Belle Results on Time-dependent $CP$ Asymmetry for $B \rightarrow D^{*-} \pi^+$

and Search for $B \rightarrow D^{*+} \pi^0$ Decay

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Interference of different tree diagrams with $V_{ub}$ ($\rightarrow \phi_3$) through $B\bar{B}$ mixing ($\rightarrow 2\phi_1$)

**CFD with $V_{cb}$**

$B^0 \bar{b} \rightarrow \bar{d} \pi^+ W^+$

$B^0(+) \bar{b} \rightarrow \bar{d} D^{*-}$

**DCSD with $V_{ub}$**

$B^0 \bar{b} \rightarrow \bar{d} \pi^+ W^+$

$B^0(+) \bar{b} \rightarrow \bar{d} D^{*-}$

Time-dependent asymmetry can be derived using the relation,

$S \sin(m \Delta) C \cos(m \Delta)$

$S = \frac{2 R \sin(2 \theta)}{\sin(\theta)}$

for $B^\rightarrow D_{final}$ states ($\Delta = (1 - \frac{2 R^2}{1 + \frac{1}{R^2}})$

$R = \frac{1}{2} (1 + \frac{1}{R^2})$
Interference of different tree diagrams with $V_{ub}$ ($\rightarrow \phi_3$) through $B\bar{B}$ mixing ($\rightarrow 2\phi_1$)

Time-dependent asymmetry can be derived using the relation,

$$\frac{\Gamma(B^0(\Delta t\rightarrow f)) - \Gamma(B^0(\Delta t\rightarrow \bar{f}))}{\Gamma(B^0(\Delta t\rightarrow f)) + \Gamma(B^0(\Delta t\rightarrow \bar{f}))} = S \sin(\Delta m_d) - C \cos(\Delta m_d)$$
**Introduction**

- Interference of different tree diagrams with $V_{ub}$ ($\rightarrow \phi_3$) through $B\bar{B}$ mixing ($\rightarrow 2\phi_1$)

![Diagram 1](CFD with $V_{cb}$)

![Diagram 2](DCSD with $V_{ub}$)

- Time-dependent asymmetry can be derived using the relation,

$$\frac{\Gamma(B^0(\Delta t \rightarrow f)) - \Gamma(B^0(\Delta t \rightarrow f))}{\Gamma(B^0(\Delta t \rightarrow f)) + \Gamma(B^0(\Delta t \rightarrow f))} = S \sin(\Delta m_d) - C \cos(\Delta m_d)$$

$$S^\pm = -2R \sin(2\phi_1 + \phi_3 \pm \delta) \quad C = \pm 1$$

for $B \rightarrow D^{\ast \pm} \pi^{\mp}$ final states \hspace{1em} (|$C$| = (1 - $R^2$)/(1 + $R^2$) \approx 1)
HFAG notation:
\[
\alpha = -\frac{S^+ + S^-}{2}, \quad c = -\frac{S^+ - S^-}{2}
\]
HFAG notation:

\[ a = -\frac{S^+ + S^-}{2}, \quad c = -\frac{S^+ - S^-}{2} \]

HFAG average for \( D^* \pi \) [2006]:
(full and partial, Babar and Belle)

\[ a = -0.037 \pm 0.011 \]
\[ c = -0.006 \pm 0.014 \]

### a parameters

<table>
<thead>
<tr>
<th>D( \pi )</th>
<th>BaBar</th>
<th>Belle</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD 73 (2006) 111101</td>
<td>-0.010 ± 0.023 ± 0.007</td>
<td>-0.050 ± 0.021 ± 0.012</td>
<td>-0.030 ± 0.017</td>
</tr>
<tr>
<td>PRD 73 (2006) 092003</td>
<td>-0.040 ± 0.023 ± 0.010</td>
<td>-0.039 ± 0.020 ± 0.013</td>
<td>-0.039 ± 0.017</td>
</tr>
<tr>
<td>Average HFAG</td>
<td>-0.034 ± 0.014 ± 0.009</td>
<td>-0.041 ± 0.019 ± 0.017</td>
<td>-0.036 ± 0.014</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D( \pi ) partial</th>
<th>BaBar</th>
<th>Belle</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD 71 (2005) 112003</td>
<td>-0.024 ± 0.031 ± 0.009</td>
<td>-0.041 ± 0.019 ± 0.017</td>
<td>-0.036 ± 0.014</td>
</tr>
<tr>
<td>PRD 73 (2006) 092003</td>
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<td>-0.036 ± 0.014</td>
</tr>
</tbody>
</table>

\( c \) \( \sim 3.5\sigma \)
AD: CFD fraction \( B(B^0 \rightarrow D^{*-}\pi^+) \) is large \( (2.76 \times 10^{-3}) \).

