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CP Violation Studies in $B^0 \to D^{(*)\pm} \pi^\mp$ in BABAR and Belle

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Abstract. We present a preliminary measurement of the time-dependent CP asymmetries in decays of $B^0$ mesons to the final states $D^{(*)\pm}\pi^\mp$ using data collected by the BABAR experiment at the PEP-II storage rings. $B$ mesons decaying to $D\pi$ are fully reconstructed, while events containing $B \to D^*\pi$ are selected using a full or a partial reconstruction technique. These results can be interpreted in terms of a constraint on the angles of the unitarity triangle to set a lower bound on $|\sin(2\beta + \gamma)|$. The Belle experiment at the KEK-B collider is performing the same kind of studies and a preliminary estimation of the achievable error is presented.

1 Introduction

The main physics goal of the BABAR and Belle experiments running on $B$-factories is the measurement of the CP-violating phase of the quark-mixing (CKM) matrix [1] and to over-constrain the unitarity triangle in order to check whether the CKM mechanism is the correct explanation of the CP violation phenomenon. The CP violation in the $B$ sector has been established by measuring the $\beta$ angle of the unitarity triangle [2], [3]. We present here an analysis to constrain $|\sin(2\beta + \gamma)|$ from the study of the time evolution for $B^0 \to D^{(*)\pm} \pi^\mp$ decays [4] [5].

2 Principle of the measurement

2.1 Time-dependent decay rates

The decays $B^0 \to D^{(*)\pm} \pi^\mp$ may proceed via a favored $b \to c \pi d$ or a doubly-CKM-suppressed $b \to u d$ amplitude. Interference between these amplitudes through $B^0$ - $\bar{B}^0$ mixing provides a time-dependent CP-violation signal.

The time-dependent decay rate for $B^0 \to D^{(*)\pm} \pi^\mp$ decays is:

$$f^\pm(\eta, \Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times$$

$$\left[1 \pm S_\eta \sin(\Delta m_d \Delta t) \mp \eta C \cos(\Delta m_d \Delta t)\right],$$

where $\tau$ is the mean $B^0$ lifetime, $\Delta m_d$ is the $B^0$ - $\bar{B}^0$ mixing frequency, and $\Delta t = t_{rec} - t_{stag}$ is the time elapsed between the $B^0 \to D^{(*)\pm} \pi$ decay ($B_{rec}$) and the decay of the other $B$ ($B_{stag}$). The superscript $(\pm)$ refers to whether the flavor of $(B_{stag})$ was $B^0$ ($\bar{B}^0$), while $\eta = +1(-1)$ for $D^+\pi^-$ ($D^-\pi^+$) final states. The $S$ and $C$ parameters can be expressed as:

$$S_\eta = \frac{2Im\lambda_\eta}{1 + |\lambda_\eta|^2}, \quad C = \frac{1 - |\lambda_\eta|^2}{1 + |\lambda_\eta|^2},$$

where we define $|\lambda| = |\lambda_+| = 1/|\lambda_-|$, and $\lambda_\pm = \pm q/p A(B^0 \to D^{(*)}\pi^\pm)/A(\bar{B}^0 \to \bar{D}^{(*)}\pi^\mp) = |\lambda|^2 e^{-(2\beta + \gamma + \delta)}, q/p$ is a function of the elements of the mixing matrix and $\delta$ is the relative strong phase between the two contributing amplitudes. The same equations apply for $B^0 \to D^{(*)}\bar{\pi}^\mp$ decays with $|\lambda|$ and $\delta$ replaced by different values $|\lambda^*|$ and $\delta^*$. The analysis strategy is similar to other BABAR and Belle time-dependent CP asymmetry measurements [2], [3]. The $B^0$ meson decaying to the $D^{(*)}\pi$ final state ($B_{rec}$) is reconstructed using a partial or a full reconstruction method. The flavor of the other $B^0$ meson ($B_{stag}$) is determined using the charge correlation with a lepton or a kaon. Each event is assigned to one of four hierarchical, mutually exclusive tagging categories. The decay time difference $\Delta t$ is computed from the distance separating the $B_{stag}$ and $B_{rec}$ vertices.

