# Improved Measurements of Branching Fractions for $B^{0} \rightarrow \pi^{+} \pi^{-}, K^{+} \pi^{-}$, and Search for $K^{+} K^{-}$at BABAR 

The BABAR Collaboration

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#### Abstract

We present preliminary measurements of branching fractions for the charmless two-body decays $B^{0} \rightarrow \pi^{+} \pi^{-}$and $K^{+} \pi^{-}$, and a search for $B^{0} \rightarrow K^{+} K^{-}$using a data sample of approximately 227 million $B \bar{B}$ decays. Signal yields are extracted with a multi-dimensional maximum likelihood fit, and the efficiency is corrected for the effects of final-state radiation. We find the charge-averaged branching fractions (in units of $10^{-6}$ ): $$
\begin{align*} \mathcal{B}\left(B^{0} \rightarrow \pi^{+} \pi^{-}\right) & =5.5 \pm 0.4 \pm 0.3  \tag{1}\\ \mathcal{B}\left(B^{0} \rightarrow K^{+} \pi^{-}\right) & =19.2 \pm 0.6 \pm 0.6  \tag{2}\\ \mathcal{B}\left(B^{0} \rightarrow K^{+} K^{-}\right) & =<0.40 \tag{3} \end{align*}
$$

The errors are statistical followed by systematic, and the upper limit on $K^{+} K^{-}$represents a confidence level of $90 \%$.

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Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309
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The BABAR Collaboration,
B. Aubert, R. Barate, D. Boutigny, F. Couderc, Y. Karyotakis, J. P. Lees, V. Poireau, V. Tisserand, A. Zghiche

Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France
E. Grauges

IFAE, Universitat Autonoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain
A. Palano, M. Pappagallo, A. Pompili

Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy
J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

Institute of High Energy Physics, Beijing 100039, China
G. Eigen, I. Ofte, B. Stugu

University of Bergen, Institute of Physics, N-5007 Bergen, Norway
G. S. Abrams, M. Battaglia, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, E. Charles, C. T. Day, M. S. Gill, A. V. Gritsan, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth,

Yu. G. Kolomensky, G. Kukartsev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, W. A. Wenzel

Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson University of Birmingham, Birmingham, B15 2TT, United Kingdom
M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizaeus, K. Peters, T. Schroeder, M. Steinke

Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
J. T. Boyd, J. P. Burke, N. Chevalier, W. N. Cottingham

University of Bristol, Bristol BS8 1TL, United Kingdom
T. Cuhadar-Donszelmann, B. G. Fulsom, C. Hearty, N. S. Knecht, T. S. Mattison, J. A. McKenna University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
A. Khan, P. Kyberd, M. Saleem, L. Teodorescu

Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
A. E. Blinov, V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, E. A. Kravchenko,
A. P. Onuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
D. Best, M. Bondioli, M. Bruinsma, M. Chao, S. Curry, I. Eschrich, D. Kirkby, A. J. Lankford, P. Lund, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker

University of California at Irvine, Irvine, California 92697, USA
C. Buchanan, B. L. Hartfiel, A. J. R. Weinstein

University of California at Los Angeles, Los Angeles, California 90024, USA
S. D. Foulkes, J. W. Gary, O. Long, B. C. Shen, K. Wang, L. Zhang

University of California at Riverside, Riverside, California 92521, USA
D. del Re, H. K. Hadavand, E. J. Hill, D. B. MacFarlane, H. P. Paar, S. Rahatlou, V. Sharma University of California at San Diego, La Jolla, California 92093, USA
J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, M. A. Mazur, J. D. Richman, W. Verkerke

University of California at Santa Barbara, Santa Barbara, California 93106, USA
T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroseberg, W. S. Lockman, G. Nesom, T. Schalk, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Piatenko, F. C. Porter, A. Ryd, A. Samuel

California Institute of Technology, Pasadena, California 91125, USA
R. Andreassen, S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff

University of Cincinnati, Cincinnati, Ohio 45221, USA
F. Blanc, P. Bloom, S. Chen, W. T. Ford, J. F. Hirschauer, A. Kreisel, U. Nauenberg, A. Olivas, P. Rankin, W. O. Ruddick, J. G. Smith, K. A. Ulmer, S. R. Wagner, J. Zhang University of Colorado, Boulder, Colorado 80309, USA
A. Chen, E. A. Eckhart, J. L. Harton, A. Soffer, W. H. Toki, R. J. Wilson, Q. Zeng Colorado State University, Fort Collins, Colorado 80523, USA
D. Altenburg, E. Feltresi, A. Hauke, B. Spaan

Universität Dortmund, Institut fur Physik, D-44221 Dortmund, Germany
T. Brandt, J. Brose, M. Dickopp, V. Klose, H. M. Lacker, R. Nogowski, S. Otto, A. Petzold, G. Schott, J. Schubert, K. R. Schubert, R. Schwierz, J. E. Sundermann

Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
D. Bernard, G. R. Bonneaud, P. Grenier, S. Schrenk, Ch. Thiebaux, G. Vasileiadis, M. Verderi

Ecole Polytechnique, LLR, F-91128 Palaiseau, France
D. J. Bard, P. J. Clark, W. Gradl, F. Muheim, S. Playfer, Y. Xie

University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Luppi, M. Negrini, L. Piemontese

Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
F. Anulli, R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, G. Finocchiaro, P. Patteri, I. M. Peruzzi, ${ }^{1}$ M. Piccolo, A. Zallo

Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy

[^0]A. Buzzo, R. Capra, R. Contri, M. Lo Vetere, M. Macri, M. R. Monge, S. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
G. Brandenburg, K. S. Chaisanguanthum, M. Morii, E. Won, J. Wu

Harvard University, Cambridge, Massachusetts 02138, USA
R. S. Dubitzky, U. Langenegger, J. Marks, S. Schenk, U. Uwer

Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
W. Bhimji, D. A. Bowerman, P. D. Dauncey, U. Egede, R. L. Flack, J. R. Gaillard, G. W. Morton, J. A. Nash, M. B. Nikolich, G. P. Taylor, W. P. Vazquez

Imperial College London, London, SW7 2AZ, United Kingdom
M. J. Charles, W. F. Mader, U. Mallik, A. K. Mohapatra

University of Iowa, Iowa City, Iowa 52242, USA
J. Cochran, H. B. Crawley, V. Eyges, W. T. Meyer, S. Prell, E. I. Rosenberg, A. E. Rubin, J. Yi Iowa State University, Ames, Iowa 50011-3160, USA
N. Arnaud, M. Davier, X. Giroux, G. Grosdidier, A. Höcker, F. Le Diberder, V. Lepeltier, A. M. Lutz, A. Oyanguren, T. C. Petersen, M. Pierini, S. Plaszczynski, S. Rodier, P. Roudeau, M. H. Schune, A. Stocchi, G. Wormser

Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
C. H. Cheng, D. J. Lange, M. C. Simani, D. M. Wright

Lawrence Livermore National Laboratory, Livermore, California 94550, USA
A. J. Bevan, C. A. Chavez, I. J. Forster, J. R. Fry, E. Gabathuler, R. Gamet, K. A. George, D. E. Hutchcroft, R. J. Parry, D. J. Payne, K. C. Schofield, C. Touramanis University of Liverpool, Liverpool L69 72E, United Kingdom
C. M. Cormack, F. Di Lodovico, W. Menges, R. Sacco

Queen Mary, University of London, E1 4 NS, United Kingdom
C. L. Brown, G. Cowan, H. U. Flaecher, M. G. Green, D. A. Hopkins, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore

University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 OEX, United Kingdom
D. Brown, C. L. Davis

University of Louisville, Louisville, Kentucky 40292, USA
J. Allison, N. R. Barlow, R. J. Barlow, C. L. Edgar, M. C. Hodgkinson, M. P. Kelly, G. D. Lafferty, M. T. Naisbit, J. C. Williams

University of Manchester, Manchester M13 9PL, United Kingdom
C. Chen, W. D. Hulsbergen, A. Jawahery, D. Kovalskyi, C. K. Lae, D. A. Roberts, G. Simi

University of Maryland, College Park, Maryland 20742, USA
G. Blaylock, C. Dallapiccola, S. S. Hertzbach, R. Kofler, V. B. Koptchev, X. Li, T. B. Moore, S. Saremi, H. Staengle, S. Willocq

University of Massachusetts, Amherst, Massachusetts 01003, USA
R. Cowan, K. Koeneke, 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, P. M. Patel, S. H. Robertson

McGill University, Montréal, Quebec, Canada H3A $2 T 8$
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, J. Reidy, D. A. Sanders, D. J. Summers, H. W. Zhao

University of Mississippi, University, Mississippi 38677, USA
S. Brunet, D. Côté, P. Taras, B. Viaud

Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7
H. Nicholson

Mount Holyoke College, South Hadley, Massachusetts 01075, USA
N. Cavallo, ${ }^{2}$ G. De Nardo, F. Fabozzi, ${ }^{2}$ 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. Baak, H. Bulten, G. Raven, H. L. Snoek, L. Wilden

