</td>
</tr>
<tr>
<td>$\psi(2S) K_S^0$ signal fraction</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>$\chi c K_S^0$ signal fraction</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Background $\Delta t$</td>
<td>$\pm 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Tag-side interference</td>
<td>$\pm 0.001$</td>
<td>$\pm 0.008$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$\pm 0.013$</td>
<td>$\pm 0.013$</td>
</tr>
</tbody>
</table>
2011 measurement of $\sin 2\phi_1$ at Belle

 Combined result to all charmonium modes

$\sin 2\phi_1 = 0.668 \pm 0.023 \text{(stat)} \pm 0.013 \text{(syst)}$

$\mathcal{A} = 0.007 \pm 0.016 \text{(stat)} \pm 0.013 \text{(syst)}$

World’s most precise measurements
BaBar’s 2009 $B \rightarrow (c\bar{c})K^{(*)0}$ results

465M $B\bar{B}$
PRD 79, 072009 (2009)

BaBar’s 2009 result with full dataset

$$\sin 2\phi_1(b \rightarrow c\bar{c}s) = 0.687 \pm 0.028 \pm 0.012$$
$$C(b \rightarrow c\bar{c}s) = 0.024 \pm 0.020 \pm 0.016$$
The two experiments agree very well.

Experimental uncertainty on $\sin 2\phi_1 \sim 3\%$ (Reference point for NP search).

$\mathcal{A}$ value is consistent with zero ($\mathcal{A} = -0.013 \pm 0.017$).

The new results provide a better constraint on the apex of the CKM triangle.
Resolving two-fold ambiguity in $\phi_1(\beta)$

\[ D^{(*)}h^0 \cos(2\beta) = \cos(2\phi_1) \]

\[ \cos 2\beta > 0 \text{ at } 86\% \text{ C.L.} \]

\[ \cos 2\beta > 0 \text{ at } 98.3\% \text{ C.L.} \]

Other measurements using $B^0 \rightarrow J/\psi K^*$
($\rightarrow K_S \pi^0$) and $D^*+D^*-K_S$ also contribute

$\cos 2\beta > 0$ $\Rightarrow$ favors the smaller $\beta$ ($<45^\circ$) solution

$\phi_1(\beta) = (21.4 \pm 0.8)^\circ$
Other ways to measure $\sin 2\phi_1(\beta)$

Charmonium
“Tree-dominated”

- $B^0 \rightarrow J/\psi K_s, \psi'K_s$
- $B^0 \rightarrow \chi_{c1} K_s, \eta_c K_s$
- $B^0 \rightarrow J/\psi K_L, J/\psi K^* \rightarrow (K_S \pi^0)$

Open charm or Charmonium
Tree-dominance, Loop may contribute

- $B^0 \rightarrow J/\psi \pi^0$
- $B^0 \rightarrow D^{(*)} + D^{(*)-}, D^+ D^-$

Charmless, $b \rightarrow s$ loop decays
“penguin-dominance”

- $B^0 \rightarrow \phi K_s, K^+ K^- K_s, K_s K_S K_S$
- $B^0 \rightarrow K_S \pi^0, \eta' K_s, \omega K_s, f_0 K_s$

Increase tree diagram contribution

Increase sensitivity to new physics
sin2$\phi_1$ in $b \to c\bar{c}d$ decays

$B^0 \to J/\psi \pi^0$

- Dominant tree diagram is Cabibbo-suppressed.
- The dominant penguin diagram is of same order and has a different weak phase; small deviation in sin2$\phi_1$ from golden modes is expected in SM.
- Evidence of CP violation at 4$\sigma$ significance (BaBar).

$B^0 \to D^{(*)} + D^{(*)-}$

- $B^0 \to D^+ D^- :$ mixture of CP-even and CP-odd; angular analysis is performed.
- $B^0 \to D^+ D^- :$ CP eigen-state.
- Evidence of direct CP violation at 3.2$\sigma$ significance (Belle).
- Belle will update soon $B^0 \to D^+ D^- :$ Expected stat error on $A$ is $\sim$0.15.

$C_f = -A_f$
\[ \sin 2\phi_1 \] in \( b \rightarrow s \bar{q} \bar{q} \) decays: penguins

- \( b \rightarrow s \) penguin dominated decays: \( B^0 \rightarrow \phi K_s, \omega K_s, \eta' K_s \)
  \( \Rightarrow \) Sensitive to new physics from loop (SUSY ..).

