Observation of the decays $B^- \rightarrow D_s^{(*)+} K^- \pi^-$

The BABAR Collaboration

March 25, 2022

Abstract

We report first observations of the decays $B^- \rightarrow D_s^{(*)+} K^- \pi^-$, using 292 fb$^{-1}$ of data collected at the $\Upsilon(4S)$ resonance energy by the BABAR detector at the PEP-II $e^+e^-$ collider. The branching fractions are measured to be $\mathcal{B}(B^- \rightarrow D_s^{(*)+} K^- \pi^-) = (1.88 \pm 0.13 \pm 0.41) \cdot 10^{-4}$ and $\mathcal{B}(B^- \rightarrow D_s^{*+} K^- \pi^-) = (1.84 \pm 0.19 \pm 0.40) \cdot 10^{-4}$.

Submitted to the 33rd International Conference on High-Energy Physics, ICHEP 06, 26 July—2 August 2006, Moscow, Russia.

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported in part by Department of Energy contract DE-AC03-76SF00515.
J. Allison, N. R. Barlow, R. J. Barlow, Y. M. Chia, C. L. Edgar, G. D. Lafferty, M. T. Naisbit, J. C. Williams, J. I. Yi

University of Manchester, Manchester M13 9PL, United Kingdom

C. Chen, W. D. Hulsbergen, A. Jawahery, C. K. Lae, D. A. Roberts, G. Simi

University of Maryland, College Park, Maryland 20742, USA

G. Blaylock, C. Dallapiccola, S. S. Hertzbach, X. Li, T. B. Moore, S. Saremi, H. Staengle

University of Massachusetts, Amherst, Massachusetts 01003, USA

R. Cowan, G. Sciolla, S. J. Sekula, M. Spitznagel, F. Taylor, R. K. Yamamoto

Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

H. Kim, S. E. McLachlin, P. M. Patel, S. H. Robertson

McGill University, Montréal, Québec, Canada H3A 2T8

A. Lazzaro, V. Lombardo, F. Palombo

Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, L. Cremaldi, V. Eschenburg, R. Godang, R. Kroeger, D. A. Sanders, D. J. Summers, H. W. Zhao

University of Mississippi, University, Mississippi 38677, USA

S. Brunet, D. Côté, M. Simard, P. Taras, F. B. Viaud

Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

H. Nicholson

Mount Holyoke College, South Hadley, Massachusetts 01075, USA

N. Cavallo,2 G. De Nardo, F. Fabozzi,3 C. Gatto, L. Lista, D. Monorchio, P. Paolucci, D. Piccolo, C. Sciacca

Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy

M. A. Baak, G. Raven, H. L. Snoek

NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop, J. M. LoSecco

University of Notre Dame, Notre Dame, Indiana 46556, USA

T. Allmendinger, G. Benelli, L. A. Corwin, K. K. Gan, K. Honscheid, D. Hufnagel, P. D. Jackson, H. Kagan, R. Kass, A. M. Rahimi, J. J. Regensburger, R. Ter-Antonyan, Q. K. Wong

Ohio State University, Columbus, Ohio 43210, USA

N. L. Blount, J. Brau, R. Frey, O. Igonkina, J. A. Kolb, M. Lu, R. Rahmat, N. B. Sinev, D. Strom, J. Strube, E. Torrence

University of Oregon, Eugene, Oregon 97403, USA

2Also with Università della Basilicata, Potenza, Italy

3Also with Università della Basilicata, Potenza, Italy
Bakel, M. Weaver, A. J. R. Weinstein, W. J. Wisniewski, M. Wittgen, D. H. Wright, A. K. Yarritu, K. Yi, C. C. Young

