TCPV in $B^0 \rightarrow \pi^+\pi^-$ decays

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UCSD

$B_{ABAR}$ 227M $B\bar{B}$

hep-ex/0501071  Thanks to Nick Danielson

$Belle$ 275M $B\bar{B}$

hep-ex/0502035
Note

CKM angle

\[ \phi_2 = \alpha \]

direct CP-violating parameter

\[ A_{\pi\pi} = -C_{\pi\pi} \]
Event Selection

Reconstruction of $B^0 \rightarrow h^+ h^-$ from oppositely charged tracks include all tracks regardless of $\pi$ or $K$.

- $5.20 < m_{ES} < 5.29$ GeV/c$^2$ & $|\Delta E| < 150$ MeV
- Positively identify $\pi$-pairs based on PID information

$5.271 < M_{bc} < 5.287$ GeV/c$^2$ & $|\Delta E| < 64$ MeV

PID performance of both detectors is checked with $D^* \rightarrow D(\rightarrow K\pi)\pi$ samples

Flavor tagging

- Assign an event to one of five mutually exclusive tagging categories.
- Assign $q = +1(-1)$ and $r (0 \leq r \leq 1)$

Both effective tagging efficiencies $\sim 30\%$
Event Selection (continuum suppression)

Fisher discriminant based on the momentum flow relative to $\pi^+\pi^-$ thrust axis

c) weighted events/0.6

d) weighted events/0.1

Fisher Discriminant

F

for signal

F

for $q\bar{q}$ background
B^0 \to \pi^+\pi^- signals

enhanced in signal events

68030 candidate events
467\pm33 signal events
1606\pm51 K\pi events
unbinned maximum likelihood fit

\[ L_k = \exp\left(-\sum_{i} n_i \varepsilon_{i,k}\right) \prod_{j} \left[ \sum_{i} n_i \varepsilon_{i,k} P_{i,k}(\vec{x}_j, \vec{\alpha}_i) \right] \]

\( k \): four flavor tagging categories

\( i \): eight signal and background hypotheses

\( \pi^+\pi^-, K^+\pi^-, K^-\pi^+, K^+K^- \) signal and background

\( n_i \): event yield of type \( i \)

\( \varepsilon_{i,k} \): tagging efficiency

\( x_j \): \( m_{ES}, \Delta E, F, \theta^+, \theta^-, \Delta t \)

\( \alpha_i \): PDF parameters
unbinned maximum likelihood fit

• Two steps for the fit.
  – signal and background yield and Kπ charge asymmetries
    • fit w/o flavor-tagging or Δt
  – 46 parameters
    • $S_{\pi\pi}, C_{\pi\pi}$
    • 12 for background PDF of $m_{ES}, \Delta E$ and $F$
    • 8 for background $\Delta t$ PDF
    • 12 for background flavor-tagging efficiency
    • 12 for background flavor-tagging efficiency asymmetries.
Unbinned CP fit results

a) BABAR Preliminary

- Events / ps
- $t$ (ps)
- Asymmetry / 2 ps

B$^0$ tagged

$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$
$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$

1st error statistical, 2nd systematic

B$^0$ tagged

$\bar{B}^0$ tagged
Event Selection (continuum suppression)

\[ e^+ e^- \rightarrow q\bar{q}, (q = u, d, s, c) \]

Event shape

B flight direction

\[ LR = \frac{\mathcal{L}_{B \bar{B}}}{\mathcal{L}_{B \bar{B}} + \mathcal{L}_{q\bar{q}}} \]