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, K. K. Gan, K. Honscheid, D. Hufnagel, P. D. Jackson, H. Kagan, R. Kass, T. Pulliam, A. M. Rahimi, R. Ter-Antonyan, Q. K. Wong Ohio State University, Columbus, Ohio 43210, USA
J. Brau, R. Frey, O. Igonkina, M. Lu, C. T. Potter, N. B. Sinev, D. Strom, J. Strube, E. Torrence University of Oregon, Eugene, Oregon 97403, USA
F. Galeazzi, M. Margoni, M. Morandin, M. Posocco, M. Rotondo, F. Simonetto, R. Stroili, C. Voci Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
M. Benayoun, H. Briand, J. Chauveau, P. David, L. Del Buono, Ch. de la Vaissière, O. Hamon, M. J. J. John, Ph. Leruste, J. Malclès, J. Ocariz, M. Pivk, L. Roos, G. Therin Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, F-75252 Paris, France

[^1]P. K. Behera, L. Gladney, Q. H. Guo, J. Panetta University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA<br>M. Biasini, R. Covarelli, S. Pacetti, M. Pioppi<br>Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy

C. Angelini, G. Batignani, S. Bettarini, F. Bucci, G. Calderini, M. Carpinelli, R. Cenci, F. Forti, M. A. Giorgi, A. Lusiani, G. Marchiori, M. Morganti, N. Neri, E. Paoloni, M. Rama, G. Rizzo, J. Walsh Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
M. Haire, D. Judd, D. E. Wagoner

Prairie View Aछ'M University, Prairie View, Texas 77446, USA
J. Biesiada, N. Danielson, P. Elmer, Y. P. Lau, C. Lu, J. Olsen, A. J. S. Smith, A. V. Telnov

Princeton University, Princeton, New Jersey 08544, USA
E. Baracchini, F. Bellini, G. Cavoto, A. D'Orazio, E. Di Marco, R. Faccini, F. Ferrarotto, F. Ferroni, M. Gaspero, L. Li Gioi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Polci, F. Safai Tehrani, C. Voena Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
H. Schröder, G. Wagner, R. Waldi

Universität Rostock, D-18051 Rostock, Germany
T. Adye, N. De Groot, B. Franek, G. P. Gopal, E. O. Olaiya, F. F. Wilson

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
R. Aleksan, S. Emery, A. Gaidot, S. F. Ganzhur, P.-F. Giraud, G. Graziani, G. Hamel de Monchenault, W. Kozanecki, M. Legendre, G. W. London, B. Mayer, G. Vasseur, Ch. Yèche, M. Zito

DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
M. V. Purohit, A. W. Weidemann, J. R. Wilson, F. X. Yumiceva University of South Carolina, Columbia, South Carolina 29208, USA
T. Abe, M. T. Allen, D. Aston, N. van Bakel, R. Bartoldus, N. Berger, A. M. Boyarski, O. L. Buchmueller, R. Claus, J. P. Coleman, M. R. Convery, M. Cristinziani, J. C. Dingfelder, D. Dong, J. Dorfan, D. Dujmic, W. Dunwoodie, S. Fan, R. C. Field, T. Glanzman, S. J. Gowdy, T. Hadig, V. Halyo, C. Hast, T. Hryn'ova, W. R. Innes, M. H. Kelsey, P. Kim, M. L. Kocian, D. W. G. S. Leith, J. Libby, S. Luitz, V. Luth, H. L. Lynch, H. Marsiske, R. Messner, D. R. Muller, C. P. O’Grady, V. E. Ozcan, A. Perazzo, M. Perl, B. N. Ratcliff, A. Roodman, A. A. Salnikov, R. H. Schindler, J. Schwiening, A. Snyder, J. Stelzer, D. Su, M. K. Sullivan, K. Suzuki, S. Swain, J. M. Thompson, J. Va'vra, M. Weaver, 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

Stanford University, Stanford, California 94305-4060, USA
M. Ahmed, S. Ahmed, M. S. Alam, J. A. Ernst, 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, R. F. Schwitters

University of Texas at Austin, Austin, Texas 78712, USA
J. M. Izen, I. Kitayama, X. C. Lou, S. Ye

University of Texas at Dallas, Richardson, Texas 75083, USA
F. Bianchi, M. Bona, 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, S. Grancagnolo, L. Lanceri, L. Vitale

Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
F. Martinez-Vidal

IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
R. S. Panvini ${ }^{3}$

Vanderbilt University, Nashville, Tennessee 37235, USA
Sw. Banerjee, B. Bhuyan, C. M. Brown, D. Fortin, K. Hamano, R. Kowalewski, 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

Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
H. R. Band, X. Chen, B. Cheng, S. Dasu, M. Datta, A. M. Eichenbaum, K. T. Flood, M. Graham, J. J. Hollar, J. R. Johnson, P. E. Kutter, H. Li, R. Liu, B. Mellado, A. Mihalyi, Y. Pan, R. Prepost, P. Tan, J. H. von Wimmersperg-Toeller, S. L. Wu, Z. Yu