2.2 Estimation of $|\lambda^{(*)}|$

In principle the ratio $|\lambda^{(*)}|$ of the magnitudes of the suppressed and favored amplitudes can be estimated from a global time-dependent fit of equation 1. In practice, this is not possible with the current BABAR statistics. As suggested in [5] [6], the value of $|\lambda^{(*)}|$ is estimated from the ratio of branching fractions $B(B^0 \to D^{(*)}\pi^\mp)/B(\bar{B}^0 \to D^{(*)}\pi^\mp)$ using the BABAR measurement [6]

$$|\lambda|(D\pi) = 0.021^{+0.004}_{-0.005}, \quad |\lambda^*|(D^*\pi) = 0.017^{+0.006}_{-0.007}$$

As this estimation is based on the approximate SU(3) symmetry and is not taking into account annihilation contributions to $B^0 \to D^{(*)}\pi^\mp$, there is an unknown, potentially large, theoretical uncertainty on $|\lambda^{(*)}|$. 
2.3 CP violation on the tag side

In the same way that the interference between the \( b \to u \) and \( b \to c \) amplitudes is present in the reco side and is used to measure the CP asymmetry, the same interference exists on the tag side and induces a time-dependent effect which cannot be neglected [7]. This effect depends on the \( B_{tag} \) decay modes. For each tagging category (i), this interference is parametrized in terms of the effective parameters \( |\lambda_i| \) and \( \delta_i \). The time-dependent decay rate becomes:

\[
f_i^t(\eta, \Delta t) \propto 1 \mp \left( a^{(s)} \mp \eta b^{(s)} - 2 \eta c_i^{(s)} \right) \sin(\Delta m_d \Delta t) + \eta \cos(\Delta m_d \Delta t)
\]

where

\[
a^{(s)} = 2|\lambda^{(s)}| \sin(2\beta + \gamma) \cos\delta^{(s)},
\]

\[
b^{(s)} = 2|\lambda^{(s)}| \sin(2\beta + \gamma) \cos\delta^{(s)},
\]

\[
c_i^{(s)} = 2\cos(2\beta + \gamma) \left( |\lambda^{(s)}| \sin\delta^{(s)} - |\lambda_i^{(s)}| \sin\delta^{(s)} \right).
\]

The \( b \) and \( c \) parameters absorb the tag side interference effects while \( a \) is independent of them. The lepton tag category does not have doubly-CKM-suppressed amplitude contribution, therefore \( |\lambda^{(s)}| = 0 \).

3 \( B^0 \to D^{(*)} \pm \pi^\mp \) full reconstruction method

In the full reconstruction method [8], the final state \( B^0 \to D^{(*)} \pm \pi^\mp \) is completely reconstructed. The \( D^+ \) is reconstructed in its decay to \( D^0 \pi^+ \), where the \( D^0 \) subsequently decays to \( K^- \pi^+ \), \( \bar{K}^- \pi^+, \bar{K}^- \pi^- \pi^+ \) or \( K^0 \pi^+ \pi^- \). The \( D^- \) is reconstructed in \( K^- \pi^- \pi^+ \) or \( K^0 \pi^- \pi^- \). After selection, signal and background are discriminated by two kinematic variables: the beam energy substituted mass, \( m_{ES} \equiv \sqrt{\left( \sqrt{s}/2 \right)^2 - p_B^2} \) and the difference between the B candidate’s measured energy and the beam energy, \( \Delta E \equiv E_B - \left( \sqrt{s}/2 \right) \). \( E_B \) (\( p_B \)) is the energy (momentum) of the B candidate in the \( e^+e^- \) center-of-mass frame and \( \sqrt{s} \) is the total center-of-mass energy. This method provides a very clean signal selection, with a small background coming mainly from combinatorics. The remaining peaking is of the order of 1%. Based on an integrated luminosity of 81.9 \( \text{fb}^{-1} \) on the \( T(4S) \) resonance, the signal yield is \( 520 \pm 87 \) events with a 85% purity for \( B^0 \to D^+ \pi^- \) and \( 4746 \pm 78 \) events with a 94% purity for \( B^0 \to D^+ \pi^- \).