(Likelihood Ratio)
**B^0 → π^+π^- signals**

**LR > 0.86**

- 2820 candidate events
- 666±43 signal events
- 247±31 Kπ events

**LR < 0.86**
For $\pi^+\pi^-$

$$p_{\pi\pi}(\Delta t, q; A_{\pi\pi}, S_{\pi\pi}) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 - q\Delta w + q(1 - 2w)[A_{\pi\pi} \cos \Delta m\Delta t + S_{\pi\pi} \sin \Delta m\Delta t]\}$$

wrong tag fraction obtained from data

For $K^+\pi^-$

$$p_{K\pi}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 - q\Delta w + q(1 - 2w)A_{K\pi}^{\text{eff}} \cos(\Delta m\Delta t)\}$$

$$A_{K\pi}^{\text{eff}} = \frac{A_\varepsilon + A_{K\pi}^{\text{eff}}}{1 + A_\varepsilon A_{K\pi}^{\text{eff}}}$$

$$A_\varepsilon = \frac{p(K^- \rightarrow \pi^-)\varepsilon_{\pi^+} - p(K^+ \rightarrow \pi^+)\varepsilon_{\pi^-}}{p(K^- \rightarrow \pi^-)\varepsilon_{\pi^+} + p(K^+ \rightarrow \pi^+)\varepsilon_{\pi^-}}$$

$$A_{K\pi} = -0.109 \pm 0.019 \text{ HFAG2004}$$

For $qq$

$$p_{qq}(\Delta t, q) = \frac{1 + q\delta_{qq}}{2} \{q_\tau \frac{e^{-|\Delta t|/\tau_{qq}}}{2\tau_{qq}} + (1 - q_\tau)\delta(\Delta t)\}$$

determined from sideband

$\delta_{qq}$ is set to 0 in default
a likelihood function

\[ L = (1 - f_{ol}) \int d\Delta t' \left\{ (f_{\pi\pi} p_{\pi\pi} + f_{K\pi} p_{K\pi}) R_{\text{sig}} (\Delta t - \Delta t') \\
+ f_{q\bar{q}} p_{q\bar{q}} R_{q\bar{q}} (\Delta t - \Delta t') \right\} + f_{ol} p_{ol} (\Delta t) \]

\[ f_{\pi\pi} + f_{K\pi} + f_{q\bar{q}} = 1 \]

\( f_{\pi\pi}, f_{K\pi}, f_{q\bar{q}} \) are event fractions as functions of \( \Delta E \) and \( M_{bc} \)

\( L_{tot} = \prod L(\Delta t_i, q_i) \) is maximized.

two free parameters: \( A_{\pi\pi} \) and \( S_{\pi\pi} \)
Unbinned CP fit results

LR > 0.86

\[ A_{\pi\pi} = +0.56 \pm 0.12 \pm 0.06 \]
\[ S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06 \]

1st error statistical, 2nd systematic
Background subtracted fit projection for all events

$\Delta E$-Mbc 2D fits to individual time intervals

\[ \tau^{+}\tau^{-} \text{ Yield} \]

\[ \tau^{+}\tau^{-} A_{CP} \]

$\Delta t$ (ps)
Significance calculation with Feldman-Cousins method

Large CP Violation,
\((A,S)=(0,0)\)
1-C.L.=5.62x10^{-8}, 5.4\sigma

Large Direct CP violation, confirmation of the previous Belle results
\((A,S)=(0,-0.62)\)
1-C.L.=5.13x10^{-5}, 4.0\sigma

both statistical and systematic errors are taken into account.

C.L. = Confidence Level
Consistency checks with Time-integrated fits

\[ A_{\pi\pi} = +0.52 \pm 0.14 \]

consistent with time-dependent fit

LR > 0.86 & 0.5 < r ≤ 1.0

Direct CP Violation!
Current experimental situation

HFAG2005

2.3σ difference between **Belle** and **BABAR**
The results support the expectation from SU(3) symmetry that

\[ A_{CP}(K^+\pi^-) \sim -\frac{1}{3} A_{CP}(\pi^+\pi^-) \]


\[ A_{CP}(K^+\pi^-) = -0.109 \pm 0.019 \]

