

Measurement of CP -Asymmetries for the Decays $B^\pm \rightarrow D_{CP}^0 K^{*\pm}$ with the BABAR Detector

The BABAR Collaboration

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Abstract

Using a sample of 227 million $\Upsilon(4S) \rightarrow B\bar{B}$ events collected with the BABAR detector at the PEP-II B Factory in 1999–2004, we study $B^- \rightarrow D^0 K^* (892)^-$ decays where $K^{*-} \rightarrow K_S^0 \pi^-$ and $D^0 \rightarrow K^- \pi^+, K^- \pi^+ \pi^0, K^- \pi^+ \pi^+ \pi^-$ (non- CP final states), $K^+ K^-, \pi^+ \pi^-$ ($CP+$ eigenstates), $K_S^0 \pi^0, K_S^0 \phi$ and $K_S^0 \omega$ ($CP-$ eigenstates). The partial rate charge asymmetries \mathcal{A}_{CP} and the ratios \mathcal{R}_{CP} defined in the literature as the sum of the B^+ and B^- partial rates to a charged K^* and a D^0 CP -eigenstate divided by the $B \rightarrow D^0 K^*$ decay rate, are sensitive to the angle γ of the CKM unitarity triangle. We measure:

$$\begin{aligned}\mathcal{A}_{CP+} &= -0.09 \pm 0.20(stat.) \pm 0.06(syst.) \\ \mathcal{A}_{CP-} &= -0.33 \pm 0.34(stat.) \pm 0.10(syst.) (+1.15 \pm 0.12) \cdot (\mathcal{A}_{CP-} - \mathcal{A}_{CP+}) \\ \mathcal{R}_{CP+} &= +1.77 \pm 0.37(stat.) \pm 0.12(syst.) \\ \mathcal{R}_{CP-} &= +0.76 \pm 0.29(stat.) \pm 0.06(syst.) \pm_{0.14}^{0.04}\end{aligned}$$

The third uncertainty quoted for the $CP-$ measurements reflects possible interference effects in the final states with ϕ and ω resonances. All results are preliminary.

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1 INTRODUCTION

The measurement of CP violation in B meson decays offers the means to over-constrain the unitarity triangle. A theoretically clean measurement of the angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ is provided by the $B^- \rightarrow D^{(*)0} K^{*-}$ [1] decay channels in which the favoured $b \rightarrow c\bar{u}s$ and suppressed $b \rightarrow u\bar{c}s$ penguin-less processes interfere [2]. In this paper we implement the method proposed by Gronau, Wyler and London by looking at the interference between $B^- \rightarrow D^0 K^{*-}$ and $B^- \rightarrow \bar{D}^0 K^{*-}$ when both D^0 and \bar{D}^0 decay to a CP eigenstate.

We define [3]:

$$\mathcal{A}_{CP\pm} = \frac{\Gamma(B^- \rightarrow D_{CP\pm}^0 K^{*-}) - \Gamma(B^+ \rightarrow D_{CP\pm}^0 K^{*+})}{\Gamma(B^- \rightarrow D_{CP\pm}^0 K^{*-}) + \Gamma(B^+ \rightarrow D_{CP\pm}^0 K^{*+})}, \quad (1)$$

$$\mathcal{R}_{CP\pm} = \frac{\Gamma(B^- \rightarrow D_{CP\pm}^0 K^{*-}) + \Gamma(B^+ \rightarrow D_{CP\pm}^0 K^{*+})}{\Gamma(B^- \rightarrow D^0 K^{*-})}. \quad (2)$$