DA: the amplitude ratio is not sizable,

\[
R \equiv \frac{A(B^0 \rightarrow D^{*+}\pi^-)}{A(B^0 \rightarrow D^{*-}\pi^+)} \simeq 0.02.
\]

: \( B^0 \rightarrow \overline{B}^0 \rightarrow D^{*-}\pi^- \) (CFD) is large compared to the DCSD amplitude.
\textbf{AD:} CFD fraction $\mathcal{B}(B^0 \to D^{*-}\pi^+)$ is large ($2.76 \times 10^{-3}$).

\textbf{DA:} the amplitude ratio is not sizable,

$$R \equiv \mathcal{A}(B^0 \to D^{*-}\pi^-)/\mathcal{A}(B^0 \to D^{*-}\pi^+) \simeq 0.02.$$

$B^0 \to \overline{B}^0 \to D^{*+}\pi^-$ (CFD) is large compared to the DCSD amplitude.

\textbf{Two possible ways for reaching $R$:}

\begin{itemize}
  \item $\tan \theta_c \frac{f_{D^*}}{f_{D_S^*}} \sqrt{\frac{\mathcal{B}(B^0 \to D^{*-}\pi^-)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)}}$
  \begin{align*}
  \text{allowing the error from the assumption of SU(3) symmetry.}
  \end{align*}
  \item $R = \sqrt{\frac{\tau_{B^0}}{\tau_{B^+}} \frac{2\mathcal{B}(B^+ \to D^{*-}\pi^0)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)}}$
  \begin{align*}
  \text{as suggested by Duniez, PLB 427 (1998), using the isospin relation.}
  \end{align*}
\end{itemize}
$B^0 \rightarrow D^{*\pi}$ partial reconstruction

High-momentum lepton is required in tag-side. Two charged pions must have high and low momentum. Vertex positions are obtained from single tracks. Proper-time difference can be derived from $z$. 

$e^-$ $e^+$
High-momentum lepton is required in tag-side.
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$B^0 \rightarrow D^*\pi$ partial reconstruction

- High-momentum lepton is required in tag-side.
- Two charged pions must have high and low momentum.
- Vertex positions are obtained from single tracks.
- Proper-time difference can be derived from $\Delta z$. 

$\Delta t = (\Delta z + \text{offset}) / \beta \gamma c$
Yield extraction for $B^0 \rightarrow D^* \pi$

- **Fit in two kinematical dimensions:** $\pi_s$ momentum along the opposite direction of $\pi_f$ ($p_{||}$) and momentum difference between $\pi_f$ and $D^*$ ($p_\delta$).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$N_{BB}$</th>
<th>$N_{\text{sig in signal region}}$</th>
<th>$S/(S+B)$</th>
<th>cut for lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle (PRD 73, 092003 (2006))</td>
<td>386 M</td>
<td>$21,773 \pm 214$</td>
<td>66%</td>
<td>$&gt; 1.2 \text{ GeV/c}$</td>
</tr>
<tr>
<td>Belle 2008 Summer</td>
<td>657 M</td>
<td>$50,196 \pm 286$</td>
<td>59%</td>
<td>$&gt; 1.1 \text{ GeV/c}$</td>
</tr>
</tbody>
</table>
**Unbinned ML fit**: 

to minimize the quantity $-2 \sum_i \ln \mathcal{L}_i$,

$$\mathcal{L}_i = f_{D^*\pi} P_{D^*\pi} + f_{D^*\rho} P_{D^*\rho} + f_{\text{unco}} P_{\text{unco}} + f_{\text{corr}} P_{\text{corr}}$$

**Time-dependent decay rates**: 

$$P(B^0 \to D^{*\pm}\pi^\mp) = \left(1/8\tau_{B^0}\right) e^{-|\Delta t|/\tau_{B^0}} [1 \mp C \cos(\Delta m \Delta t) - S^\pm \sin(\Delta m \Delta t)]$$

$$P(\bar{B}^0 \to D^{*\pm}\pi^\mp) = \left(1/8\tau_{B^0}\right) e^{-|\Delta t|/\tau_{B^0}} [1 - C \cos(\Delta m \Delta t) \mp S^\pm \sin(\Delta m \Delta t)]$$