- For a pure penguin amplitude: \( S \sim \sin 2\phi_1 \)

- With an extra CP phase from NP in penguin loop
  \[ \Delta \sin 2\phi_1 = \sin 2\phi_1^{\text{eff}} - \sin 2\phi_1 \neq 0 \]

- Significant deviation from \( \sin 2\phi_1 \) in golden modes would indicate a new physics effect.

- SM theoretical uncertainties vary mode by mode, but the deviations are expected to be positive.

- Time-dependent Dalitz analyses have been performed in three-body decays
  (such as \( B^0 \rightarrow K^+ K^- K_S \) and \( B^0 \rightarrow \pi^+ \pi^- K_S \))

---

\[ \begin{align*}
\phi K_s & \quad \text{Theoretical uncertainties} \\
\eta' K_s & \\
\pi^0 K_s & \\
\omega K_s & \\
K K K_S & \\
3 K_S &
\end{align*} \]
Interference in $B^0 \to K^+K^-K_S$ final state

- $B^0 \to K^+K^-K_S$ final state has several different paths.
- Perform a time-dependent Dalitz plot analysis to obtain best CP sensitivity and avoid bias.

See E. Ben-Haim’s talk tomorrow for details on Dalitz techniques and results on other $b \to s$ penguin modes
Multiple Solutions

- Need to handle the issue of multiple solutions
- Belle found 4 solutions ⇒ Solution 1 is preferred using external information from $B^0 \rightarrow \pi^+ \pi^- K_S$

⇒ with low $f_0(980) K_S$ (solution 1, 3) and $f_x$ (1500) $K_S$ (solution 1, 2) fractions

<table>
<thead>
<tr>
<th></th>
<th>Solution 1</th>
<th>Solution 2</th>
<th>Solution 3</th>
<th>Solution 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{CP}(f_0(980)K_S^0)$</td>
<td>$-0.30 \pm 0.29 \pm 0.11 \pm 0.09$</td>
<td>$-0.20 \pm 0.15 \pm 0.08 \pm 0.05$</td>
<td>$+0.02 \pm 0.21 \pm 0.09 \pm 0.09$</td>
<td>$-0.18 \pm 0.14 \pm 0.08 \pm 0.06$</td>
</tr>
<tr>
<td>$\phi_1^{eff}(f_0(980)K_S^0)$</td>
<td>$(31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$</td>
<td>$(26.1 \pm 7.0 \pm 2.4 \pm 2.5)^\circ$</td>
<td>$(25.6 \pm 7.6 \pm 2.9 \pm 0.8)^\circ$</td>
<td>$(26.3 \pm 5.7 \pm 2.4 \pm 5.8)^\circ$</td>
</tr>
<tr>
<td>$A_{CP}(\phi(1020)K_S^0)$</td>
<td>$+0.04 \pm 0.20 \pm 0.10 \pm 0.02$</td>
<td>$+0.08 \pm 0.18 \pm 0.10 \pm 0.03$</td>
<td>$-0.01 \pm 0.20 \pm 0.11 \pm 0.02$</td>
<td>$+0.21 \pm 0.18 \pm 0.11 \pm 0.05$</td>
</tr>
<tr>
<td>$\phi_1^{eff}(\phi(1020)K_S^0)$</td>
<td>$(32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$</td>
<td>$(26.2 \pm 8.8 \pm 2.7 \pm 1.2)^\circ$</td>
<td>$(27.3 \pm 8.6 \pm 2.8 \pm 1.3)^\circ$</td>
<td>$(24.3 \pm 8.0 \pm 2.9 \pm 5.2)^\circ$</td>
</tr>
<tr>
<td>$A_{CP}$ (others)</td>
<td>$-0.14 \pm 0.11 \pm 0.08 \pm 0.03$</td>
<td>$-0.06 \pm 0.15 \pm 0.08 \pm 0.04$</td>
<td>$-0.03 \pm 0.09 \pm 0.08 \pm 0.03$</td>
<td>$+0.04 \pm 0.11 \pm 0.08 \pm 0.02$</td>
</tr>
<tr>
<td>$\phi_1^{eff}$ (others)</td>
<td>$(24.9 \pm 6.4 \pm 2.1 \pm 2.5)^\circ$</td>
<td>$(29.8 \pm 6.6 \pm 2.1 \pm 1.1)^\circ$</td>
<td>$(26.2 \pm 5.9 \pm 2.3 \pm 1.5)^\circ$</td>
<td>$(23.8 \pm 5.5 \pm 1.9 \pm 6.4)^\circ$</td>
</tr>
</tbody>
</table>

third error: Dalitz plot model uncertainty

- BaBar found 2 solutions in the low-mass fit ($M_{(K^+K^-)} < 1.1 \text{ GeV/c}^2$)
- Solution 1 is consistent with the SM ⇒ chosen as the nominal one.

