PHYSICAL REVIEW D **76,** 111101(R) (2007)

Search for $b \to u$ transitions in $B^- \to [K^+\pi^-\pi^0]_D K^-$

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(Received 2 August 2007; published 21 December 2007)

We search for decays of a B meson into a neutral D meson and a charged kaon, with the D meson decaying into a charged kaon, a charged pion, and a neutral pion. This final state can be reached through the $b \to c$ transition $B^- \to D^0 K^-$ followed by the doubly Cabibbo-suppressed $D^0 \to K^+ \pi^- \pi^0$, or the $b \to u$ transition $B^- \to \bar{D}^0 K^-$ followed by the Cabibbo-favored $\bar{D}^0 \to K^+ \pi^- \pi^0$. The interference of these two amplitudes is sensitive to the angle γ of the unitarity triangle. We present results based on 226×10^6 $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events collected with the *BABAR* detector at SLAC. We find no significant evidence for these decays and we set a limit $R_{\rm ADS} \equiv \frac{\Gamma([K^+\pi^-\pi^0]_D K^-)+\Gamma([K^-\pi^+\pi^0]_D K^+)}{\Gamma([K^+\pi^-\pi^0]_D K^+)+\Gamma([K^-\pi^+\pi^0]_D K^-)} < 0.039$ at 95% confidence level, which we translate with a Bayesian approach into $r_B \equiv |A(B^- \to \bar{D}^0 K^-)/A(B^- \to D^0 K^-)| < 0.19$ at 95% confidence level.

DOI: 10.1103/PhysRevD.76.111101 PACS numbers: 13.25.Hw, 14.40.Nd

I. INTRODUCTION

Following the discovery of CP violation in B meson decays and the measurement of the angle β of the unitarity triangle [1] associated with the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, the focus has turned toward the measurements of the other angles α and γ. Following Ref. [2], several methods have been proposed to measure the relative weak phase between the $B^- \to D^0 K^-$ amplitude, proportional to the CKM matrix element V_{cb} (Fig. 1), and the $B^- \to \bar{D}^0 K^-$ amplitude, proportional to V_{ub}. This weak phase, which by definition is $\gamma = \arg(-V_{ub}^* V_{ud}/V_{cb}^* V_{cd})$, can be measured from the interference that occurs when the D^0 and the $\bar{D}^0$ decay to common final states.

As an extension of the method proposed in Ref. [3], we search for $B^- \to [K^+\pi^-\pi^0]_D K^-$ [4], where the CKM-favored $B^- \to D^0 K^-$ decay, followed by the doubly Cabibbo-suppressed $D^0 \to K^+\pi^-\pi^0$ decay, interferes with the CKM-suppressed $B^- \to \bar{D}^0 K^-$ decay, followed by the Cabibbo-favored $\bar{D}^0 \to K^+\pi^-\pi^0$ decay.

In order to reduce the systematic uncertainties, we measure ratios of decay rates:

$$R_{\rm ADS} \equiv \frac{\Gamma([K^+\pi^-\pi^0]_D K^-) + \Gamma([K^-\pi^+\pi^0]_D K^+)}{\Gamma([K^+\pi^-\pi^0]_D K^+) + \Gamma([K^-\pi^+\pi^0]_D K^-)} = r_B^2 + r_D^2 + 2 r_B r_D C \cos\gamma, \quad (1)$$

$$A_{\rm ADS} \equiv \frac{\Gamma([K^+\pi^-\pi^0]_D K^-) - \Gamma([K^-\pi^+\pi^0]_D K^+)}{\Gamma([K^+\pi^-\pi^0]_D K^-) + \Gamma([K^-\pi^+\pi^0]_D K^+)} = 2 r_B r_D S \sin\gamma / R_{\rm ADS}, \quad (2)$$

where $r_B \equiv |\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)}|$, $r_D^2 \equiv \frac{\mathcal{B}(D^0 \to K^+\pi^-\pi^0)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^0)}$. The C and S parameters are defined as

$$C = \frac{\int \mathcal{A}_D(\vec{m}) \bar{\mathcal{A}}_D(\vec{m}) \cos(\bar{\delta}(\vec{m}) - \delta(\vec{m}) + \delta_B) d\vec{m}}{\sqrt{\int |\bar{\mathcal{A}}_D(\vec{m})|^2 d\vec{m} \cdot \int |\mathcal{A}_D(\vec{m})|^2 d\vec{m}}}, \quad (3)$$