**Mistagging**:

taken into account in the fit,

$$P(l, \pi_f) = (1 - w_-) P(B^0 \to D^*\pi) + (1 - w_+) P(\bar{B}^0 \to D^*\pi) \quad (w_+/_- \sim 5\%)$$

**Detector resolution function**:

$J/\psi$ events are analysed and $\Delta z = z_{\mu^+} - z_{\mu^-}$ is used.
Δz fit results

<table>
<thead>
<tr>
<th>Signal</th>
<th>Description</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td><em><em>D</em> π</em>*</td>
<td>Total signal</td>
<td>Red</td>
</tr>
<tr>
<td><em><em>D</em> ρ</em>*</td>
<td>Total background</td>
<td>Black</td>
</tr>
<tr>
<td><strong>correlated bkg.</strong></td>
<td>(D** π, D* a1)</td>
<td>Purple</td>
</tr>
<tr>
<td><strong>uncorrelated bkg.</strong></td>
<td>(q̅q̅, Dπ)</td>
<td>Green</td>
</tr>
</tbody>
</table>
Δz fit results

**SF (same flavor)**
- $\pi_f$ and tagging lepton have **same charge**
\( \Delta z \) fit results

**OF (opposite flavor):** \( \pi_f \) and tagging lepton have opposite charge

- **D\( ^* \pi \) signal**
- **total background**
- **D\( ^* \rho \)**
- **correlated bkg.** (D\( ^* \pi, D^* a_1 \))
- **uncorrelated bkg.** (q\( \bar{q} \), D\( \pi \))
$S^+ = 0.057 \pm 0.019$ (stat.), $S^- = 0.038 \pm 0.020$ (stat.)

**preliminary**
\[ A = \frac{N_{\pi^- l^- (\Delta z)} - N_{\pi^+ l^+ (\Delta z)}}{N_{\pi^- l^- (\Delta z)} + N_{\pi^+ l^+ (\Delta z)}} \] (SF) \hspace{1cm} A = \frac{N_{\pi^+ l^- (\Delta z)} - N_{\pi^- l^+ (\Delta z)}}{N_{\pi^+ l^- (\Delta z)} + N_{\pi^- l^+ (\Delta z)}} \] (OF)
$A = \frac{N_{\pi^+} - (\Delta z) - N_{\pi^-} + (\Delta z)}{N_{\pi^-} - (\Delta z) + N_{\pi^+} + (\Delta z)}$ (SF)

$A = \frac{N_{\pi^+} - (\Delta z) - N_{\pi^-} + (\Delta z)}{N_{\pi^-} - (\Delta z) + N_{\pi^+} + (\Delta z)}$ (OF)

$S^+ = 0.057 \pm 0.019 \pm 0.012$

$S^+ = 0.038 \pm 0.020 \pm 0.010$

$a = 0.047 \pm 0.014 \pm 0.012$

$c = 0.009 \pm 0.014 \pm 0.012$
$A = \frac{N_{\pi^- l^-} - N_{\pi^+ l^+}}{N_{\pi^- l^-} + N_{\pi^+ l^+}}$ (SF)

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preliminary

significance of CPV is $2.6\sigma$
## Systematic uncertainties for $S^\pm$

<table>
<thead>
<tr>
<th>Source</th>
<th>$S_+$</th>
<th>$S_-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta z$ offsets</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>$R_k$</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>$R_{\text{det}}$</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>$R_{\text{np}}$</td>
<td>0.008</td>
<td>0.007</td>
</tr>
<tr>
<td>Background param.</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Phys. param.</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>Yield fit</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Resol. model</td>
<td>0.006</td>
<td>0.002</td>
</tr>
<tr>
<td>$\Delta z$ offsets floated in bkg.</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.012</td>
<td>0.010</td>
</tr>
</tbody>
</table>
Belle result using partial reconstruction is updated from the previous plot.

