Recent BaBar results on CP Violation in B decays

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Abstract.
In this talk I will review two recent results of CP Violation in B decay analyses obtained by the BaBar experiment. Using the full data set and the partial reconstruction of the D meson, BaBar has measured the CPV parameters in the $B^0 \rightarrow D^{*+}D^{*-}$ decay and in the semileptonic decay $B^0 \rightarrow D^{*+}\ell^-\bar{\nu}_\ell$.

1. Introduction
The BaBar experiment has accumulated almost 500 millions of $B\bar{B}$ pairs at the $\Upsilon(4S)$ energy during its operation time, in addition to a similar quantity of charm and tau pairs, and millions of events at lower resonances. Due to the asymmetric beam energies, B decays from the boosted $\Upsilon(4S)$ are separated about 260$\mu$m along the z axis, allowing to perform time dependent analyses and measure CP violation effects. CP violation in B decays can be manifested itself in three different ways: CP violation in decay (the so-called Direct CPV), CP violation in mixing, the probability of a $B^0$ meson to oscillate into a $B^0$ meson being different to the probability of a $B^0$ meson to oscillate into a $B^0$ meson, and then the flavour mixing amplitude, the ratio $|q/p|$, is different from unity. And the last type of CP violation which happens in the interference between mixing and decay, when a same final state can be reached by both the $B^0$ and $B^0$ mesons, and the time dependent amplitudes are different.

2. CP Violation in $B^0 \rightarrow D^{*+}D^{*-}$ decays
BaBar has measured the CP violation effects in the decay of $B^0$ mesons into $D^{*+}D^{*-}$ pairs [1]. This study is motivated by the fact that in Cabibbo suppressed $b \rightarrow (c\bar{c})d$ transitions (as $B^0 \rightarrow D^{*+}D^{*-}$) the color allowed tree amplitude gets a small contribution from penguin diagrams and the time dependent CPV asymmetry is a measure of $\sin(2\beta)$ (as it is for $B \rightarrow J/\Psi K$ in $b \rightarrow (c\bar{c})s$ transitions). According to models based on factorization and heavy quark symmetry, penguin contributions are expected to lead a few % corrections [2]. Large deviations in the measurement of $\sin(2\beta)$ from $b \rightarrow (c\bar{c})s$ and $b \rightarrow (c\bar{c})d$ transitions (i.e., from B decays into $J/\Psi K$ and $D^{*+}D^{*-}$ final states) would imply a sign of New Physics [3].

In $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ events, the time-dependent decay rate for $B^0 \rightarrow D^{*+}D^{*-}$ is given by

$$P_{\eta}^{Stag}(\Delta t) = e^{-|\Delta t|/\tau_b} \cdot \left[ 1 + S_{l_{stag}} S_\eta \sin(\Delta m_d \Delta t) + S_{stag} C \cos(\Delta m_d \Delta t) \right],$$

(1)
where $\tau_0$ is the $B^0$ lifetime averaged over the two mass eigenstates, $\Delta m_d$ is the $B^0 \bar{B}^0$ mixing frequency, and $\Delta t$ is the time interval between the $B^0 \rightarrow D^{**}$$D^{*-}$ decay ($B_{\rm rec}$) and the decay of the other $B$ ($B_{\rm tag}$) in the event. The parameter $S_{\rm tag} = +1$ ($-1$) indicates the flavor of the $B_{\rm tag}$ as a $B^0$ ($\bar{B}^0$), while $\eta = \pm 1$ indicates the $CP$ eigenvalue of the $B^0 \rightarrow D^{**}$$D^{*-}$ final state. The parameters $C$ and $S_\eta$ are given by

$$C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}; \quad S_\eta = -\frac{2\Re m(\lambda)}{1 + |\lambda|^2}; \quad \lambda = \frac{q}{p} A \; ,$$

where $A$ ($\bar{A}$) is the matrix element of the $B^0$ ($\bar{B}^0$) decay and $p$ and $q$ are the coefficients appearing in the expression of the physical mass eigenstates $B_L$, $B_H$ in terms of the flavour eigenstates $B$, $\bar{B}$:

$$|B_L\rangle = p|B\rangle + q|\bar{B}\rangle$$

$$|B_H\rangle = p|B\rangle - q|\bar{B}\rangle \; .$$

Since the $B^0 \rightarrow D^{**}$$D^{*-}$ is the decay of a scalar to two vector mesons, the final state is a mixture of $CP$ eigenstates. The $CP$-odd and $CP$-even fractions have been previously measured from the angular analysis of completely reconstructed events by both BaBar and Belle experiments [4, 5].