An unbinned maximum likelihood fit is performed on the selected candidates using the \( \Delta t \) distribution in Eq. 4 convoluted with a three-Gaussian resolution function and taking into account the probabilities of incorrect tagging. The results from the fit to the data including the systematic uncertainties summarized in Table 1 are:

\[
a = -0.022 \pm 0.038 (\text{stat}) \pm 0.021 (\text{syst}),
\]

\[
a^* = -0.065 \pm 0.038 (\text{stat}) \pm 0.021 (\text{syst}),
\]

\[
c_{\text{lep}} = 0.025 \pm 0.068 (\text{stat}) \pm 0.035 (\text{syst}),
\]

\[
c^*_{\text{lep}} = 0.031 \pm 0.070 (\text{stat}) \pm 0.035 (\text{syst}).
\]

These results can be interpreted in terms of \( \sin(2\beta + \gamma) \), \( \delta \) and \( \delta^* \) by minimizing the \( \chi^2 \)

\[
\chi^2 = \sum_i \left( \frac{x_i - x_i}{\sigma_i} \right)^2 + \chi^2(|\lambda|) + \chi^2(|\lambda^*|),
\]

where the \( x_i \) refers to the measured values for \( a^{(*)} \)

Table 1. Systematic uncertainties on \( a^{(*)} \) and \( c^{(*)} \) and the total uncertainty \( \sigma_{\text{tot}} \)

<table>
<thead>
<tr>
<th>Source</th>
<th>( \sigma_a )</th>
<th>( \sigma_{a^*} )</th>
<th>( \sigma_c )</th>
<th>( \sigma_{c^*} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertexing</td>
<td>0.015</td>
<td>0.026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tagging</td>
<td>0.004</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Background</td>
<td>0.001</td>
<td>0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fit</td>
<td>0.014</td>
<td>0.023</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total (\( \sigma_{\text{tot}} \)) | 0.021 | 0.035 |

\( c_{\text{lep}} \). The terms \( \chi^2(|\lambda|) \) and \( \chi^2(|\lambda^*|) \) are taking into account a 30% non-gaussian uncertainty on \( |\lambda^{(*)}| \). The \( \chi^2 \) is non-parabolic due to the limited physical range and to the large errors. A minimum of the \( \chi^2 \) is found for \( |\sin(2\beta + \gamma)| = 0.98 \). In order to give a frequentistic interpretation to this result, a large number of simulated experiments are performed with the same characteristics as the data and with different true values of \( \sin(2\beta + \gamma) \). The consistency of the data with a given value of \( \sin(2\beta + \gamma) \) is computed by counting the fraction of simulated experiments in which \( \chi^2(\sin(2\beta + \gamma)) - \chi^2_{\text{min}} \) is larger than in the data. The limit computed in this way is: \( |\sin(2\beta + \gamma)| > 0.69 \) at 68\% C.L. and the value: \( |\sin(2\beta + \gamma)| = 0 \) is excluded at 83\% C.L.

4 \( B^0 \to D^{(*)} \pm \pi^\mp \) partial reconstruction method

In the partial reconstruction method [9], only the \( B^0 \to D^{(*)} \pm \pi^\mp \) decay channel is considered. Only the hard pion track from the \( B^0 \) decay and the soft pion track from the decay \( D^{(*)} \to D^0 \pi \) are reconstructed. Using the two pions and kinematic constraints, a missing mass variable is computed. In this variable, signal events peak at the nominal \( D^0 \) mass with a spread of about 3 MeV/c^2, while the distribution of the combinatoric background is significantly broader. The background is mainly coming from combinatorics and from \( B^0 \to D^{(*)} \rho \). The statistics is larger than for the full reconstruction method: \( 6409 \pm 129 \) events with a lepton tag and \( 25157 \pm 323 \) events with a kaon tag for the \( T(4S) \) resonance.