$\mathcal{A}_{CP\pm}$ are the direct CP -violating asymmetries associated to each D^0 CP eigenstate. $\mathcal{R}_{CP\pm}$ is twice the ratio of the charge-averaged branching fraction of the $B \rightarrow D^0_{CP\pm} K^*$ decays to that of $B^- \rightarrow D^0 K^{*-}$. The latter branching fraction has been measured previously by BABAR [4], CLEO [5] and Belle [6]. These measurements average to $(5.7 \pm 0.6) \cdot 10^{-4}$. Both $\mathcal{A}_{CP\pm}$ and $\mathcal{R}_{CP\pm}$ carry CP -violating information. Neglecting D^0 - \bar{D}^0 mixing:

$$\mathcal{R}_{CP\pm} = 1 \pm 2r_B \cos \delta \cos \gamma + r_B^2 \quad (3)$$

$$\mathcal{A}_{CP\pm} \times \mathcal{R}_{CP\pm} = \pm 2r_B \sin \delta \sin \gamma \quad (4)$$

where δ is the CP -conserving strong phase phase difference between the $B^- \rightarrow D^0 K^{*-}$ (favoured B decay) and $B^- \rightarrow \bar{D}^0 K^{*-}$ (suppressed) amplitudes, γ is the CP -violating weak phase difference in the same processes and $r_B \simeq 0.1$ - 0.3 is the magnitude of the ratio of the amplitudes [3].

2 THE BABAR DETECTOR AND DATASET

We look for $B^- \rightarrow D_{CP}^0 K^{*-}$ decays with the data collected near the $\Upsilon(4S)$ resonance with the BABAR detector at the PEP-II storage ring between October 1999 and May 2004. We accumulated an integrated luminosity of 205 fb^{-1} on the peak (227 million $B\bar{B}$ pairs) and 16 fb^{-1} 40 MeV below the resonance. The BABAR detector is described elsewhere [7]. We focus on the components which are relevant to this analysis. Charged-particle trajectories are measured by a five-layer double sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) immersed in a 1.5 T solenoidal magnetic field. Charged-particle identification is achieved by combining the light measured in a ring-imaging Cherenkov device (DIRC) with the ionization energy loss (dE/dx) measured in the DCH and SVT. Photons are detected in a CsI(Tl) electromagnetic calorimeter (EMC) inside the coil. We use GEANT4 [8] based software to simulate the detector response and account for the varying beam and environmental conditions.

3 ANALYSIS METHOD

We reconstruct $B^- \rightarrow D^0 K^* (892)^-$ decays. We select K^{*-} candidates in the $K^{*-} \rightarrow K_S^0 \pi^-$ mode and D^0 candidates in 8 decay channels. We optimize our event-selection criteria to minimize the statistical error on the signal yield, determined for each channel using simulated signal and background events. In order to maximize statistics and as we measure ratios (asymmetries and ratios of branching fractions), we use rather relaxed criteria to define a track or a photon candidate. In general a track must originate from the interaction point within 1.5 cm in the transverse plane and 10 cm along the beam. Very soft tracks, measured only by the SVT are also used. Loose criteria are employed to separate charged pions and kaons. Pions (kaons) are identified with more than 95% (90%) efficiency by an algorithm which rejects more than 85% (95%) of the kaons (pions) in the geometrical acceptance of the DIRC. Photon candidates are isolated energy deposits in the EMC with an energy above 30 MeV and a shape consistent with that of a photon-induced shower.

K_S^0 candidates are made from oppositely charged tracks assumed to be pions. K_S^0 used to make $D^0_{CP\pm}$ (K^*) candidates are mass (mass and vertex) constrained. The pion pairs are selected according to their reconstructed invariant mass, required to be within 13 MeV/ c^2 from the known value [9]. For those used to search for a K^* we further require their flight direction and length to be as expected for a K_S^0 coming from the interaction point. The K_S^0 candidate flight path and momentum have to make an acute angle. The K_S^0 candidate flight length in the transverse plane has to exceed its uncertainty by 3 standard deviations. π^0 candidates combine pairs of photons with a total energy greater than 200 MeV and an invariant mass between 115 and 150 MeV/ c^2 . A mass constraint fit is applied to the selected π^0 candidates. K^* candidates combine a K_S^0 and a charged particle which are constrained to come from a single decay vertex. We select K^* candidates which have an invariant mass within 75 MeV/ c^2 of the known value [9]. Finally, since the K^* in $B \rightarrow D^0 K^*$ is polarized, we require $|\cos \theta_{K^*hel}| \geq 0.35$, where θ_{K^*hel} is the angle in the K^* rest frame between the daughter pion and the parent B momenta. Here and in other occurrences the helicity distribution discriminates well between a B meson decay and an event from the $e^+e^- \rightarrow q\bar{q}$ continuum.