A new analysis has been performed by BaBar using a partial reconstruction technique of the $B^0 \rightarrow D^{**}$$D^{*-}$ decay. This method has the advantage of 5 times more statistics as compared to previous analyses using full reconstruction, corresponding to an almost independent data sample. Nevertheless this technique has the penalty of higher background, leading to larger systematic uncertainties. Using 429 $fb^{-1}$ on-peak $Y(4S)$ BaBar data and 45$fb^{-1}$ off-peak data (the latter for background studies) B mesons are tagged with a lepton or a kaon that gives the flavour of one of the B mesons (called 'lepton-tag' or 'kaon-tag' respectively). The other B meson is partially reconstructed into $D^{**}$$D^{*-}$. One of the $D^*$ is completely reconstructed into $D^0\pi$, with the $D^0$ in one of the four modes $K\pi$, $K\pi\pi^0$, $K3\pi$ or $K_\pi\pi$. The fully reconstructed $D^*$ is then matched with a soft pion of opposite sign expected to come from the other $D^*$ meson. Signal candidates are selected if the kinematics is consistent with a $B^0$ decaying into a $D^* - D^0\pi$ combination with a missing $D^0$. Two unbinned maximum likelihood fits are then performed. One kinematic fit using two variables: the recoiling mass, $m_{\rm rec}$, which is the mass of the non-reconstructed $D^0$ meson and peaks at the $D^0$ mass for signal events; and a Fisher discriminant variable based on the event shape. The background sources are combinatorial background (the distributions are extracted from a wrong sign $D^* +$ soft $\pi$ data sample), light quarks from continuum (extracted from off-peak data) and a peaking $BB\bar{B}$ contribution which is taken from the simulation and it is found to be negligible. The results of the fit gives the signal fraction and the shape of the signal and background probability density functions (PDFs). They are shown in Figure 1. It gives $3843 \pm 397$ and $1129 \pm 218$ signal events for kaon and lepton tags respectively.

The result of the kinematic fit is kept and followed by a time dependent fit, which uses information of $m_{\rm rec}$ and the fisher variable but now including the time dependent function. The $\Delta t$ variable is reconstructed from the two B meson decay vertices (one from the reconstructed $D^*$, the other from the lepton or the kaon tag, making use of the beam spot constraint). The time dependent PDFs are convoluted with a resolution function. The result of the fit are the $CP$ parameters, the background and signal models, and the mistag probabilities. Mistag probabilities are about 20% and 10% for the kaon and lepton tags, respectively. The additional dilution due to tagging tracks from missing $D^0$ mesons is reduced by applying a constraint around the $D^0$ direction, obtained from data with some input from simulation (it accounts 12% for the kaon tag). The main systematic uncertainties in the analysis are related to the kinematic fit parameters, tagging dilution and interference with double Cabibbo-suppressed (DCS) decays.
Figure 1. Result of the kinematic fit of kaons (top) and lepton (bottom) tagged events, for the reconstructed mass (left plots) and the fisher variable (right plots). The total PDF (solid line), signal (dotted red line) and total background (short-dashed line) (consisted mainly of combinatorial background (dashed line) and continuum (dot-dashed line)) are superimposed.

The result of the time dependent fit is shown in Figure 2 with the time-dependent raw $CP$ asymmetry:

$$A(\Delta t) = \frac{N_{S_{tag}=1}(\Delta t) - N_{S_{tag}=-1}(\Delta t)}{N_{S_{tag}=1}(\Delta t) + N_{S_{tag}=-1}(\Delta t)}$$

(3)

The combined result for lepton and kaon tags of the CP parameters $S$ and $C$ is

Figure 2. Result of the time dependent fit for kaons (left) and lepton (right) tagged events. $B^0$ (dashed) and $\bar{B}^0$ (solid) events. Signal PDFs are superimposed in red. Only data in the $m_{rec} > 1.860$ GeV/c$^2$ are shown in these plots.