$$S = \frac{\int \mathcal{A}_D(\vec{m}) \bar{\mathcal{A}}_D(\vec{m}) \sin(\bar{\delta}(\vec{m}) - \delta(\vec{m}) + \delta_B) d\vec{m}}{\sqrt{\int |\bar{\mathcal{A}}_D(\vec{m})|^2 d\vec{m} \cdot \int |\mathcal{A}_D(\vec{m})|^2 d\vec{m}}}, \quad (4)$$

where $\vec{m}$ indicates a point in the Dalitz plane $[m^2_{K\pi}, m^2_{K\pi^0}]$, $[\mathcal{A}_D(\vec{m}), \delta(\vec{m})]([\bar{\mathcal{A}}_D(m), \bar{\delta}(m)])$ the absolute value, and the strong phase of the D^0 ($\bar{D}^0$) decay amplitude, and δ_B the strong phase difference between the two interfering B decay amplitudes. Equations (1) and (2) hold when neglecting D-mixing effects, which in the standard model (SM) give negligible corrections to γ [5] and do not affect the r_B measurement.

Determining the angle γ from the measurements of $R_{\rm ADS}$ and $A_{\rm ADS}$ requires extracting the strong phases by means of a Dalitz analysis of the three-body decay of the neutral D meson, for which the available statistics are insufficient. However, with the current statistics we can measure $R_{\rm ADS}$ and constrain r_B by exploiting the fact that in Eq. (1) $|C| \le 1$. Since the value of r_B is related to the level of interference between the diagrams of Fig. 1, high values of r_B lead to a better sensitivity to γ in any measurement involving $B \to D^0 K$ decays. Thus, r_B is a key ingredient for the extraction of γ from other measurements [6].

Both the Belle and *BABAR* collaborations have published similar measurements but in a different decay chain, $B \to DK$ with $D \to K\pi$ [7]. Unlike those measurements, we can take advantage of the smaller value of r_D, given by $r_D^2 = (0.214 \pm 0.008 \pm 0.008)\%$ [8] in $D \to K\pi\pi^0$ decays as opposed to $r_D^2 = (0.362 \pm 0.020 \pm 0.027)\%$ [9] in $D \to K\pi$ decays. This implies that for a given error on $R_{\rm ADS}$, the sensitivity to r_B is better.

II. EVENT RECONSTRUCTION AND SELECTION

The results presented in this paper are based on $226 \times 10^6 \Upsilon(4S) \to B\bar{B}$ decays collected between 1999 and 2004

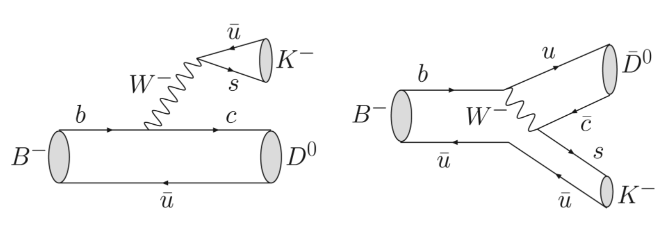

FIG. 1. Feynman diagrams for the CKM-favored $B^- \to D^0 K^-$ and the CKM- and color-suppressed $B^- \to \bar{D}^0 K^-$ decays.

with the *BABAR* detector at the PEP-II *B* factory at SLAC [10]. Approximately 7% of the collected data (15.8 fb^{-1}) have a center-of-mass (CM) energy 40 MeV below the $\Upsilon(4S)$ resonance. These "off-resonance" data are used to study backgrounds from continuum events, $e^+e^- \to q\bar{q}$ ($q = u, d, s$, or c). The *BABAR* detector is described elsewhere [11]. Charged-particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). In addition to providing precise position information for tracking, the SVT and DCH also measure the specific ionization (dE/dx), which is used for particle identification of low-momentum charged particles. At higher momenta ($p > 0.7$ GeV$/c$) pions and kaons are identified by Cherenkov radiation detected in a ring-imaging device (DIRC). The position and energy of photons are measured with an electromagnetic calorimeter (EMC) consisting of 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5T solenoidal superconducting magnet.

The event selection was developed from studies of off-resonance data and $B\bar{B}$ and continuum events simulated with Monte Carlo (MC) techniques. A large on-resonance data sample of $B^- \to D^0\pi^-$, $D^0 \to K^-\pi^+\pi^0$ events was used to validate several aspects of the simulation and analysis procedure. We refer to this mode as $B \to D\pi$.