We select D^0 in even CP ($CP+$) eigenstates (K^+K^- , $\pi^+ \pi^-$), odd CP ($CP-$) eigenstates ($K_S^0 \pi^0$, $K_S^0 \phi$ and $K_S^0 \omega$), and non- CP (flavour) eigenstates ($K^- \pi^+$, $K^- \pi^+ \pi^0$ and $K^- \pi^+ \pi^+ \pi^-$). Composite particles included in the $CP-$ modes are vertex constrained. ϕ (ω) candidates are constructed from $K^+ K^-$ ($\pi^+ \pi^- \pi^0$) particle combinations with an invariant mass required to be within 12 (20) MeV/ c^2 of the known values [9]. We further select the ω candidates with requirements on two helicity angles. The normal helicity angle, between the D^0 momentum in the rest frame of the ω and the normal to the plane containing all 3 decay pions, must have its cosine above 0.25 in magnitude. The Dalitz-helicity angle [10], defined as the angle between the momentum of one daughter pion in the ω rest frame and the direction of one of the other two pions in the rest frame of those two pions, must have a cosine with a magnitude less than 0.9.

Except for the $K_S^0 \pi^0$ final state, all D^0 candidates are mass and vertex constrained. We select D^0 candidates with an invariant mass differing from the known mass by less than 12 MeV/ c^2 for all channels except $K_S^0 \pi^0$ (30 MeV/ c^2) and $K_S^0 \omega$ (20 MeV/ c^2). These limits are about 2 standard deviations of the nearly-Gaussian resolutions.

To suppress the background due to $e^+e^- \rightarrow q\bar{q}$ reactions, $q \in \{u, d, s, c\}$, we require $|\cos \theta_B| \leq 0.9$ as, in the $\Upsilon(4S)$ rest frame, B mesons are produced with a $\sin^2 \theta_B$ distribution of the angle θ_B

of their momentum with the beam axis. We also use global event shape variables which translate quantitatively the fact that in the $\Upsilon(4S)$ rest frame, $q\bar{q}$ continuum events have a two-jet like topology whereas $B\bar{B}$ events are more spherical. We require $|\cos \theta_{thrust}| \leq 0.9$ where θ_{thrust} is the angle between the thrust axes of the B candidate and the rest of the event (i.e. what is left after removing the tracks and clusters associated with the B candidate). We construct a Fisher discriminant [11] from $\cos \theta_{thrust}$ and Legendre monomials [12] describing the energy flow in the rest of the event.

We identify final B candidates using two [nearly] independent kinematic variables: the beam-energy-substituted mass $m_{ES} = \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - p_B^2}$ and the energy difference $\Delta E = E_B^* - \sqrt{s}/2$, where the subscripts 0 and B refer to the e^+e^- -beam-system and the B candidate respectively; s is the square of the center-of-mass (CM) energy and the asterisk labels the CM frame. For all signal modes, the m_{ES} distributions are described by the same Gaussian function \mathcal{G} centered at the B mass with a 2.6 MeV/ c^2 resolution (except $K_S^0 \pi^0$ which has a 2.8 MeV/ c^2 resolution). The ΔE distribution depends more strongly on the signal mode. ΔE is centered on zero for signal with a resolution of 11–13 MeV for all channels except $K_S^0 \pi^0$ for which the resolution is asymmetric and about 30 MeV. We define a signal region $|\Delta E| < 25$ MeV for all modes except $K_S^0 \pi^0$ which uses < 50 MeV.

For those events consistent with more than one B candidate — this occurs in $< 25\%$ of selected events depending on the D^0 mode — we choose that with the smallest χ^2 formed from the differences of the measured and true D^0 and K^* masses scaled by the mass spread which includes the resolution and, for the K^* , the natural width. Simulations prove that no bias is introduced by this choice and the correct candidate is picked at least 82% of the time.