Stanford Linear Accelerator Center, Stanford, California 94309, USA

P. R. Burchat, A. J. Edwards, S. A. Majewski, B. A. Petersen, C. Roat, L. Wilden

Stanford University, Stanford, California 94305-4060, USA

S. Ahmed, M. S. Alam, R. Bula, J. A. Ernst, V. Jain, B. Pan, M. A. Saeed, F. R. Wappler, S. B. Zain

State University of New York, Albany, New York 12222, USA

W. Bugg, M. Krishnamurthy, S. M. Spanier

University of Tennessee, Knoxville, Tennessee 37996, USA

R. Eckmann, J. L. Ritchie, A. Satpathy, C. J. Schilling, R. F. Schwitters

University of Texas at Austin, Austin, Texas 78712, USA

J. M. Izen, X. C. Lou, S. Ye

University of Texas at Dallas, Richardson, Texas 75083, USA

F. Bianchi, F. Gallo, D. Gamba

Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy

M. Bomben, L. Bosisio, C. Cartaro, F. Cossutti, G. Della Ricca, S. Dittongo, L. Lanceri, L. Vitale

Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy

V. Azzolini, N. Lopez-March, F. Martinez-Vidal

IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

Sw. Banerjee, B. Bhuyan, C. M. Brown, D. Fortin, K. Hamano, R. Kowalewski, I. M. Nugent, J. M. Roney, R. J. Sobie

University of Victoria, Victoria, British Columbia, Canada V8W 3P6

J. J. Back, P. F. Harrison, T. E. Latham, G. B. Mohanty, M. Pappagallo

Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

H. R. Band, X. Chen, B. Cheng, S. Dasu, M. Datta, K. T. Flood, J. J. Hollar, P. E. Kutter, B. Mellado, A. Mihalyi, Y. Pan, M. Pierini, R. Prepost, S. L. Wu, Z. Yu

University of Wisconsin, Madison, Wisconsin 53706, USA

H. Neal

Yale University, New Haven, Connecticut 06511, USA
1 INTRODUCTION

First evidence for so-called inclusive flavor correlated production of $D_s^+$ in $B^-$ decays was reported recently [1] with a branching fraction of $\mathcal{B}(B^- \to D_s^+ X) = (1.2 \pm 0.4)\%$ [2]. These decays are mediated by a $b \to c$ quark transition and require at least three final state particles, including the production of an $s\bar{s}$ pair from the vacuum ( $s\bar{s}$ “popping”). An example for a three-body $B^-$ decay with a $D_s^+$ in the final state is $B^- \to D_s^+ K^- \pi^-$. The corresponding $\bar{B}^0$ decay is $\bar{B}^0 \to D_s^+ \bar{K}^0 \pi^-$. The Feynman diagram for $B^- \to D_s^+(s)K^-\pi^-$ decays is shown in Fig. 1. In case of $\bar{B}^0 \to D_s^+ \bar{K}^0 \pi^-$, an additional contribution from a $W$-exchange diagram with $s\bar{s}$ and $d\bar{d}$ popping may exist. If we replace the $\pi^-$ in Fig. 1, which comes from the hadronization of the $W^-$ boson with a $K^-$, we get the Cabibbo-suppressed decays $B^- \to D_s^+ K^- K^-$ and $\bar{B}^0 \to D_s^+ \bar{K}^0 K^-$. It is interesting to note that the final state $D_s^+ \bar{K}^0 K^-$ can also be reached from a $B^0$ decay. In this case the decay is mediated by a $b \to u$ quark transition, but the $W$ hadronization is not Cabibbo-suppressed. Thus a $\bar{B}^0$ can either decay directly to $D_s^+ \bar{K}^0 K^-$ or via $B^0 \bar{B}^0$ mixing followed by $B^0 \to D_s^+ \bar{K}^0 K^-$. The interference between the two decay amplitudes for decay with and without $B^0 \bar{B}^0$ mixing leads to a time-dependent $CP$-asymmetry that is sensitive to $\sin(2\beta + \gamma)$. In case the contribution from the higher $D^{**}$ resonances decaying into $D_s^+ \bar{K}$ turns out to be large, it may also be interesting to measure the resonant parameters independently from the analysis using $B \to D\pi\pi$ decays [3].

No exclusive $B^- \to D_s^{(s)+} X$ or $\bar{B}^0 \to D_s^{(s)+} X$ decay mode has hitherto been observed. Limits on the branching fractions from the analyses by other experiments are listed in Table II. In this paper we report the first measurement of the decay modes $B^- \to D_s^{(s)+} K^- \pi^-$. 