Both kaon candidates are required to satisfy kaon identification criteria, which are based on the specific ionization loss measured in the tracking devices and on the Cherenkov angles measured in the DIRC and are typically 85% efficient, depending on momentum and polar angle. Misidentification rates are at the 2% level. The π^0 candidates are reconstructed as pairs of photon candidates in the EMC, each with energy larger than 70 MeV and a lateral shower profile consistent with an electromagnetic deposit. These pairs must have a total energy greater than 200 MeV and $118 < m_{\gamma\gamma} < 145$ MeV$/c^2$. To account for the correlation between the tails in the distribution of the $K\pi\pi^0$ invariant mass and the π^0 candidate mass, we require the difference between the two measured masses to be within 32.5 MeV$/c^2$ of the expected value of $m_{D^0} - m_{\pi^0} =$ 1729.5 MeV$/c^2$ [12], retaining 90% of the signal. The remaining background from other $B^\pm \to [h_1 h_2 \pi^0]_D h_3^\pm$ [4] modes is reduced by removing events where the invariant mass of any $h_1 h_2 \pi^0$ candidate, with any particle-type assignment other than the signal hypothesis, is consistent with the D^0 meson mass, retaining 92% of the signal.

After these requirements, the background is mostly due to D^0-$\bar{D}^0$ pair production in $e^+e^- \to c\bar{c}$ events, with $\bar{D}^0 \to K^+\pi^-\pi^0$ and $D \to K^-$. To discriminate between the signal and this dominant background we use a neural network (NNet) with six quantities that distinguish continuum and $B\bar{B}$ events: $L_0 = \sum_i p_i$ and $L_2 = \sum_i p_i \cos^2\theta_i$, both calculated in the CM frame, where p_i is the momentum of particle i, θ_i is its angle relative to the thrust axis of the B candidate, and the sum runs over all tracks and clusters not used to reconstruct the B candidate; the angle in the CM frame between the thrust axes of the B candidate and of the detected remainder of the event; the polar angle of the B candidate in the CM frame; the distance of closest approach between the track of the kaon candidate from the B and the trajectory of the reconstructed D meson (this is consistent with zero for signal events, but can be larger in $c\bar{c}$ events); the distance along the beams between the reconstructed vertex of the B candidate and the vertex of the other tracks in the event, this is consistent with zero for continuum events, but is sensitive to the B lifetime for signal events.

The NNet is trained with simulated continuum and signal events. We find agreement between the distributions of all six variables in simulation, off-resonance data, and $B \to D\pi$ events. We apply a loose preselection on the NNet ($0.4 < \mathrm{NNet} < 1.0$) with a 90% efficiency for signal and a 68% rejection power for continuum, and then use the NNet itself in the likelihood fit described below to fully exploit its discriminating power.

A B-meson candidate is characterized by the energy-substituted mass $m_{\mathrm{ES}} \equiv \sqrt{(\frac{s}{2} + \vec{p}_0 \cdot \vec{p}_B)^2/E_0^2 - p_B^2}$ and energy difference $\Delta E \equiv E_B^* - \frac{\sqrt{s}}{2}$, where E and p are energy and momentum, the asterisk denotes the CM frame, the subscripts 0 and B refer to the initial e^+e^- state and B candidate, respectively, and s is the square of the CM energy. For signal events, m_{ES} is centered around the B mass with a resolution of about 2.5 MeV$/c^2$, and ΔE is centered at zero with a resolution of 17 MeV.

Considering both the case where the two kaons have the same and the opposite charge (referred to as "same-sign" and "opposite-sign" samples, respectively), 28 621 events survive the selection described above and the loose requirements $|\Delta E| < 100$ MeV and $m_{\mathrm{ES}} > 5.2$ GeV$/c^2$. While the dominant background comes from continuum events, there is still a nonnegligible contribution from $\Upsilon(4S) \to B\bar{B}$ events (denoted "$B\bar{B}$" in the following). We consider separately the $B \to D\pi$ background, since it differs from the signal only in the ΔE distribution. For this decay mode the opposite-sign $B^- \to \bar{D}^0\pi^-$ amplitude is suppressed by a factor $\approx r_B\lambda^2$, where $\lambda \approx 0.22$ is the sine of the Cabibbo angle. Therefore we expect to find a nonnegligible $B \to D\pi$ background only in the same-sign sample.