The total reconstruction efficiencies⁶ after corrections, according to simulation of signal events, are: 12.5% and 12.9% for the $CP+$ modes $D^0 \rightarrow K^+K^-$ and $\pi^+ \pi^-$; 5.0%, 10.2% and 2.3% for the $CP-$ modes $D^0 \rightarrow K_S^0 \pi^0$, $K_S^0 \phi$ and $K_S^0 \omega$; 13.5%, 5.2% and 8.0% for the $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$ and $K^- \pi^+ \pi^+ \pi^-$ non- CP modes.

4 PEAKING BACKGROUNDS

To study $B\bar{B}$ backgrounds we look in *sideband* regions away from the signal region. We define a ΔE sideband in the interval $-100 \leq \Delta E \leq -60$ and $60 \leq \Delta E \leq 200$ MeV for all modes except $D^0 \rightarrow K_S^0 \pi^0$ for which the inside limit is ± 95 rather than 60 MeV. The lower limit (-100 MeV/ c^2) is chosen to avoid selecting much of the background coming from $D^{*0} \rightarrow D^0 \pi^0/\gamma$ decays. In this ΔE sideband we see no significant evidence of a peaking background which could leak into the signal region. We define a second control region in the m_{D^0} sideband away from the D^0 mass peak. This provides sensitivity to background sources which mimic signal both in ΔE and m_{ES} : the (doubly) peaking background. This pollution comes from either charmed or charmless B meson decays which do not contain a true D^0 . As many of the possible contributions to this background are not well known, we attempt to measure this contribution by including the m_{D^0} sideband in the fit. Relevant plots are shown on the third row of Figure 1.

A notable background for the $B^- \rightarrow (D^0 \rightarrow \pi^+ \pi^-) (K^{*-} \rightarrow K_S^0 \pi^-)$ mode is the decay $B^- \rightarrow (K_S^0 \pi^+ \pi^-)_{D^0} \pi^-$ which contains the same final state as the signal but has a 600 times higher

⁶The branching fractions of the unstable daughter particles are not included.

branching fraction. We therefore explicitly veto any selected B -candidate containing a ($K_S^0 \pi^+ \pi^-$) combination within 25 MeV/ c^2 of the D^0 mass.

5 YIELD AND CP FIT

An unbinned extended maximum likelihood fit to m_{ES} distributions in the range $5.2 \leq m_{ES} \leq 5.3$ GeV/ c^2 is used to determine yields and CP -violating quantities \mathcal{A}_{CP} and \mathcal{R}_{CP} . We use a *universal* Gaussian function \mathcal{G} to describe the signal shape for all modes considered. The combinatorial background in the m_{ES} distribution is modeled using a threshold function $\mathcal{A}rg$ first considered by the Argus collaboration [13]. Its shape is governed by one parameter ξ that is left to float in the fit and a second, $E_{MAX} = \sqrt{s}/2$, which is fixed at 5.2910 GeV/ c^2 . We fit simultaneously m_{ES} distributions of nine samples (1) the non- CP , (2) $CP+$ and (3) $CP-$ D^0 modes in the (i) signal region, (ii) the m_{D^0} sideband and (iii) the ΔE sideband. We fit three types of probability density functions (PDF) combining $\mathcal{G}(m_{ES}; x_j)$ and $\mathcal{A}rg(m_{ES}; \xi)$ weighted by the unknown event yields. We call x_j , the mean and standard deviation of \mathcal{G} and ξ the shape parameters of the PDF . In the ΔE sideband, we fit: $\mathcal{A}rg$. In the m_{D^0} sideband we fit: $a_{sb} \cdot \mathcal{A}rg + b_{sb} \cdot \mathcal{G}$. where \mathcal{G} accounts for the doubly peaking B -decays. Finally, we fit: $a \cdot \mathcal{A}rg + [\cdot \mathcal{G} +] \cdot \mathcal{G}$ in the signal region. Here b is scaled from b_{sb} according to the m_{D^0} sideband and signal window widths and is fixed; c is the $B^\pm \rightarrow D^0 K^{*\pm}$ signal. The motivation to perform the fit just described is as follows: the non- CP mode sample with relatively high statistics helps constrain the PDF shape for the low statistics CP mode distributions. The ΔE sideband sample helps define the Argus background shape.