University of Wisconsin, Madison, Wisconsin 53706, USA
H. Neal

Yale University, New Haven, Connecticut 06511, USA

[^2]
## 1 INTRODUCTION

Charmless hadronic two-body $B$ decays to pions and kaons provide a wealth of information on $C P$ violation in the $B$ system, including all three angles of the unitarity triangle. The time-dependent $C P$ asymmetries in the $\pi \pi$ system can be used to measure the angle $\alpha[1]$ the decay rates for the $K \pi$ channels provide information on $\gamma[2]$; and the time-dependent $C P$ asymmetry in $\pi^{0} K_{S}^{0}$ approximately measures $\beta$ in the standard model [3] and is a sensitive probe of new physics in the $b \rightarrow s$ penguin-decay process [4. Recently, direct $C P$ violation in decay was established in the $B$ system through observation of a significant rate asymmetry between $B^{0} \rightarrow K^{+} \pi^{-}$and $\bar{B}^{0} \rightarrow K^{-} \pi^{+}$[5] . As $B$-physics experiments accumulate much larger data sets, charmless twobody $B$ decays will continue to play a critical role in testing the standard model description of $C P$ violation.

In order to extract the maximum information from these decays it is necessary to understand the underlying hadron dynamics, and measurements of branching fractions for all of the charmless two-body $B$ decays involving combinations of $\pi^{ \pm}, K^{ \pm}, \pi^{0}$, and $K_{S}^{0}$ are invaluable in testing the various theoretical approaches [7]. We present preliminary measurements of branching fractions for the decays [8] $B^{0} \rightarrow \pi^{+} \pi^{-}$and $K^{+} \pi^{-}$, and a search for the decay $B^{0} \rightarrow K^{+} K^{-}$using a data set 2.5 times larger than the one used for our previous measurements of these quantities [9. Table 1 summarizes previous experimental measurements [9, 10, 11] and current theoretical estimates of the branching fractions for these decays.

## 2 THE BABAR DETECTOR AND DATASET

The data sample used for this search contains $(226.6 \pm 2.5) \times 10^{6} \Upsilon(4 S) \rightarrow B \bar{B}$ decays collected by the BABAR detector [12] at the SLAC PEP-II $e^{+} e^{-}$asymmetric-energy storage ring. The primary detector components used in the analysis are a charged-particle tracking system consisting of a five-layer silicon vertex detector and a 40 -layer drift chamber surrounded by a $1.5-\mathrm{T}$ solenoidal magnet, and a dedicated particle-identification system consisting of a detector of internally reflected Cherenkov light (DIRC) providing $K-\pi$ separation over the range of laboratory momentum relevant for this analysis ( $1.5-4.5 \mathrm{GeV} / c$ ).

Table 1: Summary of existing branching fraction measurements (in units of $10^{-6}$ ) and theoretical estimates for the decays $B^{0} \rightarrow \pi^{+} \pi^{-}, K^{+} \pi^{-}, K^{+} K^{-}$. Theory estimates are from Beneke et al. and Keum in Ref. [7].

| Mode | $\mathcal{B}($ BABAR $)[9]$ | $\mathcal{B}($ Belle $)[10]$ | $\mathcal{B}($ CLEO $)[11]$ | Theory |
| :---: | :---: | :---: | :---: | :---: |
| $\pi^{+} \pi^{-}$ | $4.7 \pm 0.6 \pm 0.2$ | $4.4 \pm 0.6 \pm 0.3$ | $4.5_{-1.2}^{+1.4}+0.5$ | $4.6-11.0$ |
| $K^{+} \pi^{-}$ | $17.9 \pm 0.9 \pm 0.7$ | $18.5 \pm 1.0 \pm 0.7$ | $18.0_{-2.1}^{+2.3}-1.2$ | $12.7-21.0$ |
| $K^{+} K^{-}$ | $<0.6$ | $<0.7$ | $<0.8$ | $0.007-0.080$ |

Table 2: Summary of total detection efficiencies (\%) for signal decays determined in GEANT Monte Carlo samples without FSR effects, compared with the results using PHOTOS and the leadingorder QED calculation. We use the latter result in calculating the branching fraction and take the difference with PHOTOS as the systematic uncertainty. Uncertainties are statistical only.

| Mode | No FSR | PHOTOS | QED |
| :---: | :---: | :---: | :---: |
| $\pi^{+} \pi^{-}$ | $40.9 \pm 0.2$ | $39.9 \pm 0.2$ | $39.4 \pm 0.2$ |
| $K^{+} \pi^{-}$ | $39.9 \pm 0.2$ | $38.9 \pm 0.2$ | $38.4 \pm 0.2$ |
| $K^{+} K^{-}$ | $38.6 \pm 0.3$ | $37.8 \pm 0.3$ | $37.6 \pm 0.3$ |

