BABAR status and prospects for CP asymmetry measurements: $\sin(2\beta + \gamma)$

S. Ganzhur*

DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France

The recent experimental results on CP violation related to the angles of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle $2\beta + \gamma$ are summarized in these proceedings. These results are obtained with approximately 232 million $\Upsilon(4S) \to B\overline{B}$ events collected with the BABAR detector at the PEP-II asymmetric-energy B-factory at SLAC. Using the measurements on time-dependent CP asymmetries in $B^0 \to D^{(*)\mp}\pi^{\pm}$ and $B^0 \to D^{\mp}\rho^{\pm}$ decays and theoretical assumptions, one finds $|\sin(2\beta + \gamma)| > 0.64\ (0.40)$ at 68% (90%) confidence level. The perspectives of $\sin(2\beta + \gamma)$ measurement with $\overline{B}^0 \to D^{(*)0}\bar{K}^{(*)0}$ and $B^0 \to D^{(*)\mp}a_{0(2)}^{\pm}$ decay channels are also discussed.

Introductoin

A crucial part of the CP violation program in B-factories is the measurement of the angle $\gamma(\phi_3) = \arg\left(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right)$ of the unitary triangle related to the CKM matrix [1]. Decays of B_d mesons that allows one to constraint the CKM angle $2\beta + \gamma$, have either small CP asymmetry ($B \to D^{(*)}\pi$) or small branching fractions ($B \to D^{(*)}K^{(*)}$). This makes the CP violation effect hard to measure. Furthermore, due to presence of two hadronic parameters in the observables (r and δ, the amplitude ratio and the strong phase difference between two amplitudes) it is difficult to cleanly extract the weak phase information, although approaches based on SU(3) symmetry exists.

I. THE BABAR DETECTOR AND DATASET

The data used in the presented analyzes were recorded with the BABAR detector at the PEP-II asymmetric-energy storage rings, and consist of 211 fb^{-1} collected on the $\Upsilon(4S)$ resonance (on-resonance sample), and 21 fb^{-1} collected at an e^+e^- center-of-mass (CM) energy approximately 40 MeV below the resonance peak (off-resonance sample). This corresponds to approximately 232 million $\Upsilon(4S) \to B\overline{B}$ recorded events.

The BABAR detector is described in detail in Ref. [2].

II. CP ASYMMETRY IN $B^0 \to D^{(*)\mp}\pi^{\pm}/\rho^{\pm}$ DECAYS

The decay modes $B^0 \to D^{(*)\mp}\pi^{\pm}$ have been proposed to measure $\sin(2\beta + \gamma)$ [3]. In the Standard Model the decays $B^0 \to D^{(*)+}\pi^-$ and $\overline{B}^0 \to D^{(*)+}\pi^-$ proceed through the $\overline{b} \to \overline{u}cd$ and $b \to c$ amplitudes A_u and A_c, respectively. The relative weak phase between these two amplitudes is γ. When combined with $B^0\overline{B}^0$ mixing,

this yields a weak phase difference of $2\beta + \gamma$ between the interfering amplitudes.

The decay rate distribution for $B \to D^{(*)\pm}\pi^{\mp}$ is

$$P_\eta^{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times \left[1 \mp S^{\zeta}\sin(\Delta m\Delta t) \mp \eta C\cos(\Delta m\Delta t)\right], \qquad (1)$$

where τ is the B^0 lifetime averaged over the two mass eigenstates, Δm is the $B^0 - \overline{B}^0$ mixing frequency, and Δt is the difference between the time of the $B \to D^{(*)\pm}\pi^{\mp}$ (B_{rec}) decay and the decay of the other B (B_{tag}) in the event. The upper (lower) sign in Eq. 1 indicates the flavor of the B_{tag} as a B^0 ($\overline{B}^0$), while $\eta = +1\ (-1)$ and $\zeta = +$ $(-)$ for the B_{rec} final state $D^{(*)-}\pi^+$ ($D^{(*)+}\pi^-$). The parameters C and $S^{\pm}$ are given by

$$C \equiv \frac{1 - r^2}{1 + r^2}, \qquad S^{\pm} \equiv \frac{2r}{1 + r^2}\sin(2\beta + \gamma \pm \delta). \qquad (2)$$

Here δ is the strong phase difference between A_u and A_c and $r \equiv |A_u/A_c|$. Since A_u is doubly CKM-suppressed with respect to A_c, one expects r to be small of order 2%. Due to the small value of r, large data samples are required for a statistically significant measurement of S.