$C = +0.15 \pm 0.09 \pm 0.04$ and $S = -0.34 \pm 0.12 \pm 0.05$. 
Considering the dilution by the $CP$-odd component, $S=S_{*}(1-2R_{\perp})$, and taking $R_{\perp}$ from a previous BaBar result \[4\]: $C_{*}=-0.15\pm0.09\pm0.04$ and $S_{*}=-0.49\pm0.18\pm0.07\pm0.04$. Results are compatible with BaBar and Belle measurements and with the Standard Model predictions.

3. CPV in $B^{0}\to D^{*}\ell\nu$

The BaBar experiment has also performed a measurement of the CP violation parameters in the B semileptonic decay $B^{0}\to D^{*}\ell\nu$. If $CP$ is violated in mixing, the probability of a $B^{0}$ to oscillate to a $\bar{B}^{0}$ is different from the probability of a $B^{0}$ to oscillate to a $B^{0}$ and thus we expect to observe a sizable value for the asymmetry:

$$A_{CP} = \frac{N(B^{0}\to\bar{B}^{0}) - N(\bar{B}^{0}\to B^{0})}{N(B^{0}B^{0}) + N(\bar{B}^{0}\to\bar{B}^{0})} \approx 2\delta_{CP}. \quad (4)$$

where $\delta_{CP} = 1 - |q/p|$. Any deviation from unity of the ratio $|q/p|$ implies $CP$ violation in mixing. The Standard Model prediction is $A_{CP} = -(4.1 \pm 0.6) \times 10^{-4}$ \[6\]. A large deviation from $\delta_{CP} = 1$ would be therefore a clear evidence of New Physics beyond the Standard Model.

The semileptonic asymmetry $A_{SL}$ measured at flavour experiments can also be expressed as:

$$A_{SL} = \frac{N(\bar{B}^{0}\to B^{0}\to \ell^{+}X) - N(B^{0}\to \bar{B}^{0}\to \ell^{-}X)}{N(B^{0}\to B^{0}\to \ell^{+}X) + N(B^{0}\to \bar{B}^{0}\to \ell^{-}X)}. \quad (5)$$

A large deviation from expectations in $A_{SL}$ ($4\sigma$) has been observed by the D0 experiment at Fermilab using same sign dimuon events \[7\], which could be attributed to $B_{s}$ oscillations. Results of the Heavy Flavour Averaging Group from CLEO, BaBar, Belle, D0 and LHCb data gives $A_{SL} = -0.0003 \pm 0.0021$ for the $B_{s}$ system, and $|q/p| = 1.0002 \pm 0.0011$ \[8\].

A new measurement of $A_{SL}$ has been performed by BaBar using partial reconstruction of $B^{0}\to D^{*}\ell\nu$ and kaon tags. Using $428fb^{-1}$ on-peak $\Upsilon(4S)$ data and $45fb^{-1}$ off-peak data (the latter for background studies). In this analysis one B meson is partially reconstructed in the semileptonic channel by selecting a lepton plus the soft pion from the $D^{*}$ decay into $D^{0}\pi$. The flavour of the other B meson is obtained using a kaon tag. When mixing occurs the lepton from one B and the kaon tag have the same charge, and the semileptonic asymmetry is defined as:

$$A_{SL} = \frac{N(\ell^{+}K^{+}_T) - N(\ell^{-}K^{-}_T)}{N(\ell^{+}K^{+}_T) + N(\ell^{-}K^{-}_T)}. \quad (6)$$

In practice there are two kaon tag categories: when the kaon is coming from the B meson ($B_{tag}$) and when the kaon comes from a Cabibbo Favoured $D^{0}$ decay ($D_{tag}$), giving also a same charge combination of the lepton and kaon. The information of the decay vertex distance, $\Delta z$, which is the difference between the reconstructed and tagged vertex, and the cosine of the angle defined by the kaon and the lepton tracks, are used to separate these two categories. The asymmetry observed in the $B_{tag}$ and $D_{tag}$ samples has contributions from the semileptonic asymmetry $A_{SL}$ and from the reconstruction and tagging asymmetries:

$$A(B_{tag}) = A_{rec} + A_{tag} + A_{SL} \quad (7)$$

$$A(D_{tag}) = A_{rec} + A_{tag} + \chi_{d}A_{SL} \quad (8)$$

$\chi_{d}$ being the integrated mixing probability for $B^{0}$ mesons. The $D_{tag}$ contribution is the main source of background in this analysis but it is useful to disentangle physical and detector charge effects.