## 3 ANALYSIS METHOD

The data sample used in this analysis is similar to that used in the BABAR measurements of direct $C P$ violation in $K^{+} \pi^{-}\left[5\right.$ and time-dependent $C P$-violating asymmetry amplitudes $S_{\pi \pi}$ and $C_{\pi \pi}$ [13] (the reader is referred to those references for further details on the analysis technique). Relative to the event selection applied in the $C P$ analyses, we remove the requirement on the difference in the decay times $(\Delta t)$ between the two $B$ mesons in order to minimize systematic uncertainty on the branching fraction measurements. All other selection criteria are identical to those applied in Refs. [5, 13. We identify $B \rightarrow h^{+} h^{-}(h=\pi$ or $K)$ candidates with selection requirements on track and Cherenkov-angle $\left(\theta_{c}\right)$ quality, $B$-decay kinematics, and event topology, and determine signal and background yields through a multi-dimensional maximum-likelihood fit. The final sample contains 69264 events and is defined by requirements on the energy difference, $|\Delta E|<150 \mathrm{MeV}$, and energy-substituted mass, $5.20<m_{\mathrm{ES}}<5.29 \mathrm{GeV} / c^{2}$, of the selected $B$ candidates 14.

The efficiency of the selection criteria is determined in large samples of GEANT-based Monte Carlo simulated signal decays. We include the effects of electromagnetic radiation from charged particles using the PHOTOS simulation package [15. The addition of final-state radiation (FSR) leads to the development of a low-energy tail in the distribution of $\Delta E$ for $B^{0} \rightarrow h^{+} h^{-}$signal candidates, which can cause some fraction of events to fail the $|\Delta E|<150 \mathrm{MeV}$ requirement. We have implemented a detailed QED calculation [16] up to $\mathcal{O}(\alpha)$ in order to correct the efficiency obtained by the PHOTOS simulation. Table 2 summarizes the comparison of the efficiencies for the different modes assuming no FSR, the PHOTOS result, and the QED calculation. For the branching fraction measurement we use the efficiency as determined by the QED calculation, and take the difference with respect to PHOTOS as the systematic uncertainty.

In addition to signal $\pi^{+} \pi^{-}, K^{+} \pi^{-}$, and (possibly) $K^{+} K^{-}$events, the selected sample includes background from the process $e^{+} e^{-} \rightarrow q \bar{q}(q=u, d, s, c)$. Possible backgrounds from other $B$ decays are small relative to the signal yields ( $<1 \%$ ), and are treated as a systematic uncertainty. We use an unbinned, extended maximum-likelihood fit to extract simultaneously signal and background yields in the three topologies $(\pi \pi, K \pi$, and $K K)$. The fit uses the discriminating variables $m_{\mathrm{ES}}$, $\Delta E, \theta_{c}$, and the Fisher discriminant $\mathcal{F}$ described in Ref. [9], where the likelihood for event $j$ is obtained by summing the product of the event yield $n_{i}$ and probability $\mathcal{P}_{i}$ over the signal and background hypotheses $i$. The total likelihood for the sample is

$$
\begin{equation*}
\mathcal{L}=\exp \left(-\sum_{i} n_{i}\right) \prod_{j}\left[\sum_{i} n_{i} \mathcal{P}_{i}\left(\vec{x}_{j} ; \vec{\alpha}_{i}\right)\right] \tag{4}
\end{equation*}
$$

The probabilities $\mathcal{P}_{i}$ are evaluated as the product of the probability density functions (PDFs) with parameters $\overrightarrow{\alpha_{i}}$, for each of the independent variables $\vec{x}_{j}=\left\{m_{\mathrm{ES}}, \Delta E, \mathcal{F}, \theta_{c}^{+}, \theta_{c}^{-}\right\}$, where $\theta_{c}^{+}$and $\theta_{c}^{-}$are the Cherenkov angles for the positively- and negatively-charged tracks, respectively. The largest correlation between the $\vec{x}_{j}$ is $13 \%$ for the pair ( $m_{\mathrm{ES}}, \Delta E$ ) and we have confirmed that it has negligible effect on the fitted yields. For both signal and background, the $K^{ \pm} \pi^{\mp}$ yields are parameterized as $n_{K^{ \pm} \pi^{\mp}}=n_{K \pi}\left(1 \mp \mathcal{A}_{K \pi}\right) / 2$, and we fit directly for the total yield $n_{K \pi}$ and the asymmetry $\mathcal{A}_{K \pi}$. The result for $\mathcal{A}_{K \pi}$ is used only as a consistency check and does not supersede our previously published result [5].