<table>
<thead>
<tr>
<th>a parameters</th>
<th>HFAG ICHEP 2008 PRELIMINARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dπ full</td>
<td></td>
</tr>
<tr>
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<tr>
<td>Dπ partial</td>
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<td>Dρ</td>
<td></td>
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</tr>
<tr>
<td>D*π full</td>
<td></td>
</tr>
<tr>
<td>BaBar</td>
<td>-0.024 ± 0.031 ± 0.009</td>
</tr>
<tr>
<td>Average HFAG</td>
<td>-0.024 ± 0.032</td>
</tr>
<tr>
<td>D*π partial</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>-0.047 ± 0.014 ± 0.012</td>
</tr>
</tbody>
</table>
Updated HFAG average

Belle result using partial reconstruction is updated from the previous plot

HFAG average for $D^*\pi$ [2008]:
(full and partial, Babar and Belle)

\[ a = -0.040 \pm 0.010 \]
\[ c = -0.007 \pm 0.012 \]
Estimate for $R$

- $2\phi_1 + \phi_3$ is to be derived from $S$ using the relation,
  \[ S^\pm = -2R \sin(2\phi_1 + \phi_3 \pm \delta). \]

- $2\phi_1 + \phi_3$ results in Belle (PRD 73, 092003 (2006)) were assuming SU(3)-breaking effect as 30% on $R$.

- Very recent publication from Babar (PRD 78, 032005 (2008)) is mentioning the effect as 10% – 15%.
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- Another way using isospin relation has not been tested for a decade due to its small amplitude.

  $B(B^+ \rightarrow D^{*+}\pi^0) < 1.7 \times 10^{-4}$ (90% C.L.) was only available from CLEO’s results, PRL 80, 2762 (1998).
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  $\mathcal{B}(B^+ \to D^{*+}\pi^0) < 1.7 \times 10^{-4}$ (90% C.L.) was only available from CLEO’s results, PRL 80, 2762 (1998).

- Assuming $R = 0.02$, and with $\mathcal{B}(B^0 \to D^{*-}\pi^+) = 2.76 \times 10^{-3}$ from PDG, $\mathcal{B}(B^+ \to D^{*+}\pi^0) = 5.9 \times 10^{-7}$. 
B^+ \rightarrow D^{*+}\pi^0 \text{ reconstruction}

\begin{align*}
B^+ \rightarrow D^{*+}\pi^0 & \rightarrow D^0\pi^+_s \\
& \rightarrow K^-\pi^+ \\
& \rightarrow K^-\pi^+\pi^0 \\
& \rightarrow K^-\pi^+\pi^-\pi^+ \\
& \rightarrow K_S\pi^+\pi^-
\end{align*}

- 4 sub-decay modes are combined in reconstruction.
$B^+ \rightarrow D^{*+}\pi^0$ reconstruction

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- Likelihood is calculated through the combination of SFW, $\cos \theta_B$, $\Delta z$ and $\cos \theta_h$. 
4 sub-decay modes are combined in reconstruction.

Likelihood is calculated through the combination of SFW, $\cos \theta_B$, $\Delta z$ and $\cos \theta_h$.

Its requirements are applied with the flavor information, for the maximal point of $S/\sqrt{S+B}$ in the signal region ( $|\Delta E| < 0.1$ GeV, $5.27$ GeV/$c^2 < M_{bc} < 5.29$ GeV/$c^2$ ).
Extraction of $B^+ \rightarrow D^{*+} \pi^0$ event and $R$

- Two-dimensional unbinned extended-ML fit
Extraction of $B^+ \rightarrow D^{*+}\pi^0$ event and $R$

- Two-dimensional unbinned extended-ML fit

![Graphs showing data distributions and fits for $D^{*+}\pi^0$ signal, total, $\overline{B}^0 \rightarrow D^{*+}\rho^-$, other $B\overline{B}$ bkg., and $q\overline{q}$ bkg.](image)

- $D^{*+}\pi^0$ signal
- total
- $\overline{B}^0 \rightarrow D^{*+}\rho^-$
- other $B\overline{B}$ bkg.
- $q\overline{q}$ bkg.
Extraction of $B^+ \to D^{*+}\pi^0$ event and $R$

Two-dimensional unbinned extended-ML fit

Signal event is extracted as $4.5^{+4.1}_{-3.4}$ in the signal region from 657 $B\bar{B}$ pairs ($\varepsilon = 0.56\%$ from MC).

$$B(B^+ \to D^{*+}\pi^0) = [1.2^{+1.1}_{-0.9}\,(\text{stat})^{+0.3}_{-0.9}\,(\text{syst})] \times 10^{-6}$$