In order to compute the time difference \( \Delta t \) the \( B^0 \to D^{(*)} \pm \pi^\mp \) decay position along the beam axis is estimated by fitting the hard pion track with a beam spot constraint in the plane perpendicular to the beams. The typical \( \Delta t \) resolution is \( \sim 1 \) ps.
The analysis is carried out with a series of unbinned maximum likelihood fits performed simultaneously on the on- and off-resonance data samples and independently for the lepton-tagged and kaon-tagged events. The parameters \( S_+ \) and \( S_- \) from Eq. 1 are extracted from the lepton tags while \( a \), \( b \) and \( c \) of Eq. 4 are determined from kaon tags. Combining both tagging categories:

\[
\begin{align*}
    a &= -0.063 \pm 0.024\text{(stat)} \pm 0.017\text{(syst)} \\
    c_{\text{lep}} &= -0.004 \pm 0.037\text{(stat)} \pm 0.020\text{(syst)}.
\end{align*}
\]

The systematic uncertainties are summarized in Table 2.

A \( \chi^2 \) similar to Eq. 8 is minimized and a probabilistic interpretation of the result identical to the one exposed in section 3 allows to give the following limits on \( |\sin(2\beta + \gamma)| \), assuming a 30% non-gaussian error on \(|\lambda|\):

\[
|\sin(2\beta + \gamma)| > 0.88 \text{ at 68% C.L.} \quad |\sin(2\beta + \gamma)| > 0.75 \text{ at 90% C.L.} \quad |\sin(2\beta + \gamma)| > 0.62 \text{ at 95% C.L.}
\]

and the value \( |\sin(2\beta + \gamma)| = 0 \) is excluded at 98.3% C.L.

### Table 2. Systematic uncertainties on \( S_- \), \( S_+ \), \( a \), \( b \) and \( c^{(s)} \) and the total uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>( S_- )</th>
<th>( S_+ )</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>3.0</td>
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<td>5.0</td>
<td>4.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Bkg CP content</td>
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<td>10.0</td>
<td>13.0</td>
<td>7.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Fit</td>
<td>5.0</td>
<td>7.0</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Detector</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>6.0</td>
<td>10.0</td>
</tr>
<tr>
<td>MC stat</td>
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<td>13.0</td>
<td>8.0</td>
<td>4.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Total</td>
<td>20.0</td>
<td>21.0</td>
<td>19.0</td>
<td>11.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

### 5 Combined results

The results from the full reconstruction and the partial reconstruction method are combined and give the following limits:

\[
|\sin(2\beta + \gamma)| > 0.89 \text{ at 68% C.L.} \quad |\sin(2\beta + \gamma)| > 0.76 \text{ at 90% C.L.} \quad |\sin(2\beta + \gamma)| = 0 \text{ is excluded at 99.5% C.L.}
\]

As there is a large theoretical uncertainty on the value of \( |\lambda^{(v)}| \), the lower limit on \( |\sin(2\beta + \gamma)| \) is plotted in Fig. 1 as a function of \( r = |\lambda| \) for various values of the confidence level. In this case \( r = |\lambda| \) and \( |\lambda^*| \) are assumed to be equal.

### 6 Status of \( B^0 \to D^{(*)}\pm \pi^\mp \) in Belle

The Belle experiment is performing similar studies on \( B^0 \to D^{(*)}\pi \). For the partial reconstruction technique, with 78 fb\(^{-1}\) of data and including background effect, the expected statistical uncertainty on \( 2|\lambda|\sin(2\beta + \gamma) \) is equal to \( \pm 0.029 \). For the full reconstruction method, with the complete data sample available this summer, estimated from a Monte-Carlo simulation study and not taking into account background effect, the statistical uncertainty on \( 2|\lambda|\sin(2\beta + \gamma) \) is equal to \( \pm 0.028 \).

### References

8. The BABAR Collaboration, B. Aubert et al., SLAC-PUB-10103, hep-ex/0308018.