The eight parameters describing the background shapes for $m_{\mathrm{ES}}, \Delta E$, and $\mathcal{F}$ are all allowed to vary freely in the maximum-likelihood fit. We use a threshold function [17] for $m_{\mathrm{ES}}$ ( 1 parameter), a second-order polynomial for $\Delta E$ ( 2 parameters), and a sum of two Gaussian distributions for $\mathcal{F}$ (5 parameters). For the signal shape in $m_{\mathrm{ES}}$, we use a single Gaussian distribution to describe all three channels and allow the mean and width to vary freely in the fit. For $\Delta E$, we use the sum of two Gaussian distributions (core + tail), where the core parameters are common to all channels and allowed to vary freely, and the tail parameters are determined separately for each channel from Monte Carlo simulation and fixed in the fit. Given that the tail is dominated by FSR effects, we take the shape directly from the Monte Carlo samples after correcting for the difference between PHOTOS and the QED calculation. For the signal shape in $\mathcal{F}$, we use an asymmetric Gaussian function with different widths below and above the mean. All three parameters are determined in Monte Carlo simulation and fixed in the maximum-likelihood fit. The $\theta_{c}$ PDFs are obtained from a sample of approximately $430000 D^{*+} \rightarrow D^{0} \pi^{+}\left(D^{0} \rightarrow K^{-} \pi^{+}\right)$decays reconstructed in data, where $K^{\mp} / \pi^{ \pm}$tracks are identified through the charge correlation with the $\pi^{ \pm}$from the $D^{* \pm}$ decay. The PDFs are constructed separately for $K^{+}, K^{-}, \pi^{+}$, and $\pi^{-}$tracks as a function of momentum and polar angle using the measured and expected values of $\theta_{c}$, and its uncertainty. We use the same PDFs for signal and background events.

Table 3 summarizes the fitted signal and background yields, and $K \pi$ charge asymmetries. We find a value of $\mathcal{A}_{K \pi}$ consistent with our previously published result, and a background asymmetry consistent with zero. The signal yields are somewhat higher than the values reported in Ref. [5] due to the removal of the $\Delta t$ selection requirement and the addition of the radiative tail in the signal $\Delta E$ PDF. In order to quantify the effect of FSR on the fitted yields, we perform a second fit using a single Gaussian for the $\Delta E$ PDF allowing the mean and width to vary freely. The results are shown in the second column of Table 3 where we find that ignoring FSR lowers the $\pi \pi$ yield by $4.5 \%$ and the $K \pi$ yield by $2.4 \%$.

As a crosscheck, in Figs. $\mathbb{1}$ and 2 we compare the PDF shapes (solid curves) to the data using the event-weighting technique described in Ref. [18. For each plot, we perform a fit excluding the variable being plotted and use the fitted yields and covariance matrix to determine a weight that each event is either signal or background. The distribution is normalized to the yield for the given component and can be compared directly to the assumed PDF shape. For $m_{\mathrm{ES}}, \Delta E$, and $\mathcal{F}$, we find excellent agreement for signal $\pi \pi$ and $K \pi$ events (Fig. (1), as well as the sum of all channels for background events (Fig. (2). We have verified separately that the background PDF shapes agree for all three channels. Figure 3 shows the likelihood ratio $\mathcal{L}_{S} / \sum \mathcal{L}_{i}$ for all 69264 events in the fitted sample, where $\mathcal{L}_{S}$ is the likelihood for a given signal hypothesis, and the summation in the denominator is over all signal and background components in the fit. We find satisfactory agreement between data (points with error bars) and the distributions obtained by directly generating events from the PDFs (histograms).

Table 3: Summary of the branching fraction fit using a sample of approximately 227 million $B \bar{B}$ pairs. For comparison, we show the results using a single Gaussian for the signal $\Delta E \mathrm{PDF}$, which would correspond to an analysis that ignores FSR effects.

| Parameter | Nominal Fit | Ignoring FSR |
| :---: | :---: | :---: |
| $N_{\pi \pi}$ | $491 \pm 35$ | $469 \pm 34$ |
| $N_{K \pi}$ | $1674 \pm 53$ | $1634 \pm 52$ |
| $\mathcal{A}_{K \pi}$ | $-0.135 \pm 0.030$ | $-0.135 \pm 0.030$ |
| $N_{K K}$ | $3.0 \pm 13.1$ | $5.3 \pm 12.6$ |
| $N_{b \pi \pi}$ | $32977 \pm 194$ | $32998 \pm 194$ |
| $N_{b K \pi}$ | $20761 \pm 169$ | $20801 \pm 169$ |
| $\mathcal{A}_{b K \pi}$ | $0.002 \pm 0.008$ | $0.002 \pm 0.008$ |
| $N_{b K K}$ | $13358 \pm 126$ | $13356 \pm 126$ |



Figure 1: Distributions (points with error bars) of $m_{\mathrm{ES}}, \Delta E$, and $\mathcal{F}$ for signal $\pi^{+} \pi^{-}(\mathrm{a}, \mathrm{b}, \mathrm{c})$ and $K^{+} \pi^{-}$(d,e,f) decays using the weighting technique described in Ref. [18]. Solid curves represent the corresponding PDFs used in the fit. The distribution of $\Delta E$ for $K^{+} \pi^{-}$events is shifted due to the assignment of the pion mass for all tracks.