Since the expected CP asymmetry in the selected B decays is small, this measurement is sensitive to the interference between the $b \to u$ and $b \to c$ amplitudes in the decay of B_{tag}. To account for this "tagside interference", we use a parametrization which is described in Ref. [4]. The $S^{\pm}$ coefficient are replaced with three others

$$\begin{aligned}
a &= 2r\sin(2\beta + \gamma)\cos\delta \\
b &= 2r'\sin(2\beta + \gamma)\cos\delta' \\
c &= 2\cos(2\beta + \gamma)(r\sin\delta - r'\sin\delta')
\end{aligned} \qquad (3)$$

For each tagging category, independent of the decay mode $\{D\pi, D^*\pi, D\rho\}$, the tagside interference is parametrized in terms of the effective parameters r' and δ'. One notes, $r' = 0$ for the lepton tagging category.

Two different analysis techniques, full reconstruction [5] and partial reconstruction [6] were used for the $\sin(2\beta + \gamma)$ measurement with $B^0 \to D^{(*)\mp}\pi^{\pm}$.

The full reconstruction technique is used to measure the CP asymmetry in $B^0 \to D^{(*)\mp}\pi^{\pm}$ and $B^0 \to D^{*\mp}\rho^{\pm}$

*Electronic address: ganzhur@cea.fr

decays [7]. From a time-dependent maximum likelihood fit the following parameters related to the CP violation angle $2\beta+\gamma$ are obtained:

$$\begin{aligned}
a^{D\pi} &= -0.010 \pm 0.023 \pm 0.007 \\
c_{\mathrm{lep}}^{D\pi} &= -0.033 \pm 0.042 \pm 0.012 \\
a^{D^*\pi} &= -0.040 \pm 0.023 \pm 0.010 \\
c_{\mathrm{lep}}^{D^*\pi} &= 0.049 \pm 0.042 \pm 0.015 \\
a^{D\rho} &= -0.024 \pm 0.031 \pm 0.009 \\
c_{\mathrm{lep}}^{D\rho} &= -0.098 \pm 0.055 \pm 0.018
\end{aligned} \qquad (4)$$

where the first error is statistical and the second is systematic. The systematic error for $B^0 \to D^{*\mp}\rho^{\pm}$ includes the maximum bias of asymmetry parameters due to possible dependence of r on the $\pi\pi^0$ invariant mass. For the measurement of $2r\cos(2\beta+\gamma)\sin\delta$ parameter only the lepton-tagged events are used due to a presence of tag-side CP violation effect [4].
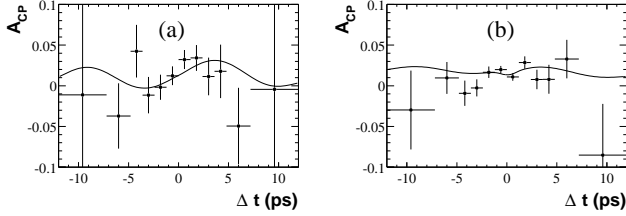

FIG. 1: Raw asymmetry for (a) lepton-tagged and (b) kaon-tagged events of $B^0 \to D^{*\mp}\pi^{\pm}$ decay mode using the method of the partial reconstruction. The curves represent the projections of the PDF for the raw asymmetry.