III. LIKELIHOOD FIT AND RESULTS

The signal and background yields are extracted by maximizing the extended likelihood $\mathcal{L} = e^{-N'} \prod_{i=1}^{N} \mathcal{L}_i(\vec{x}_i)/N!$. Here $N' = N_{DK} + N_{\mathrm{cont}} + N_{BB} + N_{D\pi}$ is the sum of the yields of the signal and the three background contributions (including both the same-sign and the opposite-sign components), $\vec{x} = \{\mathrm{NNet}, \Delta E, m_{\mathrm{ES}}\}$, N is the number of events in the selected sample, and the likelihood of the individual events ($\mathcal{L}_i$) is

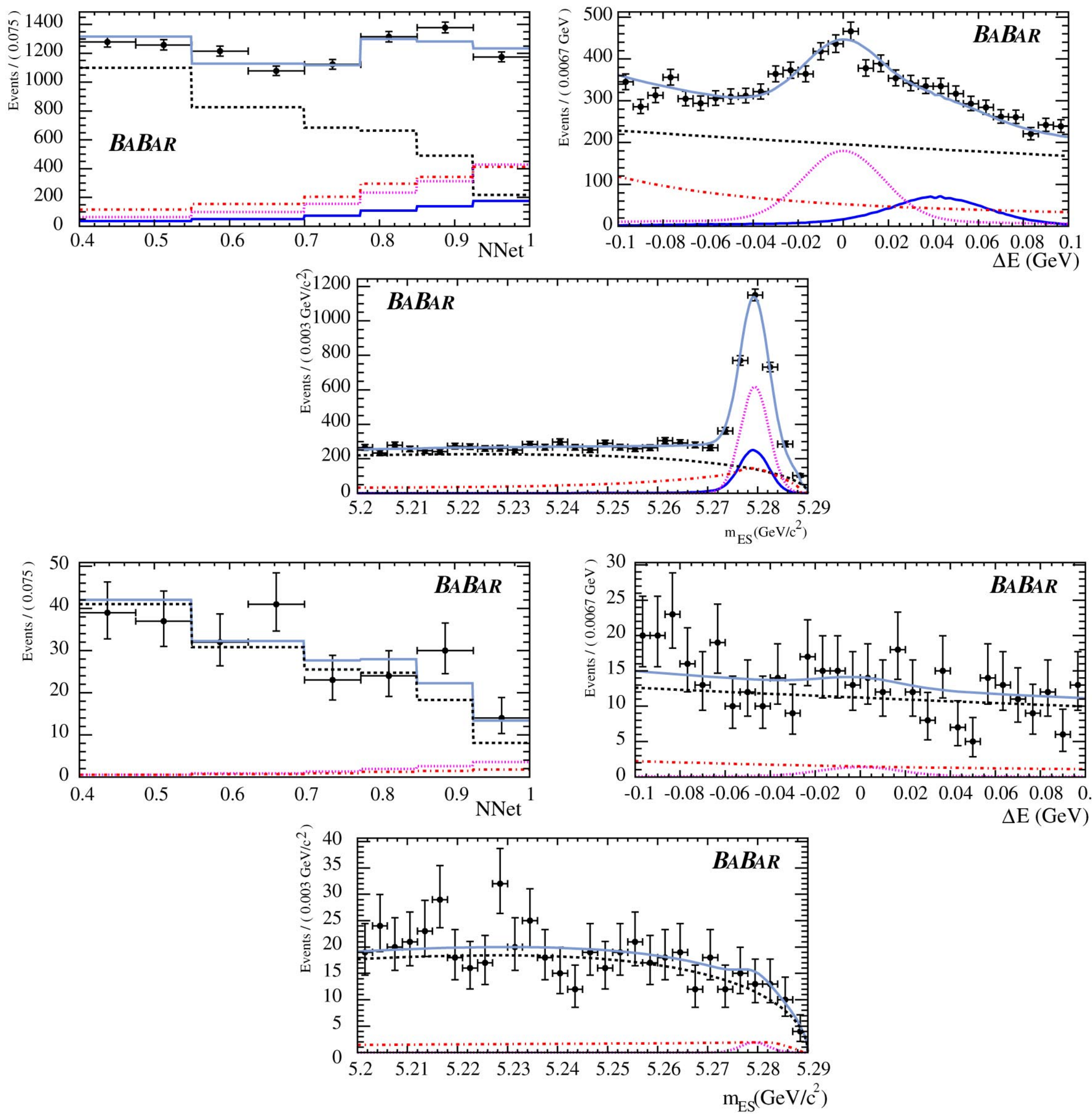

FIG. 2 (color online). Likelihood fit projections of the NNet, ΔE, and $m_{\rm ES}$ distributions separately for the same (top) and opposite (bottom) sign samples. To visually enhance the signal, the distributions for the latter sample are shown after cuts, with a 67% signal efficiency, on the ratios between the signal and the total likelihood of all the variables other than the one shown. The points with error bars represent the data, while the dashed, dashed-dotted, and solid lines represent the contributions from continuum, $B\bar{B}$, and $D\pi$ backgrounds, respectively. The dotted line represents the signal contribution, visible only in the same-sign sample.