Figure 2: Distributions of a) $m_{\mathrm{ES}}$, b) $\Delta E$, and c) $\mathcal{F}$ for $q \bar{q}$ background events (points with error bars) using the weighting technique described in Ref. [18]. Solid curves represent the corresponding PDFs used in the fit.


Figure 3: The likelihood ratio $\mathcal{L}_{S} / \sum \mathcal{L}_{i}$, where $\mathcal{L}_{S}$ is the likelihood for each event to be a signal $\pi \pi$ (left), $K \pi$ (middle), or $K K$ (right) event. The points with error bars show the distribution obtained on the fitted data sample, while the histograms show the distributions obtained by generating signal (red) and background (blue) events directly from the PDFs.

Table 4: Summary of relative systematic uncertainties on yields, efficiencies, and number of $B \bar{B}$ pairs. For the $K^{+} K^{-}$yield we show the absolute uncertainty. The total uncertainties for $\pi^{+} \pi^{-}$ and $K^{+} \pi^{-}$are calculated as the sum in quadrature of the individual contributions.

| Source | $\pi^{+} \pi^{-}$ | $K^{+} \pi^{-}$ | $K^{+} K^{-}$ |
| :---: | :---: | :---: | :---: |
| yields | $3.8 \%$ | $1.8 \%$ | 6.8 |
| efficiency | $2.6 \%$ | $2.5 \%$ | $2.0 \%$ |
| $N_{B \bar{B}}$ | $1.1 \%$ | $1.1 \%$ | $1.1 \%$ |
| Total | $4.7 \%$ | $3.3 \%$ | $\mathrm{n} / \mathrm{a}$ |

## 4 SYSTEMATIC STUDIES

Systematic uncertainties on the branching fractions arise from uncertainties on the selection efficiency, signal yield, and number of $B \bar{B}$ events in the sample. Uncertainty on the efficiency is dominated by track reconstruction ( $1.6 \%$ ) and the effect of FSR $(1.3 \%)$, which is taken to be the difference between the efficiency as determined in the PHOTOS simulation and the QED calculation (Table 2). Uncertainty on the fitted signal yields is dominated by the shape of the signal PDF for $\mathcal{F}(2.9 \%$ for $\pi \pi, 1.5 \%$ for $K \pi)$ and potential bias $(2.2 \%$ for $\pi \pi, 0.9 \%$ for $K \pi)$ in the fitting technique determined from large samples of Monte Carlo signal events and a large ensemble of pseudo-experiments generated from the PDF shapes. Uncertainties due to imperfect knowledge of the PDF shapes for $m_{\mathrm{ES}}, \Delta E$, and $\theta_{c}$ are all less than $1 \%$. Table 4 summarizes the total uncertainty on the branching fractions, which is calculated as the sum in quadrature of the individual uncertainties.

## 5 RESULTS and SUMMARY

Table 5 summarizes the preliminary results for the charge-averaged branching fractions. For comparison, we use the efficiencies and signal yields determined under the assumption of no FSR and find $\mathcal{B}\left(B^{0} \rightarrow \pi^{+} \pi^{-}\right)=5.1 \times 10^{-6}$ and $\mathcal{B}\left(B^{0} \rightarrow K^{+} \pi^{-}\right)=18.1 \times 10^{-6}$, which are consistent with our previously published results [9]. Taking into account FSR effects leads to an increase of the branching fractions by approximately $8 \%$ and $6 \%$ for $\pi \pi$ and $K \pi$, respectively. The upper limit on the signal yield for $K K$ is given by the value of $N_{0}$ for which $\int_{0}^{N_{0}} \mathcal{L}_{\text {max }} d N / \int_{0}^{\infty} \mathcal{L}_{\text {max }} d N=0.90$, corresponding to a one-sided $90 \%$ confidence interval. Here, $\mathcal{L}_{\text {max }}$ is the likelihood as a function of $N$, maximized with respect to the remaining fit parameters. We find $N_{0}=25.9$, and the branching fraction is calculated by increasing the signal yield upper limit and reducing the efficiency by their respective total errors (Table (4). For the purpose of combining with measurements by other experiments, we have also evaluated the central value for the branching fraction and find $\mathcal{B}\left(B^{0} \rightarrow K^{+} K^{-}\right)=(4 \pm 15 \pm 8) \times 10^{-8}$.