In the partial reconstruction of a $B^0 \to D^{*\mp}\pi^{\pm}$ candidate, only the hard (high-momentum) pion track π_h from the B decay and the soft (low-momentum) pion track π_s from the decay $D^{*-} \to \overline{D}^0\pi_s^-$ are used. Applying kinematic constraints consistent with the signal decay mode, the four-momentum of the non-reconstructed, "missing" D is calculated. Signal events are peaked in the m_{miss} distribution at the nominal D^0 mass. This method eliminates the efficiency loss associated with the neutral D meson reconstruction. The CP asymmetry independent on the assumption on $r^{D^*\pi}(r^*)$ measured with this technique is [8]

$$\begin{aligned}
a^{D^*\pi} &= -0.034 \pm 0.014 \pm 0.009 \\
c_{\mathrm{lep}}^{D^*\pi} &= -0.019 \pm 0.022 \pm 0.013
\end{aligned} \qquad (5)$$

where the first error is statistical and the second is systematic. This measurement deviates from zero by 2.0 standard deviations. Figure 1 shows the raw, time-dependent CP asymmetry

$$A(\Delta t) = \frac{N_{B^0}(\Delta t) - N_{\overline{B}^0}(\Delta t)}{N_{B^0}(\Delta t) + N_{\overline{B}^0}(\Delta t)} \qquad (6)$$

In the absence of background and with high statistics, perfect tagging, and perfect Δt measurement,

$A(\Delta t)$ would be a sinusoidal oscillation with amplitude $2r\sin(2\beta+\gamma)\cos\delta$.

Two methods for interpreting these results in terms of constraints on $|\sin(2\beta+\gamma)|$ are used. Both methods involve minimizing a χ^2 function that is symmetric under the exchange $\sin(2\beta+\gamma) \to -\sin(2\beta+\gamma)$, and applying the method of Ref. [9]. In the first interpretation method, no assumption regarding the value of r^* is made. The resulting 95% lower limit for the mode $B^0 \to D^{*\mp}\pi^{\pm}$ is shown as a function of r^* in Figure 2. The second interpretation assumes that $r^{(*)}$ can be estimated from the Cabibbo angle, the ratio of branching fractions $\mathcal{B}(B^0 \to D^{(*)+}_s\pi^-)/\mathcal{B}(B^0 \to D^{(*)-}\pi^+)$, and the ratio of decay constants $f_{D^*}/f_{D^*_s}$. The confidence level as a function of $|\sin(2\beta+\gamma)|$ is shown in Figure 3. This method yields the lower limits $|\sin(2\beta+\gamma)| > 0.64\ (0.40)$ at 68% (90%) C.L.
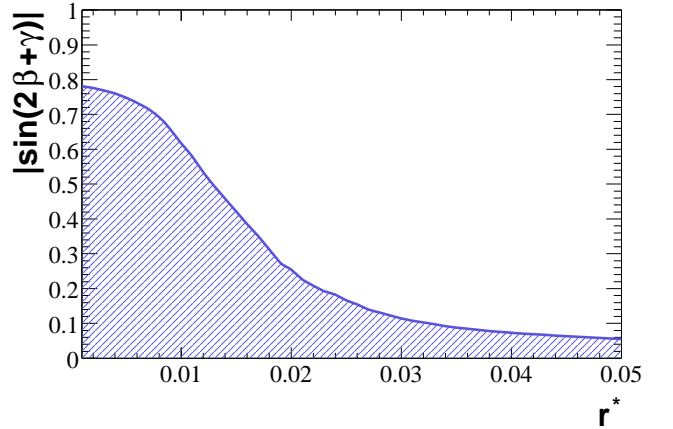

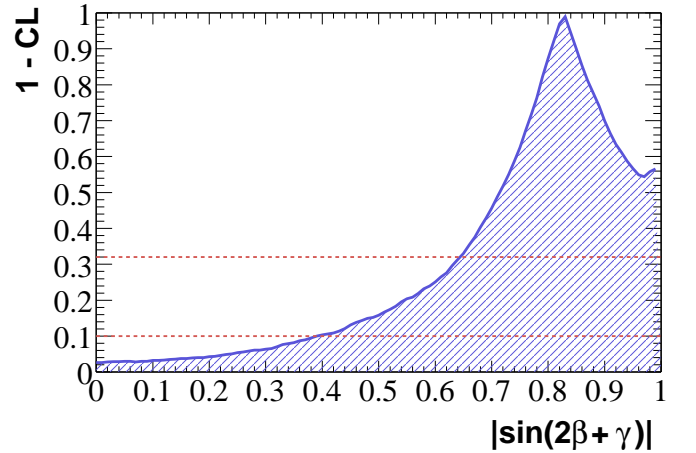FIG. 2: Lower limit on $|\sin(2\beta+\gamma)|$ at 90% CL as a function of $r^{(*)}$, for $r^{(*)} > 0.001$.