2 THE $\textit{BaBar}$ DETECTOR AND DATASET

The analysis uses a sample of approximately 292 fb$^{-1}$, which corresponds to about 324 million $\Upsilon(4S)$ decays into $B\bar{B}$ pairs collected with the $\textit{BaBar}$ detector at the PEP-II [4] asymmetric-energy $B$-factory. The $\textit{BaBar}$ detector is described elsewhere [5] and only the components crucial to this analysis are summarized here. Charged particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-particle identification,
and the direction of flight of the oppositely-charged tracks, that come from a common vertex displaced from the through the use of the helicity angle $\theta$. Ionization energy loss ($dE/dx$) in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device are used. Photons are identified and measured using a thallium-doped CsI-crystal electromagnetic calorimeter. These systems are located inside a 1.5 T solenoidal superconducting magnet. We use GEANT4 software to simulate interactions of particles traversing the BABAR detector, taking into account the varying detector conditions and beam backgrounds.

### 3 ANALYSIS METHOD

The optimal selection criteria as well as the probability density distributions of selection variables are determined by a blind analysis based on Monte Carlo (MC) simulation of both signal and background. For the calculation of the expected signal yield we assume $\mathcal{B}(B^- \to D^{(*)}_s K^- \pi^-)$ to be $10^{-4}$ (i.e. about 10% of the measured $\mathcal{B}(B^- \to D^+ \pi^- \pi^-)$). We use MC samples of our signal modes and, to simulate background, inclusive samples of $B^+B^-$ (784 fb$^{-1}$), $B^0\bar{B}^0$ (774 fb$^{-1}$), $c\bar{c}$ (247 fb$^{-1}$), and $q\bar{q}$, $q = u,d,s$ (246 fb$^{-1}$). In addition, we use large samples of simulated events of rare background modes which have final states similar to the signal. We have verified that our MC correctly describes the data by comparing distributions of various selection variables.

Candidates for $D^+_s$ mesons are reconstructed in the modes $D^+_s \to \phi \pi^+$, $K^{*0} K^+$, and $K^0_s K^+$. The $K^0_s$ candidates are reconstructed from two oppositely-charged tracks, that come from a common vertex displaced from the $e^+e^-$ interaction point. We require the significance of this displacement (measured flight distance divided by an estimated error) to exceed 2. All other tracks are required to originate less than 1.5 cm away from the $e^+e^-$ interaction point in the transverse plane and less than 10 cm along the beam axis. Charged kaon candidates must satisfy kaon identification criteria that are typically around 92% efficient, depending on momentum and polar angle, and have a pion misidentification rate at the 5% level. The $\phi \to K^+K^-$, $K^{*0} \to K^-\pi^+$ and $K^0_s \to \pi^+\pi^-$ candidates are required to have invariant masses close to their nominal masses (we require the absolute differences between their measured masses and the nominal values to be in the range $\pm 15$ MeV, $\pm 50$ MeV and $\pm 10$ MeV, respectively). The polarizations of the $K^{*0}$ and $\phi$ mesons in the $D^+_s$ decays are employed to reject backgrounds through the use of the helicity angle $\theta_H$, defined as the angle between the $K^-$ momentum vector and the direction of flight of the $D^+_s$ in the $K^{*0}$ or $\phi$ rest frame. The $K^{*0}$ and $\phi$ candidates are required to have $|\cos\theta_H|$ greater than 0.5.

The $D^{*+}$ candidates are reconstructed in the mode $D^{*+} \to D^+_s \gamma$. The photons are accepted if their energy is greater than 100 MeV. The $D^+_s$ and $D^{*+}$ candidates are required to have invariant