<table>
<thead>
<tr>
<th>Name</th>
<th>Solution (1)</th>
<th>Solution (2)</th>
<th>Correlation (solution 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 $A_{CP}(\phi K_S^0)$</td>
<td>$0.14 \pm 0.19 \pm 0.02$</td>
<td>$0.13 \pm 0.18$</td>
<td>1.0 -0.09 -0.28 0.09</td>
</tr>
<tr>
<td>2 $\beta_{eff}(\phi K_S^0)$</td>
<td>$0.13 \pm 0.13 \pm 0.02$</td>
<td>$0.14 \pm 0.14$</td>
<td>1.0 0.54 0.65</td>
</tr>
<tr>
<td>3 $A_{CP}(f_0 K_S^0)$</td>
<td>$0.01 \pm 0.26 \pm 0.07$</td>
<td>$-0.49 \pm 0.25$</td>
<td>1.0 0.25</td>
</tr>
<tr>
<td>4 $\beta_{eff}(f_0 K_S^0)$</td>
<td>$0.15 \pm 0.13 \pm 0.03$</td>
<td>$3.44 \pm 0.19$</td>
<td>1.0</td>
</tr>
</tbody>
</table>
CPV results in $B^0 \to K^+ K^- K^0_S$

In the $\phi$ mass region

465M BB  
$arXiv:0808.0700$

In the low-mass  
($M_{(K^+ K^-)} < 1.1$ GeV/c$^2$)

$\phi_1$ by $B \to (cc)K^0 = (21.4 \pm 0.8)^\circ$

Consistent with SM expectation at current sensitivity
Compilation of effective $b \rightarrow s \sin 2\phi_1$ measurements

- Precision is still limited by statistics.
- More data is needed to see possible deviation from $\sin 2\phi_1$
- We need $O(10 \, ab^{-1})$ integrated luminosity to obtain sensitivities at the $O(10^{-2})$ precision.
- Sensitivity will then be comparable with theoretical uncertainties.
Summary

- World’s most precise sin2φ₁ measurement from Belle (new!).

- The CKM angle φ₁(β) is measured with < 1° precision in B factories.

- sin2φ₁ has been measured in B→(cc)K⁰ decays with great accuracy (~3%) (provides strongest constraint on ρ-η).

- Comparison with b→s penguin modes could reveal new physics effects (current measurements are consistent with SM but are still statistically limited).

- Further updates are expected from Belle (with more data and improved tracking): B⁰→ηcKs, D⁺D⁻, η′K⁰, KSK₅Ks.

- Looking forward to high precision measurements from SuperB factories!

\[ \phi_1(\beta) = (21.4 \pm 0.8)^\circ \]
BACK UP
**sin2\(\phi_1\) Measurement (Belle, 535 M BB)**

535M BB  
PRL 98, 031802 (2007)

\[ \sin^2\phi_1 \approx 7484 \]  
Purity = 97%

\[ \sin^2\phi_1 \approx 6512 \]  
Purity = 56%

\[ \sin^2\phi_1(J/\psi K^0) = 0.642 \pm 0.031 \pm 0.017 \]  
\[ A(J/\psi K^0) = 0.018 \pm 0.021 \pm 0.014 \]
$B^0 \rightarrow K^+ K^- K^*_s$ signals

$N_{\text{sig}} (B^0 \rightarrow K^+ K^- K^*_s, K^*_S \rightarrow \pi^+ \pi^-) = 1176 \pm 51$

$N_{\text{sig}} (B^0 \rightarrow K^+ K^- K^*_s, K^*_S \rightarrow \pi^0 \pi^0) = 160 \pm 19$

(BaBar also did separate fits to low-mass ($M_{(K+K^-)} < 1.1$ GeV/$c^2$) and high-mass region ($M_{(K+K^-)} > 1.1$ GeV/$c^2$)

continuum background

arXiv:0808:0700

PRD 82, 073011 (2010)
Projections of Dalitz distribution ($M_{K^+K^-}$)