FIG. 3: The shaded region denotes the allowed range of $|\sin(2\beta+\gamma)|$ for each confidence level. The horizontal lines show, from top to bottom, the 68% and 90% CL.

III. $\overline{B}^0 \to D^{(*)0}\bar{K}^{(*)0}$ DECAYS

The decay modes $\overline{B}^0 \to D^{(*)0}\bar{K}^0$ have been proposed for determination of $\sin(2\beta + \gamma)$ from measurement of time-dependent CP asymmetries [10]. In the Standard Model the decays of B^0 and $\overline{B}^0$ mesons into final state $D^{(*)0}K_S^0$ proceed through the $b \to c$ and $\bar{b} \to \bar{u}$ amplitudes, respectively. Due to relatively large CP asymmetry ($r_B \equiv |A(\overline{B}^0 \to \bar{D}^{(*)0}\bar{K}^0)|/|\overline{B}^0 \to D^{(*)0}\bar{K}^0)| \simeq 0.4$) these decay channels look very attractive for such a measurement. Since the parameter r_B can be measured with sufficient data sample by fitting the C coefficient in time distributions, the measured asymmetry can be interpreted in terms of $\sin(2\beta + \gamma)$ without additional assumptions. However, the branching fractions of such decays are relatively small ($\sim 5 \cdot 10^{-5}$). That is way the large data sample is still required.

From the measured signal yields [11], we find

$$\begin{aligned}
\mathcal{B}(\overline{B}^0 \to D^0\bar{K}^0) &= (5.3 \pm 0.7 \pm 0.3) \times 10^{-5} \\
\mathcal{B}(\overline{B}^0 \to D^{*0}\bar{K}^0) &= (3.6 \pm 1.2 \pm 0.3) \times 10^{-5} \quad (7) \\
\mathcal{B}(\overline{B}^0 \to D^0\bar{K}^{*0}) &= (4.0 \pm 0.7 \pm 0.3) \times 10^{-5} \\
\mathcal{B}(\overline{B}^0 \to \bar{D}^0\bar{K}^{*0}) &< 1.1 \times 10^{-5} \text{ at 90\% C.L.}
\end{aligned}$$

where the uncertainties are statistical and systematic, respectively. Figure 4 shows the ΔE distributions of candidates with $|m_{\text{ES}} - 5280| < 8$ MeV/c^2 for the sums of the reconstructed D^0 decay modes.
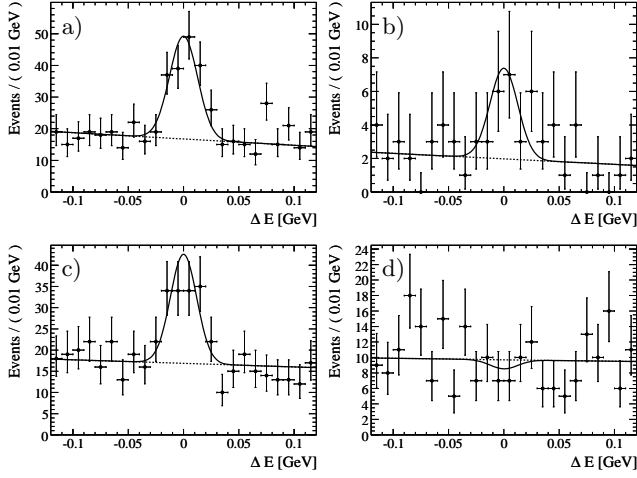

FIG. 4: Distribution of ΔE for a) $\overline{B}^0 \to D^0\bar{K}^0$, b) $\overline{B}^0 \to D^{*0}\bar{K}^0$, c) $\overline{B}^0 \to D^0\bar{K}^{*0}$, and d) $\overline{B}^0 \to \bar{D}^0\bar{K}^{*0}$ candidates with $|m_{\text{ES}} - 5280 \text{ MeV}/c^2| < 8$ MeV/c^2. The points are the data, the solid curve is the projection of the likelihood fit, and the dashed curve represents the background component.