The values of ξ obtained for each data sample were found to be consistent with each other, but subject to large uncertainties. We have therefore constrained ξ to take the same value for all data samples in the fit. We assume that the B decays found in the m_{D^0} sideband have the same final states as the signal and that we can therefore fit the same Gaussian to the signal and doubly peaking B background.

Furthermore, the CP samples (in the signal region) are split into the B^- and B^+ sub-samples. The likelihood function is written so as to directly extract the four physical quantities, \mathcal{A}_+ , \mathcal{A}_- , \mathcal{R}_+ and \mathcal{R}_- . The doubly peaking B -background is assumed to *not* violate CP and so is split equally between the B^- and B^+ sub-samples. This assumption is considered further when we discuss the systematic uncertainties. Fig. 1 shows graphically the results of the fit. The nominal fit results are shown in table 1.

	non- CP	$CP+$	$CP-$
Yield	498 ± 29	34.4 ± 6.9	15.1 ± 5.8
N_{peak}	10.9 ± 6.6	2.5 ± 1.3	2.4 ± 2.2
\mathcal{A}_{CP}		-0.09 ± 0.20	-0.33 ± 0.34
\mathcal{R}_{CP}		1.77 ± 0.37	0.76 ± 0.29

Table 1: Results from the fits. For each D^0 mode class, we give the event yield, the peaking background contribution, \mathcal{A}_{CP} and \mathcal{R}_{CP} . The uncertainties are statistical only.

The fit stability and accuracy have been studied by performing 1000 simulated experiments at