| Experiment | Decay Mode | Upper limit (@90% C.L.) |
|------------|------------|--------------------------|
| ARGUS      | $B^- \to D^+_s K^- \pi^-$ | $8 \times 10^{-4}$ |
|            | $B^- \to D^{*+}_s K^- \pi^-$ | $12 \times 10^{-4}$ |
| CLEO       | $B^- \to D^+_s K^- \pi^-$ | $5 \times 10^{-4}$ |
|            | $B^- \to D^{*+}_s K^- \pi^-$ | $6.8 \times 10^{-4}$ |
masses in the interval $[-10, 10]$ MeV/$c^2$ (for $D_{s}^+$) and $[-15, 10]$ MeV/$c^2$ (for $D_{s}^{*+}$) from their nominal values \[^1\] (the $D_{s}^+$ mass resolution is around 6 MeV/$c^2$, and the asymmetric mass cut on $D_{s}^{*+}$ has an efficiency of about 90%). All $D_{s}^+$ candidates are mass-constrained. The invariant mass of the $D_{s}^{*+}$ is calculated after a mass constraint on the daughter $D_{s}^+$ has been applied. Subsequently, all $D_{s}^{*+}$ candidates are subjected to a mass-constrained fit.

We also require that photons from $D_{s}^{*+}$ are inconsistent with $\pi^0$ hypothesis when combined with any other photon having an energy greater than 150 MeV in the event (the $\pi^0$ veto window is $\pm 10$ MeV/$c^2$). Finally, the $B^-$ meson candidates are formed using the reconstructed combinations of $D_{s}^+ K^- \pi^-$ and $D_{s}^{*+} K^- \pi^-$. The background from continuum $q \bar{q}$ production (where $q = u, d, s, c$) is suppressed based on the event topology. We calculate the angle ($\theta_T$) between the thrust axis of the $B$ meson candidate and the thrust axis of all other particles in the event in the center-of-mass frame (c.m.). In this frame, $B \bar{B}$ pairs are produced approximately at rest and have a uniform $\cos \theta_T$ distribution. In contrast, $q \bar{q}$ pairs are produced in the c.m. frame with high momenta, which results in a $|\cos \theta_T|$ distribution peaking at 1. $|\cos \theta_T|$ is required to be smaller than 0.8. In addition, the ratio of the second and zeroth order Fox-Wolfram moments \[^10\] must be less than 0.3.

We extract the signal using the kinematical variables $m_{ES} = \sqrt{E_b^{s2} - (\sum_i p_i^s)^2}$ and $\Delta E = \sum_i \sqrt{m_i^2 + p_i^s^2} - E_b^s$, where $E_b^s$ is the beam energy in the c.m. frame, $p_i^s$ is the c.m. momentum of the daughter particle $i$ of the $B^-$ meson candidate, and $m_i$ is the mass hypothesis for particle $i$. For signal events, $m_{ES}$ peaks at the $B^-$ meson mass with a resolution of about 2.6 MeV/$c^2$ and $\Delta E$ peaks near zero with a resolution of 13 MeV, indicating that the $B^-$ candidate has a total energy consistent with the beam energy in the c.m. frame. The $B^-$ candidates are required to have $|\Delta E| < 25$ MeV (around 2$\sigma$ of the signal $\Delta E$ resolution) and $m_{ES} > 5.2$ GeV/$c^2$.

The fraction of events with multiple $B^-$ candidates is estimated using the MC simulation and found to be around 3% for $D_{s}^+ K^- \pi^-$ and 9% for $D_{s}^{*+} K^- \pi^-$ combinations. In each event with more than one $B^-$ candidate that passes the selection requirements, we select the one with the lowest $|\Delta E|$ value.

After all selection criteria are applied, we estimate the $B^-$ reconstruction efficiencies, excluding the subsequent branching fractions (see Table 2).

Table 2: Reconstruction efficiencies for $B^- \rightarrow D_{s}^{(*)+} K^- \pi^-$ decays (excluding the subsequent branching fractions).

| Decay mode | $D_{s}^+ \rightarrow \phi \pi^+$ | $D_{s}^+ \rightarrow K^{-0} K^+$ | $D_{s}^+ \rightarrow K^{-0} K^+$ |
|------------|----------------------|----------------------|----------------------|
| $B^- \rightarrow D_{s}^+ K^- \pi^-$ | 11.0% | 7.0% | 10.0% |
| $B^- \rightarrow D_{s}^{*+} K^- \pi^-$ | 5.3% | 3.4% | 4.8% |

Background events that pass these selection criteria are represented by approximately equal amounts of $q \bar{q}$ continuum and $B \bar{B}$ events. We parametrize their $m_{ES}$ distribution by a threshold function \[^11\]:

$$f(m_{ES}) \sim m_{ES} \sqrt{1 - x^2} \exp[-\xi(1 - x^2)],$$

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where \( x = 2m_{ES}/\sqrt{s} \), \( \sqrt{s} \) is the total energy of the beams in their center of mass frame, and \( \xi \) is the fit parameter.