\[ -\frac{1}{3} A_{CP}(\pi^+\pi^-) = -0.19 \pm 0.04 \]
### Systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>$S_{\pi\pi}$</th>
<th>$C_{\pi\pi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-flavor identification</td>
<td>±0.005</td>
<td>±0.015</td>
</tr>
<tr>
<td>$\tau_{B0}$ and $\Delta m_d$</td>
<td>±0.001</td>
<td>±0.004</td>
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<tr>
<td>PDF parameters</td>
<td>±0.017</td>
<td>±0.018</td>
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<tr>
<td>Potential bias</td>
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<td>±0.007</td>
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<td>SVT alignment</td>
<td>±0.010</td>
<td>±0.002</td>
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<tr>
<td>Beam spot</td>
<td>±0.010</td>
<td>±0.010</td>
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<tr>
<td>Tag-side interference</td>
<td>±0.008</td>
<td>±0.023</td>
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<tr>
<td><strong>total</strong></td>
<td>±0.027</td>
<td>±0.035</td>
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</tbody>
</table>

<table>
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<tr>
<th>Source</th>
<th>$S_{\pi\pi}$</th>
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<tr>
<td>wrong tag</td>
<td>±0.01</td>
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</tr>
<tr>
<td>physics param.</td>
<td>&lt;0.01</td>
<td>±0.01</td>
</tr>
<tr>
<td>resolution func</td>
<td>±0.04</td>
<td>±0.01</td>
</tr>
<tr>
<td>bkg Dt shape</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>event fraction</td>
<td>±0.02</td>
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<tr>
<td>fit bias</td>
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<tr>
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<td>+0.03</td>
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<td><strong>total</strong></td>
<td>±0.06</td>
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Validity check: Background (1)

- Background correlation with flavor tagging
  - The $\Delta E$ shape of $q\bar{q}$ B.G. depends on flavor tagging. We use different parameters for the fit.
    - BaBar: 4 different categories
    - Belle $r$-dependence (6 intervals x 2 for LR)