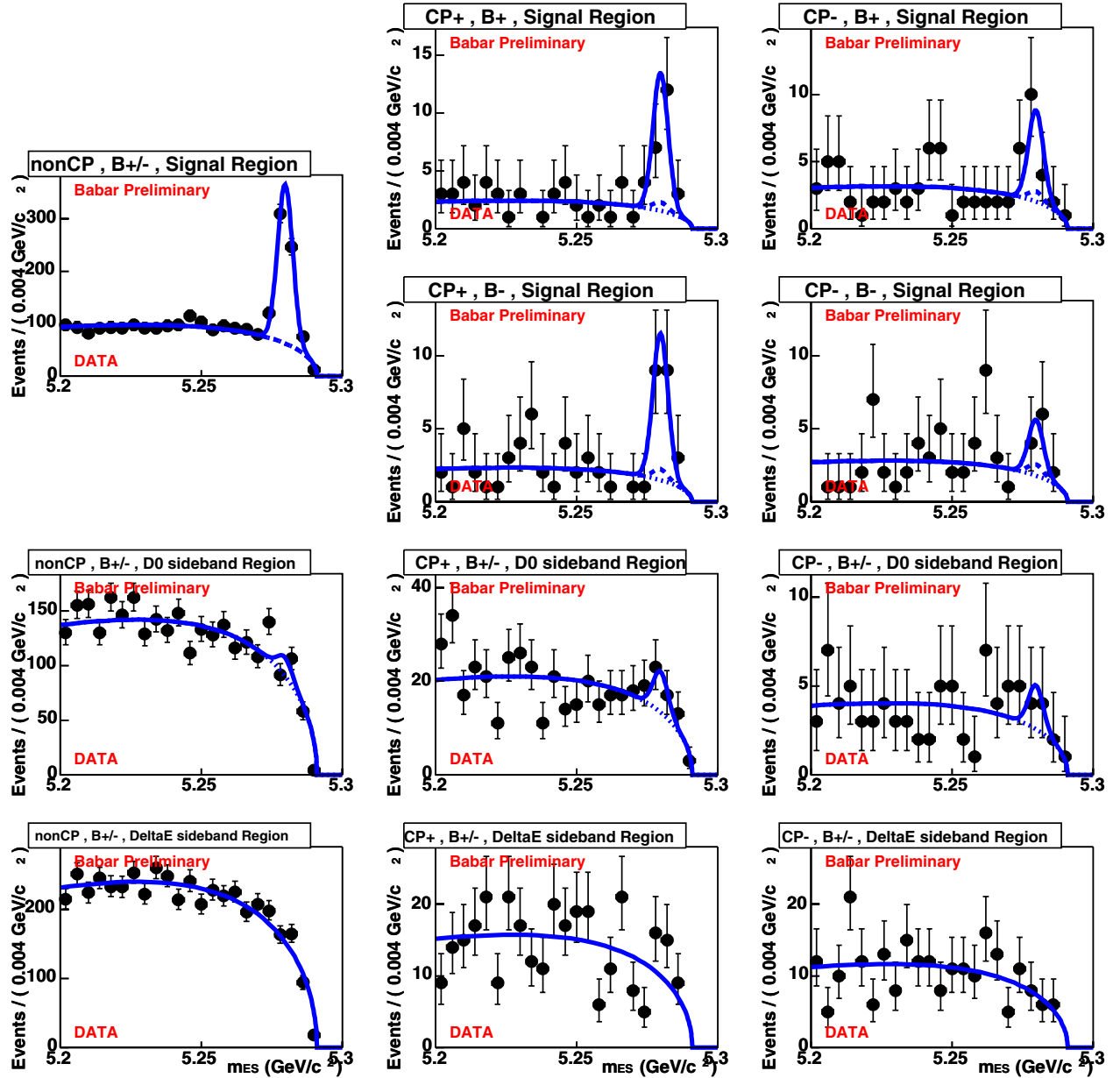


Figure 1: The simultaneous fit. The m_{ES} distributions are shown for the non-CP modes in the first column, CP⁺ modes in the second column and CP⁻ in the third. The fits in the signal region are shown in the top two rows, fits of the peaking background in the m_{D^0} sideband are in the third row and the fits of the background in the ΔE sideband are in the fourth. For the CP modes in the signal region, B⁺ and B⁻ distributions are shown separately in the first and second rows.

the optimum found by the fit in the parameter space. The value of the likelihood function in the fit falls well within the range observed with the simulated experiments.

The yields we observe for the non- CP modes are compatible with our previous measurements of the $B^- \rightarrow D^0 K^{*-}$ branching ratio [4]. The statistical significance of the $CP+$ ($CP-$) yields are 6.8 (2.9) standard deviations. It should be noted that the measured \mathcal{A}_{CP-} could differ from the physical quantity, as background under the ϕ and ω resonances with odd and even CP could be present. These possible interference effects are accounted for in the systematics.

6 SYSTEMATIC STUDIES

6.1 CP -asymmetries

Although most systematic errors cancel in the asymmetries, three effects must be considered. An asymmetry inherent to the detector or analysis may exist. After running the analysis code on a high statistics $B^- \rightarrow D^0 \pi^-$ sample (with K^* cuts removed), the final selection shows an asymmetry of $(-1.9 \pm 0.8)\%$. We quote a systematic uncertainty of $\pm 2.7\%$.

The second substantial systematic effect is that due to a possible CP -asymmetry in the peaking background. Although there is no physics ansatz that requires the peaking background to be asymmetric, it cannot be excluded. To get an estimate, we remark that if there is an asymmetry $\mathcal{A}_{\sqrt{1-\parallel}}$, a systematic error on \mathcal{A}_{CP} is given by $\mathcal{A}_{\sqrt{1-\parallel}} \times \frac{1}{b}$, where b is the contribution of the peaking background and c the signal yield. Assuming conservatively $\mathcal{A}_{\sqrt{1-\parallel}} \leq 50\%$, we obtain systematic errors of $\pm 3.5\%$ and $\pm 8.0\%$ on \mathcal{A}_{CP+} and \mathcal{A}_{CP-} respectively.