Combinatorial and continuum backgrounds are suppressed using event shape variables and the vertex probability of the $\ell\pi$ vertex. The signal is selected using the missing mass squared.
variable: \( \mathcal{M}_\nu^2 \equiv (E_{\text{beam}} - E_{D^*} - E_t)^2 - (\vec{p}_{D^*} + \vec{p}_t)^2 \), assuming that the B meson is at rest and that the D* direction is the one from the soft pion. The number of signal events is obtained with a minimum \( \chi^2 \) fit to the \( \mathcal{M}_\nu^2 \) distribution in the interval \(-10 < \mathcal{M}_\nu^2 < 2.5 \text{ GeV}^2/c^4\). D*, D** and combinatorial backgrounds are floated in the fit, using simulated distributions. The continuum background is fixed from off-peak data, and the small peaking background contribution is taken from the simulation. A total of \((5945 \pm 7) \cdot 10^3\) events are selected in the signal region, which is about 30% of the total sample. The result of the fit is displayed in Figure 3.

Figure 3. \( \mathcal{M}_\nu^2 \) distribution for the data (points with error bars), and the fitted contributions from the various sample components.

The \(|q/p|\) parameter is obtained from an extended maximum likelihood binned fit to the \( \Delta t \) and \( \cos \theta_{K\ell} \) distributions of the unmixed (with different charge for the lepton and the kaon) and mixed (with the same charge for the lepton and the kaon) subsamples. The time dependent decay rate for the mixed and unmixed samples are described in terms of the average width of the two \( B^0 \) mass eigenstates, \( \Gamma_0 \), and the width difference \( \Delta \Gamma \). Several parameters are introduced to take into account the interference between Cabibbo Favoured and Double Cabibbo suppressed decays on the tag side. The theoretical distributions have to be convoluted with the resolution function. Mistag probabilities have to be taken into account, which are different for the \( B_{tag} \) and for the reconstructed B meson. The tagging and reconstruction asymmetries are disentangled using the \( D_{tag} \) sample. The result of the fit are shown in Figures 4 and 5, for the \( \Delta t \) and \( \cos \theta_{K\ell} \) projections, for the mixed and unmixed samples. Signal and background contributions are shown in the figures. The raw asymmetry as function of \( \Delta t \) is also shown in Figure 4.

The result of the fit gives the value of \(|q/p| - 1 = 0.29 \pm 0.84^{+1.68}_{-1.78} \cdot 10^{-5}\) (which is kept blinded until the analysis is completed, including systematic uncertainties) and parameters describing signal and background events. The main systematic in the analysis is coming from the sample composition. The semileptonic asymmetry results in the value: \( A_{CP} = 0.06 \pm 0.17^{+0.36}_{-0.32} \), which is compatible with previous results from B factories and with Standard Model predictions.
4. More BaBar results on CPV

Other recent results from BaBar not covered in this talk concern the measurement of the CKM angles $\alpha$ [9] and $\gamma$ [10].

5. Summary

New precise measurements on CP violation in B decays using a partial reconstruction technique have been performed by the BaBar experiment. The CPV parameters $C_+$ and $S_+$ have been obtained from partial reconstruction of $B^0 \to D^{\ast+}D^{\ast-}$, and the $\delta_{CP}$ parameter and the semileptonic asymmetry $A_{SL}$ have been measured from partial reconstruction of $B^0 \to D^*\ell\nu$ events. Results are in agreement with other measurements from B-factories and with Standard Model predictions.

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Figure 5. $\cos\theta_{\ell K}$ distribution for the data (points with error bars) and the fitted contributions from the various sample components.

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