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deslope.pipi.140.dat
```

- $LR$ (Likelihood Ratio) vs. $r$ (flavor tag quality)
- $tag\ flavor = 0$

- Data points and error bars
• understanding for the Background
  – $K\pi$ background is well understood
    • BaBar: $K\pi$ asymmetry and B.R.
    • Belle: consistent with expectation from misidentification probability
  – qq background
    • BaBar: PDF parameters are simultaneously fitted. The PDF describes $m_{ES}$, $\Delta E$, $F$ and $\Delta t$ distributions well.
    • Belle: $M_{bc}$, $DE$ PDFs describe the sideband region well. $\Delta t$ PDF is determined from sideband events well.
Validity check: Background (3)

- **Background asymmetry**
  - BaBar: the asymmetries are determined from the fit for individual flavor-tagging categories.
  - Belle: qq background is assumed to be 0 in the fit. The asymmetry (less than 1%) is measured from sideband events. It is taken into account in the systematic error.

- **Two-photon background**
  - two-photon events \((e^+e^- \rightarrow e^+e^- \mu^+\mu^-)\) (~ 50 events) in the sideband for high-\(p\) lepton tagged events with SVD2.
  - flavor asymmetry in sideband events due to acceptance difference between forward and backward.
  - negligibly small contribution in the signal box
  - removing the background using electron probability, momentum and direction, muon probability.
Validity check: Likelihood

• How to treat correlation between discriminating variables?
  – Belle: 12 different parameter values for \( \Delta E \) PDF of continuum background. No correlation in \( M_{bc}, \Delta t \) PDFs.

• Issues for small statistics
  – Belle: small single event sensitivity (-0.05 at most for \( S_{\pi\pi} \)).
  – Belle: statistical significance with Feldman-Cousins method

• Inclusion of events in poor S/N regions
  – Belle: the CP fit for various subsets (low LR, high LR, low r, high r, \( \Delta E \) > or < 0, PID cut dependence), consistent within statistical error.
Validity check: $\Delta t$ determination

- How well the resolution function obtained from control samples describe charmless modes?
  - Belle: no parameter differences of the resolution function between control and $\pi^+\pi^-$ sample in MC.
  - No change in CP fit results with correction obtained from the above MC.
  - Validation of the resolution function with measurements of $B^0$ lifetime and $\Delta m_d$.
  - **BaBar**: $\tau_{B^0}=1.60\pm0.04$ ps, $\Delta m_d = 0.523\pm0.028$ ps$^{-1}$
  - **Belle**: $\pi\pi$ sample $\tau_{B^0}=1.50\pm0.07$ ps
    - $K\pi$ sample $\tau_{B^0}=1.51\pm0.04$ ps, $\Delta m_d = 0.46\pm0.03$ ps$^{-1}$
Validity check: Tag side

- How to estimate tag side interference
  - Belle: we generate two toy-MC experiments with and without the tag side interference (40000 experiments each) and see the difference.
$\phi_2(\alpha)$ with isospin analysis

HFAG2005

- $B \to \pi\pi$ (S/C from BABAR)
- $B \to \pi\pi$ (S/A from Belle)

Combined

no C/A$_{00}$

1 - CL

$\alpha$ (deg)
Summary

- BABAR (2004): $-0.09 \pm 0.15 \pm 0.04$
- Belle (2005): $-0.56 \pm 0.12 \pm 0.06$
- Average: $-0.37 \pm 0.10$

- BABAR (2004): $-0.30 \pm 0.17 \pm 0.03$
- Belle (2005): $-0.67 \pm 0.16 \pm 0.06$
- Average: $-0.50 \pm 0.12$
backup slides
### Systematic errors

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including uncertainties in the b.k.g and Final State Radiation

Validity check: CP fit cut dependence for ππ events

<table>
<thead>
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<th></th>
<th>Apipi</th>
<th>Spipi</th>
<th># of events</th>
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</thead>