A study using simulated \( B^0 \) and \( B^+ \) decays shows that some background events with distributions in \( m_{ES} \) and in \( \Delta E \) peaking near the signal region are expected in reconstructed \( B^- \rightarrow D_s^+ K^- \pi^- \) candidates due to charmless and charmonium \( B^- \) decays with the same set of particles in the final state. For \( B^- \rightarrow D_s^{(*)+} K^- \pi^- \), no background of this kind is expected, due to the presence of the \( \gamma \), which suppresses charmless and charmonium decay contributions. The peaking contribution is evaluated using the data by reconstructing \( "D_s^{(*)+} K^- \pi^-" \) combinations, where \( "D_s^{(*)+}" \) candidates are selected from \([±40, ±25]\) MeV sidebands around the \( D_s^+ \) nominal mass. In this procedure, we use the same selection requirements, as for the signal, except that \( "D_s^{(*)+}" \) candidates are not mass constrained. The resulting \( m_{ES} \) spectra are shown in Figure 2. We fit the distributions using an extended unbinned maximum likelihood (ML) fit with a sum of a Gaussian (with a width and central value fixed from the MC simulation) and a threshold function \( f(m_{ES}) \) with the floating shape and normalization (see detailed expression of the likelihood function is Section 5). The fit yields 34 ± 12 events in the “signal” \( m_{ES} \) peak for \( "D_s^{(*)+} K^- \pi^-" \) and 3 ± 7 for \( "D_s^{(*)+} K^- \pi^-" \). Since the sideband interval is 1.5 times larger than the \( D_s^+ \) mass region used for signal selection, this translates into 23 ± 8 peaking background events expected in \( B^- \rightarrow D_s^+ K^- \pi^- \).

We also study cross-feed between the signal modes and other decays with final states similar to our signal modes, including \( D_s^{(*)+} K^- K^- \). The cut on \( \Delta E \) of the \( B^- \) candidates effectively suppresses the cross-feed contributions, which do not exceed 2% of the reconstructed signal after all the selection criteria are applied.

4 SYSTEMATIC STUDIES

The summary of the systematic uncertainties is presented in Table 3. The total relative systematic error is estimated to be 22% for each \( B^- \) decay mode, with the largest contribution coming from the \( D_s^+ \) branching fractions uncertainty (15%). Other significant sources of systematic errors are found to be due to the difference between the selection efficiency in MC events and in the data.
(estimated using the control mode $B^- \rightarrow D^- D^0$, $D^0 \rightarrow K^- \pi^+$), and also due to the efficiency dependence on the $D^{(s)+} K^-$ invariant mass and its potential effect if the resonant contribution is present.

Table 3: Summary of relative systematic errors (in %) for $B^- \rightarrow D_s^{(*)+} K^- \pi^-$ decays.

| Source                              | $B^- \rightarrow D_s^+ K^- \pi^-$ | $B^- \rightarrow D_s^{(*)+} K^- \pi^-$ |
|-------------------------------------|-----------------------------------|---------------------------------------|
| $B$ counting                        | 1.1                               | 1.1                                   |
| MC statistics                       | 0.8                               | 1.4                                   |
| Tracking                            | 5                                 | 5                                     |
| Particle identification efficiency  | 4                                 | 4                                     |
| $K^0_S$ efficiency                 | 0.5                               | 0.5                                   |
| $\gamma$ (from $D^{(*)+} \rightarrow D^+ \gamma$) efficiency | –                                | 2                                     |
| $B$ of sub-decays                   | 15                                | 15                                    |
| Peaking background contribution     | 6                                 | 3                                     |
| Cross-feed contribution             | 1                                 | 2                                     |
| Selection efficiency, Data/MC       | 12                                | 12                                    |
| Signal and background shape uncertainty | 3                               | 3                                     |
| $M(D^{(*)-} K^+)$ efficiency dependence | 7                               | 9                                     |
| Total                               | 22                                | 22                                    |