defined as

$$\mathcal{L}_i(\vec{x}_i) = \frac{N_{DK}}{1+R_{\rm ADS}} f_{DK}^{RS}(\vec{x}_i) + \frac{N_{\rm cont}}{1+R_{\rm cont}} f_{\rm cont}^{RS}(\vec{x}_i) + \frac{N_{BB}}{1+R_{BB}} f_{BB}^{RS}(\vec{x}_i) + N_{D\pi} f_{D\pi}(\vec{x}_i) \qquad (5)$$

for same-sign events and

$$\mathcal{L}_i(\vec{x}_i) = \frac{N_{DK} R_{\rm ADS}}{1+R_{\rm ADS}} f_{DK}^{WS}(\vec{x}_i) + \frac{N_{\rm cont} R_{\rm cont}}{1+R_{\rm cont}} f_{\rm cont}^{WS}(\vec{x}_i) + \frac{N_{BB} R_{BB}}{1+R_{BB}} f_{BB}^{WS}(\vec{x}_i) \qquad (6)$$

for opposite-sign events. In these equations we have defined R parameters for the backgrounds analogous to those for the signal, defined in Eq. (1). The individual probability density functions (PDFs) f are derived from MC and are built as the product of one-dimensional distributions of the three variables. The only exception is the $m_{\rm ES}$ and ΔE PDF for the $D\pi$ background, where we use a two-dimensional nonparametric distribution [13] due to a nonnegligible correlation between these two variables. The NNet distributions are all modeled with a histogram with eight bins between 0.4 and 1. The $m_{\rm ES}$ distributions are modeled with a Gaussian in the case of the signal, a threshold function

[14] in the case of the continuum background, and the sum of a threshold function and a Gaussian function with an exponential tail in the case of the $B\bar{B}$ background. Finally, the ΔE distributions are parametrized with the sum of two Gaussians in the case of the signal, an exponential in the case of the continuum background, and a sum of two exponentials in the case of the $B\bar{B}$ background. For $m_{\rm ES}$ and ΔE of the $B\bar{B}$ and continuum background, we use different parameters for same-sign and opposite-sign sample.

We perform the fit by floating the four total yields (N_{DK}, $N_{\rm cont}$, N_{BB}, and $N_{D\pi}$), the three R variables and the shape parameters of the threshold function used to parametrize the $m_{\rm ES}$ distribution for the same- and opposite-sign continuum background separately. Figure 2 shows the distributions of the three variables in the selected sample, with the likelihood projections overlaid. The fit yields $R_{\rm ADS} = 0.013^{+0.010}_{-0.004}$, $N_{DK} = (14.7 \pm 0.6) \times 10^2$, $N_{\rm cont} = (239.3 \pm 2.1) \times 10^2$, $N_{BB} = (25.5 \pm 1.6) \times 10^2$, $N_{D\pi} = (6.7 \pm 0.4) \times 10^2$, $R_{\rm cont} = 3.05 \pm 0.07$, $R_{BB} = 0.42 \pm 0.07$.

Equation (5) assumes equal efficiencies for the same- and opposite-sign signal samples, regardless of the difference in the Dalitz structure. This has been demonstrated to be true in MC within a relative statistical error of 4%. We then consider this as a systematic error on $R_{\rm ADS}$. We also repeat the fit by varying the PDF parameters obtained from MC within their statistical errors and by estimating $f_{\rm cont}^{RS/WS}$ on off-resonance data and $f_{DK}^{RS/WS}$ on exclusively reconstructed $D\pi$ events. To account for the observed variations, we assign a 0.0076 systematic error on $R_{\rm ADS}$. The uncertainty due to B decays with distributions similar to the signal, in particular $B \to D^{(*)}\pi$, D^*K, $D^{(*)}K^*$, and $KK\pi\pi^0$, is estimated by varying their branching fractions within their known errors and found to be $6 \cdot 10^{-5}$ on $R_{\rm ADS}$, and therefore negligible. The quality of the simulation of B decays to final states with charm mesons that might mimic the signal has been checked by comparing data and MC samples in the sidebands of the ΔE distribution where these decays dominate. Similarly, we searched the sidebands of the $m_{D^0} - m_{\pi^0}$ distribution for background from charmless B decays and found no evidence of it.