<tbody>
<tr>
<td>ΔE&gt;0</td>
<td>+0.53 ± 0.16</td>
<td>-0.70 ± 0.22 - 0.20</td>
<td>1238</td>
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<tr>
<td>ΔE&lt;0</td>
<td>+0.59 +0.16 - 0.17</td>
<td>-0.63 +0.25 - 0.23</td>
<td>1582</td>
</tr>
<tr>
<td></td>
<td>ΔE</td>
<td>&lt;1σ</td>
<td>+0.52 ± 0.13</td>
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<tr>
<td></td>
<td>ΔE</td>
<td>&lt;2σ</td>
<td>+0.56 +0.11 - 0.12</td>
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<tr>
<td>multi track</td>
<td>+0.55 ± 0.13</td>
<td>-0.77 +0.18 - 0.17</td>
<td>2179</td>
</tr>
<tr>
<td>single track</td>
<td>+0.54 +0.27 - 0.29</td>
<td>-0.20 +0.41 - 0.40</td>
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<tr>
<td>flavor tag bin 1</td>
<td>+3.62 +1.70 - 1.72</td>
<td>-0.72 +2.28 - 2.27</td>
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<tr>
<td>flavor tag bin 2</td>
<td>+0.87 +0.53 - 0.54</td>
<td>-1.48 +0.56 - 0.52</td>
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<tr>
<td>flavor tag bin 3</td>
<td>+0.32 +0.42 - 0.43</td>
<td>+0.02 ± 0.67</td>
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<tr>
<td>flavor tag bin 4</td>
<td>+0.18 ± 0.31</td>
<td>-0.25 +0.47 - 0.45</td>
<td>292</td>
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<td>flavor tag bin 5</td>
<td>+0.33 ± 0.29</td>
<td>-0.67 +0.37 - 0.32</td>
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<td>flavor tag bin 6</td>
<td>+0.71 +0.13 - 0.14</td>
<td>-0.75 +0.23 - 0.21</td>
<td>190</td>
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<tr>
<td>KLR &gt; 0.86</td>
<td>+0.57 ± 0.13</td>
<td>-0.65 +0.19 - 0.18</td>
<td>884</td>
</tr>
<tr>
<td>KLR &lt; 0.86</td>
<td>+0.51 +0.23 - 0.24</td>
<td>-0.76 +0.34 - 0.32</td>
<td>1936</td>
</tr>
<tr>
<td>original</td>
<td>-0.56 ± 0.12</td>
<td>-0.67 ± 0.16</td>
<td>2820</td>
</tr>
</tbody>
</table>
Validity check: CP fit cut dependence of $\pi\pi$ events
Current experimental situation

inside the physical boundary!

\[ S_{\pi\pi} = -0.99 \pm 0.21 \]
\[ A_{\pi\pi} = +0.60 \pm 0.15 \]

\[ S_{\pi\pi} = -0.33 \pm 0.24 \]
\[ A_{\pi\pi} = +0.46 \pm 0.17 \]

2.3\( \sigma \) difference between Belle and BaBar

combined

BaBar 227M

140fb\(^{-1}\)

113fb\(^{-1}\)
Validity check (lifetime fit with $B^0 \to \pi^+ \pi^-$)

Lifetime fit

$\tau_{B^0} = 1.50 \pm 0.07 \text{ ps}$

2820 events

good agreement with the World Average (W.A.) Value

$\tau_{B^0} = 1.536 \pm 0.014 \text{ ps \ PDG2004}$
Validity check with $B^0 \to K^+ \pi^-$

We extract $B^0 \to K^+ \pi^-$ events

Lifetime fit $\tau_{B^0} = 1.51 \pm 0.04$ ps

$\Delta m = 0.46 \pm 0.03$ ps$^{-1}$

in total 4,293
[including 2,207 $K^+ \pi^-$] events

good control sample because of the similar topology to $B^0 \to \pi^+ \pi^-$

consistent with the WA values
Validity check with $B^0 \rightarrow K^+\pi^-$

**CP fit results**

- Total 4293 events:
  - $B_0$: 2106
  - $B_0b$: 2187

- $A_{K\pi} = -0.06 \pm 0.06$
  - Consistent with the WA value

- $S_{K\pi} = +0.09 \pm 0.08$
  - In agreement with null asymmetry
Background asymmetry

\( \pi \pi \) sideband

\[
\begin{align*}
B0: & 42467, \ B0b: 42090 \\
A &= +0.02 \pm 0.01 \\
S &= +0.02 \pm 0.03
\end{align*}
\]

\( K \pi \) sideband

\[
\begin{align*}
B0: & 43577, \ B0b: 43308 \\
A &= +0.00 \pm 0.01 \\
S &= +0.01 \pm 0.03
\end{align*}
\]

No background asymmetry

possible background asymmetries are included in the systematic error
**Belle** measurement with 275M BB pairs

\[
Br(\pi^0 \pi^0) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6}
\]

\[
A_{CP}(\pi^0 \pi^0) = +0.44^{+0.53}_{-0.52} \pm 0.17
\]

hep-ex/0408101