5 RESULTS

Figure 3 shows the $m_{\text{ES}}$ distributions for the reconstructed candidates $B^- \rightarrow D_s^+ K^- \pi^-$ and $B^- \rightarrow D_s^{(*)+} K^- \pi^-$. For each mode, we perform an extended unbinned ML fit to the $m_{\text{ES}}$ distributions using the candidates from all $D_s^+$ decay modes combined. We fit the $m_{\text{ES}}$ distributions with the sum of the function $f(m_{\text{ES}})$ characterizing the combinatorial background and a Gaussian function to describe the signal. The mean and width of the Gaussian function, the threshold shape parameter $\xi$, and the numbers of signal ($n_{\text{sig}}$) and background ($n_{\text{bkg}}$) events are free parameters of the fit. The likelihood function is given by:

$$L = \frac{e^{-(n_{\text{sig}} + n_{\text{bkg}})}}{N!} \prod_{i=1}^{N} (n_{\text{sig}} P_{i}^{\text{sig}} + n_{\text{bkg}} P_{i}^{\text{bkg}}),$$

where $P_{i}^{\text{sig}}$ and $P_{i}^{\text{bkg}}$ are the probability density functions for the signal and background, $N$ is the total number of events in the fit and $i$ is the index over all events in the fit.

The fit yields $393 \pm 25$ events in the $B^- \rightarrow D_s^+ K^- \pi^-$ mode. Taking into account the estimated peaking background contribution, we obtain $370 \pm 26$ signal events for $B^- \rightarrow D_s^{(*)+} K^- \pi^-$. The
Figure 3: $m_{ES}$ spectra for the $B^- \rightarrow D_s^+ K^- \pi^-$ (left) and $B^- \rightarrow D_s^{*-} K^- \pi^-$ (right) using the data. Solid curves show the fit results, as explained in the text. Dashed lines in the signal regions correspond to the background components of the fit.

number of $B^- \rightarrow D_s^{*+} K^- \pi^-$ signal events from the fit is $164 \pm 17$ (no peaking contribution is subtracted in this mode as it was estimated to be consistent with 0). We also fit signal yields in each of the $D_s^+$ modes, fixing the width and central values of the signal Gaussians to that of the combined fit, letting the background level and shape float. The ratio of the signal yields between submodes is consistent with the expectations from MC.

The total signal yield in each $B^-$ decay mode is calculated as a sum over $D_s^+$ modes, fixing the width and central values of the signal Gaussians to that of the combined fit, letting the background level and shape float. The ratio of the signal yields between submodes is consistent with the expectations from MC.

$$n_{sig} = B \cdot N_{BB} \cdot \sum_i B_i \cdot \epsilon_i,$$

where $N_{BB}$ is the number of produced $B \bar{B}$ pairs, $B_i$ is the product of the intermediate branching ratios and $\epsilon_i$ is the reconstruction efficiency (from Table 2). As an input to the calculation, we used branching fraction numbers from [9] and [12]. The relative systematic uncertainties are converted into absolute numbers using the measured central values. The results are:

$$B(B^- \rightarrow D_s^+ K^- \pi^-) = (1.88 \pm 0.13 \pm 0.41) \cdot 10^{-4}$$

$$B(B^- \rightarrow D_s^{*-} K^- \pi^-) = (1.84 \pm 0.19 \pm 0.40) \cdot 10^{-4}$$

In summary, two decay modes of charged $B$ mesons are observed for the first time. The significance of the observation is 14.2$\sigma$ for $B^- \rightarrow D_s^+ K^- \pi^-$ and 9.6$\sigma$ for $B^- \rightarrow D_s^{*-} K^- \pi^-$.  

6 ACKNOWLEDGMENTS

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and
National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l’Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, Ministerio de Educación y Ciencia (Spain), and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation.

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