The B decay dynamics can modify the expectation for the ratio r_B. The magnitude of this ratio can be probed by measuring the rate for the decays $\overline{B}^0 \to D^{(*)0}\bar{K}^{*0}$ and $\overline{B}^0 \to \bar{D}^{(*)0}\bar{K}^{*0}$ using the self-tagging decay $\bar{K}^{*0} \to K^-\pi^+$. The $\overline{B}^0 \to D^0\bar{K}^{*0}$ and $\overline{B}^0 \to \bar{D}^0\bar{K}^{*0}$ decays are distinguished by the correlation between the charges of

the kaons produced in the decays of the neutral D and the $\bar{K}^{*0}$. This charge correlation in the final state is diluted by the presence of the doubly-Cabibbo-suppressed decays $D^0 \to K^+\pi^-, K^+\pi^-\pi^0$, and $K^+\pi^-\pi^+\pi^-$. The ratio r_B is related to the experimental observable $\mathcal{R}$ defined for the $D^0 \to K^+\pi^-$ decay as

$$\begin{aligned}
\mathcal{R} &= \frac{\Gamma(\overline{B}^0 \to (K^+\pi^-)_D\bar{K}^{*0})}{\Gamma(\overline{B}^0 \to (K^-\pi^+)_D\bar{K}^{*0})} \\
&= r^{(*)2}_B + r_D^2 + 2r^{(*)}_B r_D \cos(\gamma + \delta), \quad (8)
\end{aligned}$$

where

$$r_D = \frac{|\mathcal{A}(D^0 \to K^+\pi^-)|}{|\mathcal{A}(D^0 \to K^-\pi^+)|}, \quad (9)$$

$$\delta = \delta_B + \delta_D, \quad (10)$$

and δ_B and δ_D are strong phase differences between the two B and D decay amplitudes, respectively. From the measured B branching fractions (Eq. 7), values of r_D [12] and Eq. 8, one obtains $r < 0.40$ at the 90% C.L. To conclude, the present signal yields combined with this limit on r suggest that a substantially larger data sample is needed for a competitive time-dependent measurement of $\sin(2\beta + \gamma)$ in $\overline{B}^0 \to D^{(*)0}\bar{K}^0$ decays.

IV. $B^0 \to D^{(*)\mp}a_{0(2)}^{\pm}$ DECAYS

Recently it was proposed to consider the $B^0 \to D^{(*)\mp}a_{0(2)}^{\pm}$ decays for measurement of $\sin(2\beta + \gamma)$ [13]. The decay amplitudes of B mesons to light scalar or tensor mesons such as a_0^+ or a_2^+, emitted from a weak current, are significantly suppressed due to the small decay constants $f_{a_{0(2)}}$. Thus, the absolute value of the CKM-suppressed and favored amplitudes become comparable. As a result, the CP asymmetry in such decays is expected to be large. However, the theoretical predictions of the branching fractions for $B^0 \to D^{(*)\mp}a_{0(2)}^{\pm}$ is expected of the order of $(1 \div 4) \cdot 10^{-6}$ [14]. The main uncertainty in the branching fractions of these decay modes is due to unknown $B \to a_{0(2)}X$ transition form factors. One way to verify the expectations and test a validity of the factorization approach is to measure the branching fractions for the more abundant decay modes $B^0 \to D_s^{(*)+}a_{0(2)}$.