Finally a systematic correction must be applied to \mathcal{A}_{CP-} which stems from the background under the ϕ and ω resonances. Looking at the $D^0 \rightarrow K^- K^+ K_S^0$ Dalitz plot [14] we see a contribution of the $a_0(980)$ under the ϕ . The $a_0(980)$ is a 0^{++} state which induces a $CP+$ pollution. We crudely estimate a bias on \mathcal{A}_{CP-} with a linear dependance on the difference of the measured asymmetries, $\delta\mathcal{A}_{CP-} = 1.15 \pm 0.12 \cdot (\mathcal{A}_{CP-} - \mathcal{A}_{CP+})$ which we quote as a separate systematic uncertainty.

6.2 \mathcal{R}_{CP}

\mathcal{R}_{CP} are ratios of rates of processes differing by the final state of the D^0 . We have to consider the uncertainties affecting the selection algorithms for the differing D channels. They bring small correction factors which account for the difference between the actual detector response and the simulation model. The main effects stem from the approximate modeling of the tracking efficiency (1.2 % per track), the K_S^0 reconstruction efficiency for $CP-$ modes of the D^0 (2.0 % per K_S^0), the π^0 reconstruction efficiency for the $K_S^0 \pi^0$ channel (3 %) and the efficiency and misidentification probabilities from the particle identification (2 % per track). A substantial effect is the uncertainty on the measured branching ratios [9]. We find 4.8 % and 7.5 % for the systematic uncertainties on the selection of the D^0 to $CP+$ and $CP-$ channels and 4.0 % for D^0 to non- CP channels. Altogether, we find systematic uncertainties on the relative efficiencies to be 6.2 % and 8.5 % on \mathcal{R}_{CP+} and \mathcal{R}_{CP-} respectively. Here also we quote as a separate systematic uncertainty, a possible bias due to structure under the ϕ and ω resonances. We conservatively estimate this bias to lie between -18 and -5% using the $D^0 \rightarrow K^- K^+ K_S^0$ Dalitz plot [14].

7 PHYSICS RESULTS

We quote the final results:

$$\begin{aligned}\mathcal{A}_{CP+} &= -0.09 \pm 0.20(stat.) \pm 0.06(syst.) \\ \mathcal{A}_{CP-} &= -0.33 \pm 0.34(stat.) \pm 0.10(syst.) (+1.15 \pm 0.12) \cdot (\mathcal{A}_{CP-} - \mathcal{A}_{CP+}) (bias) \\ \mathcal{R}_{CP+} &= +1.77 \pm 0.37(stat.) \pm 0.12(syst.) \\ \mathcal{R}_{CP-} &= +0.76 \pm 0.29(stat.) \pm 0.06(syst.) \pm_{0.14}^{0.04} (bias)\end{aligned}$$

For the $CP-$ measurements, the third uncertainty reflects a possible bias due to interference effects in the final states with ϕ and ω resonances.

These can be compared with the preliminary results by the Belle collaboration [6] using 95.8 $B\bar{B}$ pairs: $\mathcal{A}_{CP+} = -0.02 \pm 0.33 \pm 0.07$; $\mathcal{A}_{CP-} = +0.19 \pm 0.50 \pm 0.04$. The results are in agreement at the one standard deviation level. As expected our statistical errors are reduced. We quote much larger systematic uncertainties because we account for a possibly high CP -asymmetry in the background and for structures under the ϕ and ω resonances whereas reference [6] does not.

We use equation (3) to derive $r_B^2 = 0.23 \pm 0.24$. Although the central value is large (it translates to $r_B=0.47$), a null value is within one-standard deviation.

8 SUMMARY

In summary, we present preliminary observations of the decays of charged B mesons to a K^* and a D^0 where the latter particle is seen in final states of even and odd CP . We express the results in terms of \mathcal{R}_{CP} and \mathcal{A}_{CP} . With more statistics, these quantities will constrain r_B , the ratio of amplitudes defined in equations (3 and 4) and the angle γ of the unitary triangle by application of the Gronau-London-Wyler method.

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