submitted PRL
Validity check: single event sensitivity

Acp

Scp

at most -0.04 in $S\pi\pi$
RMS: 0.110

MINOS:
+0.113
-0.116

RMS: 0.153

MINOS:
+0.163
-0.156
Interpretation: $|P/T|$ and $\delta$

\begin{align*}
A(B^0 \to \pi^+ \pi^-) &= -\left( |T| e^{i\delta_T} e^{i\phi_3} + |P| e^{i\delta_P} \right), \\
A(\bar{B}^0 \to \pi^+ \pi^-) &= -\left( |T| e^{i\delta_T} e^{-i\phi_3} + |P| e^{i\delta_P} \right), \\
\lambda_{\pi\pi} &= e^{i2\phi_2} \frac{1+|P/T| e^{i(\delta+\phi_3)}}{1+|P/T| e^{i(\delta-\phi_3)}}
\end{align*}

\[ S_{\pi\pi} = [\sin 2\phi_2 + 2 |P/T| \sin(\phi_1 - \phi_2) \cos \delta - |P/T|^2 \sin 2\phi_1] / R_{\pi\pi}, \]

\[ A_{\pi\pi} = -[2 |P/T| \sin(\phi_1 + \phi_2) \sin \delta] / R_{\pi\pi}, \]

\[ R_{\pi\pi} = 1 - 2 |P/T| \cos(\phi_1 + \phi_2) \cos \delta + |P/T|^2 \]


4 parameters

$\delta \equiv \delta_P - \delta_T$

Strong phase difference

$|P/T|$ Theory $\sim 0.15\sim 0.45$


$\sin 2\phi_1 = 0.726 \pm 0.037$ (HFAG 2004)
Interpretation: $|P/T|$ and $\delta$

We scan $\phi_2$ with a constraint of $0^\circ < \phi_1 + \phi_2 < 180^\circ$ $\phi_1 = 23.5 \pm 1.6^\circ$ to search for the minimum C.L. for various $|P/T|$ and $\delta$.

model-independent 95.4% confidence interval

$-180^\circ < \delta < -4^\circ$ \quad $|P/T| > 0.17$

Exclude $\delta > 0$ and $|P/T| = 0$ with 4$\sigma$ significance
Interpretation: $\phi_2$ constraint using isospin

M. Gronau and D. London, PRL 65, 3381 (1990)

$$\frac{1}{\sqrt{2}} A^{+-} = \frac{1}{\sqrt{2}} A^{00}$$

<table>
<thead>
<tr>
<th>Amplitude for</th>
<th>$A^{+-} (\bar{A}^{+-})$</th>
<th>$B^0 (\bar{B}^0) \rightarrow \pi^+ \pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^{00} (\bar{A}^{00})$</td>
<td>$B^0 (\bar{B}^0) \rightarrow \pi^0 \pi^0$</td>
<td></td>
</tr>
<tr>
<td>$A^{+0} (\bar{A}^{-0})$</td>
<td>$B^+ (\bar{B}^-) \rightarrow \pi^+ \pi^0 (\pi^- \pi^0)$</td>
<td></td>
</tr>
</tbody>
</table>

$$\widetilde{A}^{ij} = e^{2\phi_2} \overline{A}^{ij}$$

$$S_{\pi\pi} = \sqrt{1 - A^2_{\pi\pi}} \sin(2\phi_2 + 2\theta)$$

We use the HFAG summer 2004 values for the branching ratios of $B^0 \rightarrow \pi^+ \pi^-$, $\pi^0 \pi^0$, $B^+ \rightarrow \pi^+ \pi^0$ and direct CP asymmetry of $B^0 \rightarrow \pi^0 \pi^0$.

We use the statistical treatment of J. Charles et al., hep-ph/0406184
\[ \text{Belle measurement with 275M B\overline{B} pairs} \]

\[ Br(\pi^0 \pi^0) = (2.3^{+0.4+0.2}_{-0.5-0.3}) \times 10^{-6} \]
\[ A_{CP}(\pi^0 \pi^0) = +0.44^{+0.53}_{-0.52} \pm 0.17 \]

\[ \text{BABAR measurement with 227M B\overline{B} pairs} \]

\[ Br(\pi^0 \pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6} \]
\[ A_{CP}(\pi^0 \pi^0) = +0.12 \pm 0.56 \pm 0.06 \]

\[ \text{First } A_{CP}(B^0 \rightarrow \pi^0 \pi^0) \text{ measurements in the summer 2004.} \]
Interpretation: $\phi_2$ constraint with isospin

95.4% confidence interval

$0^\circ < \phi_2 < 19^\circ$ and $71^\circ < \phi_2 < 180^\circ$

Belle

using HFAG summer 2004

J. Charles et al., hep-ph/0406184
Future prospect

Projection of KEKB Luminosity

$L_{\text{peak}} = 1.4 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

$L_{\text{tot}} = 350 \text{fb}^{-1}$ (Feb. 8, 2005)

$\sim 10^{10} \text{BB/yr}!!$

& similar number of $\tau^+\tau^-$

Major upgrade of KEKB & Belle detector
(>1yr shutdown)

Crab cavities

Future prospect

$L_{\text{peak}}$ (cm$^{-2}$s$^{-1}$) $1.4 \times 10^{34}$

$L_{\text{int}}$ 330 fb$^{-1}$ $5 \times 10^{34}$

$\sim 1 \text{ ab}^{-1}$ $5 \times 10^{35}$

$\sim 10 \text{ ab}^{-1}$
Future prospect

assuming the current measured values

Current

\( \phi_2 \) (degrees)

Super-B factories can pin down the \( \phi_2 \) value.