Using a sample of about 230 million $\Upsilon(4S) \to B\overline{B}$ no evidence for these decays were observed [15]. This allowed one to set upper limits at 90% C.L. on the branching fractions to be

$$\begin{aligned}
\mathcal{B}(B^0 \to D_s^+a_0^-) &< 1.9 \cdot 10^{-5} \\
\mathcal{B}(B^0 \to D_s^+a_2^-) &< 1.9 \cdot 10^{-4} \quad (11) \\
\mathcal{B}(B^0 \to D_s^{*+}a_0^-) &< 3.6 \cdot 10^{-5} \\
\mathcal{B}(B^0 \to D_s^{*+}a_2^-) &< 2.0 \cdot 10^{-4}
\end{aligned}$$

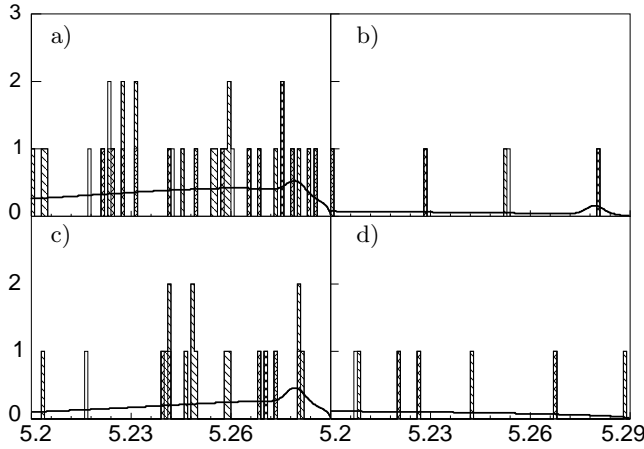Figure 5 shows the m_{ES} distributions for the reconstructed candidates $B^0 \to D_s^+a_0^-$, $B^0 \to D_s^+a_2^-$, $B^0 \to$

FIG. 5: Distributions of m_{ES} for a) $B^0 \to D_s^+ a_0^-$, b) $B^0 \to D_s^+ a_2^-$, c) $B^0 \to D_s^{*+} a_0^-$, d) $B^0 \to D_s^{*+} a_2^-$ candidates overlaid with the projection of the maximum likelihood fit. Contributions from the three D_s^+ decay modes are shown with different hatching styles: $\phi\pi^+$ is cross hatched, $\overline{K}^{*0}K^+$ is hatched, and $K_S^0 K^+$ is white.

$D_s^{*+}a_0^-$ and $B^0 \to D_s^{*+}a_2^-$. For each B decay mode, an unbinned maximum-likelihood fit is performed using the candidates from the three D_s^+ decay modes.

The upper limit value for $B^0 \to D_s^+ a_0^-$ is lower than the theoretical expectation, which might indicate the need to revisit the $B \to a_0 X$ transition form factor estimate. It might also imply the limited applicability of the factorization approach for this decay mode. The measured upper limits suggest that the branching ratios of $B^0 \to D^{(*)+}a_{0(2)}^-$ are too small for CP-asymmetry mea-

surements given the present statistics of the B-factories. The measurement of $\sin(2\beta + \gamma)$ in $B^0 \to D^{(*)+}a_{0(2)}^-$ decays is an interesting program for the future experiments such as Super$B$-factories.

Conclusion

The substantial constraint on the CKM angles $2\beta + \gamma$ comes from the measurements of time-dependent CP asymmetry in the $B^0 \to D^{(*)\mp}\pi^\pm$ and $B^0 \to D^\mp\rho^\pm$ decays. The BABAR experiment has used two techniques such as full and partial reconstruction to increase the signal yields in the $D^{*\mp}\pi^\pm$ channel. The combined BABAR and BELLE results [16] for CP violation in the most precisely measured decay channel $D^{*\mp}\pi^\pm$ is

$$a^{D^*\pi} = 2r^* \sin(2\beta + \gamma)\cos\delta = -0.037 \pm 0.011 \quad (12)$$

This measurement performed at the level of one per cent deviates from zero by 3.4 standard deviations. Future updates are therefore of a great interest. We interpret the BABAR result in terms of $\sin(2\beta + \gamma)$ and find $|\sin(2\beta + \gamma)| > 0.64$ (0.40) at 68% (90%) C.L. using a frequentist method.

The BABAR experiment has measured the branching fractions of $\overline{B}^0 \to D^{(*)0}\overline{K}^{(*)0}$ and set up the limit on $B^0 \to D^{(*)\mp}a_{0(2)}^\pm$ decays. The present signal yields and established limits suggest that a substantially larger data sample is needed for a competitive time-dependent measurement of $\sin(2\beta + \gamma)$ with these decay channels.

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