Following a Bayesian approach, we extract r_B by defining the posterior distribution

$$\mathcal{L}(r_B) = \frac{\int p(r_B, r_D, \xi)\mathcal{L}(R_{\rm ADS}(r_B, r_D, \xi))dr_D d\xi}{\int p(r_B, r_D, \xi)\mathcal{L}(R_{\rm ADS}(r_B, r_D, \xi))dr_D d\xi dr_B}, \quad (7)$$

where $\xi = C\cos\gamma$, $R_{\rm ADS}(r_B, r_D, \xi)$ is given in Eq. (1), and $p(r_B, r_D, \xi)$ is the prior distribution for these three quantities. They are considered uncorrelated, with ξ and r_B uniformly distributed in the range of $[-1, 1]$ and $[0, 1]$, respectively. The prior distribution for r_D is a Gaussian consistent with $r_D^2 = (0.214 \pm 0.008 \pm 0.008)\%$ [8]. The likelihood $\mathcal{L}(R_{\rm ADS})$ is obtained by convolving the likelihood returned by the fit with a Gaussian of width 0.0076, equivalent to the systematic uncertainty.

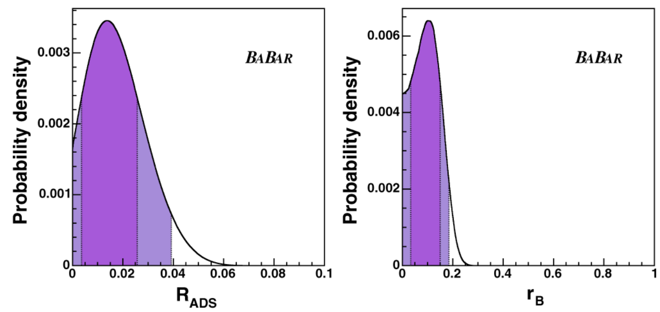

FIG. 3 (color online). Likelihood function for $R_{\rm ADS}$ (left) and r_B (right). The latter is obtained in a Bayesian approach, assuming flat prior distributions for r_B and $\xi = C\cos\gamma$. The 68% and 95% regions are shown in dark and light shading, respectively.

Figure 3 shows $\mathcal{L}(R_{\rm ADS})$ and $\mathcal{L}(r_B)$. We set a 95% confidence level (C.L.) limit by integrating the likelihood, starting from $R_{\rm ADS} = 0$ ($r_B = 0$), thus excluding unphysical values, and we define the 68% C.L. region, for each variable $r = R_{\rm ADS}$ or r_B, as the interval where $\mathcal{L}(r) > \mathcal{L}_{\rm min}$ and $68\% = \int_{\mathcal{L}(r)>\mathcal{L}_{\rm min}} \mathcal{L}(r)dr$.

IV. CONCLUSIONS

In summary, we measure the ratio of the rate for the $B^\pm \to [K^\mp\pi^\pm\pi^0]_D K^\pm$ decay to the favored decay $B^\pm \to [K^\pm\pi^\mp\pi^0]_D K^\pm$ to be $R_{\rm ADS} = 0.013^{+0.012}_{-0.010}$. While this result is consistent with and similar in sensitivity to the completely independent previously published results [7], it is obtained using a different D decay mode. Because the measurement is not statistically significant, we set a 95% C.L. limit $R_{\rm ADS} < 0.039$. We use this information to infer the ratio between the rates of the $B^- \to \bar{D}^0K^-$ and $B^- \to D^0K^-$ decays to be $r_B = 0.091 \pm 0.059$ and consequently set a limit $r_B < 0.19$ at 95% C.L.

ACKNOWLEDGMENTS

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), MEC (Spain), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

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[4] Charge conjugation is implied throughout the paper. Also, we use the notation $B^- \to [h_1^+ h_2^- \pi^0]_D h_3^-$ (with $h_i = \pi$ or K) for the decay chains $B^- \to \tilde{D}^0 h_3^-$, where $\tilde{D}^0$ is either a D^0 or a $\bar{D}^0$ and $\tilde{D}^0 \to h_1^+ h_2^- \pi^0$. We also refer to h_3 as the π or K from the B.

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