In summary, we have presented preliminary updated measurements of charge-averaged branching fractions for the decays $B^{0} \rightarrow \pi^{+} \pi^{-}$and $B^{0} \rightarrow K^{+} \pi^{-}$, where FSR effects have been taken into account. We find a value of $\mathcal{A}_{K \pi}$ consistent with the result in Ref. [5], and branching fractions $6-8 \%$ higher due to the effect of FSR on the efficiency and signal-yield determination. This difference should be taken into account when comparing with previous measurements of these quantities (Table (1) that do not include these effects. Our results are consistent with current theoretical

Table 5: Summary of branching fraction results in a sample of $(226.6 \pm 1.2) \times 10^{6} B \bar{B}$ pairs. We show signal yields $N_{S}$, total detection efficiencies $(\epsilon)$ and branching fractions $\mathcal{B}$ in units of $10^{-6}$. The errors are statistical and systematic, respectively, and the upper limit on $B^{0} \rightarrow K^{+} K^{-}$corresponds to the $90 \%$ confidence level.

| Mode | $N_{S}$ | $\epsilon(\%)$ | $\mathcal{B}\left(10^{-6}\right)$ |
| :--- | :---: | :---: | :---: |
| $\pi^{+} \pi^{-}$ | $491 \pm 35 \pm 11$ | $39.4 \pm 0.2 \pm 0.9$ | $5.5 \pm 0.4 \pm 0.3$ |
| $K^{+} \pi^{-}$ | $1674 \pm 53 \pm 15$ | $38.4 \pm 0.2 \pm 0.8$ | $19.2 \pm 0.6 \pm 0.6$ |
| $K^{+} K^{-}$ | $3.0 \pm 13.1 \pm 6.8(<25.9)$ | $37.6 \pm 0.3 \pm 0.8$ | $<0.40$ (90\% C.L.) |

estimates using various techniques [7]. We find no evidence for the decay $B^{0} \rightarrow K^{+} K^{-}$and set an upper limit of $4.0 \times 10^{-7}$ at the $90 \%$ confidence level.

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## References

[1] M. Gronau, Phys. Rev. Lett. 63, 1451 (1989); M. Gronau and D. London, Phys. Rev. Lett. 65, 3381 (1990).
[2] M. Gronau, J. L. Rosner, and D. London, Phys. Rev. Lett. 73, 21 (1994); R. Fleischer and T. Mannel, Phys. Rev. D 57, 2752 (1998); M. Neubert and J. L. Rosner, Phys. Lett. B 441, 403 (1998); A. J. Buras and R. Fleischer, Eur. Phys. Jour. C 11, 93 (1999); for a recent review see M. Gronau and J. L. Rosner, hep-ph/0311280 (2003).
[3] R. Fleischer, Phys. Lett. B 365, 399 (1996).
[4] M. Gronau, Y. Grossman, and J. L. Rosner, Phys. Lett. B 579, 331 (2004).
[5] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 93, 131801 (2004).
[6] Y. Chao et al., Phys. Rev. Lett. 93, 191802 (2004).
[7] M. Ciuchini et al., Phys. Lett. B 515, 33 (2001); C. W. Bauer, S. Fleming, D. Pirjol, and I. W. Stewart, Phys. Rev. D 63, 114020 (2001); M. Beneke and M. Neubert, Nucl. Phys. B 675, 333 (2003); J. Charles et al., Eur. Phys. Jour. C 31, 503 (2003); Y.-Y. Keum, Pramana 63, 1151 (2004); C.-W. Chiang, M. Gronau, J. L. Rosner, and D. A. Suprun, Phys. Rev. D 70, 034020 (2004); A. J. Buras, R. Fleischer, S. Recksiegel, and F. Schwab, Nucl. Phys. B 697, 133 (2004).
[8] The use of charge conjugate modes is implied throughout this paper unless otherwise stated.
[9] BABAR Collaboration, B. Aubert et al., Phys. Rev. Lett. 89, 281802 (2002).
[10] Belle Collaboration, Y. Chao et al., Phys. Rev. D 69, 111102 (2004).
[11] CLEO Collaboration, A. Bornheim et al., Phys. Rev. D 68, 052002 (2003).
[12] BABAR Collaboration, B. Aubert et al., Nucl. Instrum. Methods A479, 1-116 (2002).
[13] BABAR Collaboration, B. Aubert et al., hep-ex/0501071, to appear in Phys. Rev. Lett. (2005).
[14] The variables $\Delta E$ and $m_{E S}$ are defined in Ref. [5].
[15] E. Barberio and Z. Was, Comput. Phys. Commun. 79, 291 (1994). We use version 2.03.
[16] E. Baracchini and G. Isidori, hep-ph/0508071
[17] ARGUS Collaboration, H. Albrecht et al., Z. Phys. C 48, 543 (1990).
[18] M. Pivk and F. R. Le Diberder, physics/0402083, submitted to Nucl. Instr. Methods.


[^0]:    ${ }^{1}$ Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

[^1]:    ${ }^{2}$ Also with Università della Basilicata, Potenza, Italy

[^2]:    ${ }^{3}$ Deceased