The peak around 1 GeV/$c^2$: $\phi(1020)$ and $f_0(980)$
CPV results in $B^0 \rightarrow \pi^+ \pi^- K_S$

$N_{\text{sig}} = 1944 \pm 98$

Dalitz plot variable $m_{\pi^+ \pi^-}$

$\pi^+ \pi^- K_S \beta(\rho K_S)$

$N_{\text{sig}} = 2182 \pm 64$

$\phi_1$ by $B \rightarrow (cc) K^0 = (21.4 \pm 0.8)^\circ$
$B^0 \rightarrow K^0\pi^0$

Belle used both $K_S$ and $K_L$ to reconstruct the signal. For $K_L$ reconstruction known B energy and $K_L$ direction are used.

BaBar : $N_{\text{sig}} (B^0 \rightarrow K_S\pi^0) = 411 \pm 24$

Belle : $N_{\text{sig}} (B^0 \rightarrow K_S\pi^0) = 634 \pm 34$

$N_{\text{sig}} (B^0 \rightarrow K_L\pi^0) = 285 \pm 52 (3.7\sigma)$
\( \sin 2\phi_1^{\text{eff}} = 0.67 \pm 0.31 \pm 0.08 \)
\( \mathcal{A} = -C = 0.14 \pm 0.13 \pm 0.06 \)
\( S = 0.55 \pm 0.20 \pm 0.03 \)
\( C = 0.13 \pm 0.13 \pm 0.03 \)
\[ \text{SM expectation using } B^0 \rightarrow J/\psi K^0 \text{ value} \]

\[ N_{\text{sig}} = 118 \pm 18 \]

\[ S = +0.11 \pm 0.46 \pm 0.07 \]

\[ A = -C = -0.09 \pm 0.29 \pm 0.06 \]

\[ N_{\text{sig}} = 121 \pm 13 \]

\[ S = +0.55 \pm 0.26 - 0.29 \pm 0.02 \]

\[ C = -0.52 \pm 0.22 - 0.20 \pm 0.03 \]
$B^0 \to \eta' K^0$

Seven final states for $B^0 \to \eta' K^0$

- $\eta'\rho\gamma, \eta'\gamma\pi^\pm \pi^\mp, \eta_3\pi^\mp \pi^\mp K^0_S (\pi^+ \pi^-)$
- $\eta'\rho\gamma, \eta'\gamma\pi^+ \pi^- K^0_S (\pi^0 \pi^0)$
- $\eta'\eta_\gamma\pi^\mp \pi^\mp, \eta_3\pi^\mp \pi^\mp K^0_L$

$N_{\text{sig}} (\eta'K_S) = 1457 \pm 43$
$N_{\text{sig}} (\eta'K_L) = 341 \pm 23$

B mass was used in case of $\eta'K_L$ to re-calculate unknown $K_L$ momentum

$N_{\text{sig}} (B^0 \to \eta'K_S) = 1421 \pm 46$
$N_{\text{sig}} (B^0 \to \eta'K_L) = 454 \pm 39$

All final states are combined together
\[ B^0 \rightarrow \eta'K^0 \]

**535M BB**

PRL 98, 031802 (2007)

\[ \begin{align*}
S & = +0.67 \pm 0.11 \\
A & = -0.03 \pm 0.07 \\
\end{align*} \]

**467M BB**

PRD 79, 052003 (2009)

\[ \begin{align*}
S & = +0.53 \pm 0.08 \pm 0.02 \\
C & = -0.11 \pm 0.06 \pm 0.02 \\
\end{align*} \]

\[ \begin{align*}
S & = +0.82^{+0.17}_{-0.19} \pm 0.02 \\
C & = -0.09^{+0.13}_{-0.14} \pm 0.02 \\
\end{align*} \]

**BELLE**

\[ \begin{align*}
S & = +0.64 \pm 0.10 \pm 0.04 \\
A & = -C = -0.01 \pm 0.07 \pm 0.05 \\
\end{align*} \]

\[ \begin{align*}
S & = +0.57 \pm 0.08 \pm 0.02 \\
C & = -0.08 \pm 0.06 \pm 0.02 \\
\end{align*} \]
More statistics is needed to see possible deviation from $\sin 2\phi_1$
$\sin2\phi_1$ in $B \to (c\bar{c})K^0$ decays

Background subtracted, good tagged only

CP Violation is observed in all modes

$B^0 \to J/\psi K_S$

$S = 0.671 \pm 0.029$

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(Stat errors only)