($< 3.6 \times 10^{-6}$ at 90% C.L.) $\Rightarrow R < 0.051$ (90% C.L.)
Main systematic uncertainties for $\mathcal{B}(B^+ \to D^{*+}\pi^0)$

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic error (number of events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>H_0</td>
</tr>
<tr>
<td>$\Delta E \text{ shift of } B \to D^{*+}\rho^-$</td>
<td>$0.0^{+\sigma}_{-\sigma}$</td>
</tr>
<tr>
<td>Fraction of backgrounds</td>
<td>$0.8^{+\sigma}_{-\sigma}$</td>
</tr>
<tr>
<td>Gaussian width of background PDF</td>
<td>$0.5^{+\sigma}_{-\sigma}$</td>
</tr>
<tr>
<td>2D correlation for $q\bar{q}$ and $B^+ \to D^{*+}\pi^0$</td>
<td>$0.0^{+\sigma}_{-\sigma}$</td>
</tr>
<tr>
<td>Fit bias</td>
<td>$0.0^{+\sigma}_{-0.5}$</td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>$1.2^{+\sigma}_{-3.2}$</td>
</tr>
</tbody>
</table>
Summary

- \( a = 0.047 \pm 0.014 \pm 0.012 \), \( c = 0.009 \pm 0.014 \pm 0.012 \)

  CPV in \( B \to D^{*-} \pi^+ \) is found to be 2.6\( \sigma \) from lepton-tag analysis of 657 M \( B\bar{B} \) pairs at Belle.

- \( \mathcal{B}(B^+ \to D^{*+} \pi^0) < 3.6 \times 10^{-6} \), \( R < 0.051 \) at 90% C.L.

  from isospin relation. Estimate of \( R \) is still much better in SU(3)-related measurement. (Much data will be needed for using isospin, \( \sim \times 10 \) or more ..)

- Weak phase \( 2\phi_1 + \phi_3 \) can be extracted using \( S^\pm \). Additional kaon-tag analysis will be achieved in near future. SU(3) symmetry will be used to obtain \( 2\phi_1 + \phi_3 \), at that time.
Other systemic uncertainties for $\mathcal{B}(B^+ \rightarrow D^{*+} \pi^0)$

<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}$ requirement</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Delta M$ requirement</td>
<td>3.3</td>
</tr>
<tr>
<td>Secondary branching fractions</td>
<td>3.3</td>
</tr>
<tr>
<td>Track finding efficiency</td>
<td>5.1</td>
</tr>
<tr>
<td>Particle identification</td>
<td>4.4</td>
</tr>
<tr>
<td>$\pi^0$ reconstruction</td>
<td>4.1</td>
</tr>
<tr>
<td>$K^-_S$ reconstruction</td>
<td>0.3</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.5</td>
</tr>
<tr>
<td>Number of $B\bar{B}$ pairs</td>
<td>1.4</td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>9.8</td>
</tr>
</tbody>
</table>
Experimental and theoretical estimate for $R$

\[ R = \tan \theta_c \frac{f_{D^*}}{f_{D_s^*}} \sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^{*-} \pi^+)}{\mathcal{B}(B^0 \rightarrow D_s^{*+} \pi^-)}} \]

- **Belle** PRD 73, 092003 (2006)

  \[ R(\%) = 2.0 \pm 0.7 \text{ (stat and syst)} \pm 0.6 \text{ (SU(3)-breaking)} \]

- **Babar** PRD 78, 032005 (2008) (for $R(D^* \pi)$)

  \[ R(\%) = 1.81^{+0.16}_{-0.15} \text{ (stat)} \pm 0.09 \text{ (syst)} \pm 0.10 \text{ (} f_D \text{)} \]

  \[ \pm \text{ SU(3)-breaking (10} - 15\% \text{ on } R) \]

  - still $15 - 20\%$ error on $R$

\[ \mathcal{B}(B^0 \rightarrow D_s^{*-} \pi^+) = [2.6^{+0.5}_{-0.4} \pm 0.2] \times 10^{-5} \]

\[ \mathcal{B}(B^0 \rightarrow D_s^{*+} \pi^-) = [2.76 \pm 0.13] \times 10^{-3} \]

\[ f_{D^*}/f_{D_s^*} = 1.24 \pm 0.07 \text{ (lattice QCD)} \]

$W$-exchange contribution (only seen in $B^0 \rightarrow D^{*\pm} \pi^\mp$) is included ($\sim 5\%$) in SU(3)-breaking.