

Measurement of B Decays to $\phi K\gamma$

B. Aubert,¹ M. Bona,¹ D. Boutigny,¹ F. Couderc,¹ Y. Karyotakis,¹ J. P. Lees,¹ V. Poireau,¹ V. Tisserand,¹ A. Zghiche,¹ E. Grauges,² A. Palano,³ J. C. Chen,⁴ N. D. Qi,⁴ G. Rong,⁴ P. Wang,⁴ Y. S. Zhu,⁴ G. Eigen,⁵ I. Ofte,⁵ B. Stugu,⁵ G. S. Abrams,⁶ M. Battaglia,⁶ D. N. Brown,⁶ J. Button-Shafer,⁶ R. N. Cahn,⁶ E. Charles,⁶ M. S. Gill,⁶ Y. Groysman,⁶ R. G. Jacobsen,⁶ J. A. Kadyk,⁶ L. T. Kerth,⁶ Yu. G. Kolomensky,⁶ G. Kukartsev,⁶ D. Lopes Pegna,⁶ G. Lynch,⁶ L. M. Mir,⁶ T. J. Orimoto,⁶ M. Pripstein,⁶ N. A. Roe,⁶ M. T. Ronan,⁶ W. A. Wenzel,⁶ P. del Amo Sanchez,⁷ M. Barrett,⁷ K. E. Ford,⁷ T. J. Harrison,⁷ A. J. Hart,⁷ C. M. Hawkes,⁷ A. T. Watson,⁷ T. Held,⁸ H. Koch,⁸ B. Lewandowski,⁸ M. Pelizaeus,⁸ K. Peters,⁸ T. Schroeder,⁸ M. Steinke,⁸ J. T. Boyd,⁹ J. P. Burke,⁹ W. N. Cottingham,⁹ D. Walker,⁹ D. J. Asgeirsson,¹⁰ T. Cuhadar-Donszelmann,¹⁰ B. G. Fulsom,¹⁰ C. Hearty,¹⁰ N. S. Knecht,¹⁰ T. S. Mattison,¹⁰ J. A. McKenna,¹⁰ A. Khan,¹¹ P. Kyberd,¹¹ M. Saleem,¹¹ D. J. Sherwood,¹¹ L. Teodorescu,¹¹ V. E. Blinov,¹² A. D. Bukin,¹² V. P. Druzhinin,¹² V. B. Golubev,¹² A. P. Onuchin,¹² S. I. Serednyakov,¹² Yu. I. Skovpen,¹² E. P. Solodov,¹² K. Yu. Todyshev,¹² D. S. Best,¹³ M. Bondioli,¹³ M. Bruinsma,¹³ M. Chao,¹³ S. Curry,¹³ I. Eschrich,¹³ D. Kirkby,¹³ A. J. Lankford,¹³ P. Lund,¹³ M. Mandelkern,¹³ W. Roethel,¹³ D. P. Stoker,¹³ S. Abachi,¹⁴ C. Buchanan,¹⁴ S. D. Foulkes,¹⁵ J. W. Gary,¹⁵ O. Long,¹⁵ B. C. Shen,¹⁵ K. Wang,¹⁵ L. Zhang,¹⁵ H. K. Hadavand,¹⁶ E. J. Hill,¹⁶ H. P. Paar,¹⁶ S. Rahatlou,¹⁶ V. Sharma,¹⁶ J. W. Berryhill,¹⁷ C. Campagnari,¹⁷ A. Cunha,¹⁷ B. Dahmes,¹⁷ T. M. Hong,¹⁷ D. Kovalskyi,¹⁷ J. D. Richman,¹⁷ T. W. Beck,¹⁸ A. M. Eisner,¹⁸ C. J. Flacco,¹⁸ C. A. Heusch,¹⁸ J. Kroseberg,¹⁸ W. S. Lockman,¹⁸ G. Nesom,¹⁸ T. Schalk,¹⁸ B. A. Schumm,¹⁸ A. Seiden,¹⁸ P. Spradlin,¹⁸ D. C. Williams,¹⁸ M. G. Wilson,¹⁸ J. Albert,¹⁹ E. Chen,¹⁹ C. H. Cheng,¹⁹ A. Dvoretzki,¹⁹ F. Fang,¹⁹ D. G. Hitlin,¹⁹ I. Narsky,¹⁹ T. Piatenko,¹⁹ F. C. Porter,¹⁹ G. Mancinelli,²⁰ B. T. Meadows,²⁰ K. Mishra,²⁰ M. D. Sokoloff,²⁰ F. Blanc,²¹ P. C. Bloom,²¹ S. Chen,²¹ W. T. Ford,²¹ J. F. Hirschauer,²¹ A. Kreisel,²¹ M. Nagel,²¹ U. Nauenberg,²¹ A. Olivas,²¹ W. O. Ruddick,²¹ J. G. Smith,²¹ K. A. Ulmer,²¹ S. R. Wagner,²¹ J. Zhang,²¹ A. Chen,²² E. A. Eckhart,²² A. Soffer,²² W. H. Toki,²² R. J. Wilson,²² F. Winklmeier,²² Q. Zeng,²² D. D. Altenburg,²³ E. Feltresi,²³ A. Hauke,²³ H. Jasper,²³ J. Merkel,²³ A. Petzold,²³ B. Spaan,²³ T. Brandt,²⁴ V. Klose,²⁴ H. M. Lacker,²⁴ W. F. Mader,²⁴ R. Nogowski,²⁴ J. Schubert,²⁴ K. R. Schubert,²⁴ R. Schwierz,²⁴ J. E. Sundermann,²⁴ A. Volk,²⁴ D. Bernard,²⁵ G. R. Bonneaud,²⁵ E. Latour,²⁵ Ch. Thiebaut,²⁵ M. Verderi,²⁵ P. J. Clark,²⁶ W. Gradl,²⁶ F. Muheim,²⁶ S. Playfer,²⁶ A. I. Robertson,²⁶ Y. Xie,²⁶ M. Andreotti,²⁷ D. Bettoni,²⁷ C. Bozzi,²⁷ R. Calabrese,²⁷ G. Cibinetto,²⁷ E. Luppi,²⁷ M. Negrini,²⁷ A. Petrella,²⁷ L. Piemontese,²⁷ E. Prencipe,²⁷ F. Anulli,²⁸ R. Baldini-Ferroli,²⁸ A. Calcaterra,²⁸ R. de Sangro,²⁸ G. Finocchiaro,²⁸ S. Pacetti,²⁸ P. Patteri,²⁸ I. M. Peruzzi,²⁸ * M. Piccolo,²⁸ M. Rama,²⁸ A. Zallo,²⁸ A. Buzzo,²⁹ R. Contri,²⁹ M. Lo Vetere,²⁹ M. M. Macri,²⁹ M. R. Monge,²⁹ S. Passaggio,²⁹ C. Patrignani,²⁹ E. Robutti,²⁹ A. Santroni,²⁹ S. Tosi,²⁹ G. Brandenburg,³⁰ K. S. Chaisanguanthum,³⁰ C. L. Lee,³⁰ M. Morii,³⁰ J. Wu,³⁰ R. S. Dubitzky,³¹ J. Marks,³¹ S. Schenk,³¹ U. Uwer,³¹ D. J. Bard,³² W. Bhimji,³² D. A. Bowerman,³² P. D. Dauncey,³² U. Egede,³² R. L. Flack,³² J. A. Nash,³² M. B. Nikolich,³² W. Panduro Vazquez,³² P. K. Behera,³³ X. Chai,³³ M. J. Charles,³³ U. Mallik,³³ N. T. Meyer,³³ V. Ziegler,³³ J. Cochran,³⁴ H. B. Crawley,³⁴ L. Dong,³⁴ V. Eyges,³⁴ W. T. Meyer,³⁴ S. Prell,³⁴ E. I. Rosenberg,³⁴ A. E. Rubin,³⁴ A. V. Gritsan,³⁵ A. G. Denig,³⁶ M. Fritsch,³⁶ G. Schott,³⁶ N. Arnaud,³⁷ M. Davier,³⁷ G. Grosdidier,³⁷ A. Höcker,³⁷ V. Lepeltier,³⁷ F. Le Diberder,³⁷ A. M. Lutz,³⁷ A. Oyanguren,³⁷ S. Pruvot,³⁷ S. Rodier,³⁷ P. Roudeau,³⁷ M. H. Schune,³⁷ J. Serrano,³⁷ A. Stocchi,³⁷ W. F. Wang,³⁷ G. Wormser,³⁷ D. J. Lange,³⁸ D. M. Wright,³⁸ C. A. Chavez,³⁹ I. J. Forster,³⁹ J. R. Fry,³⁹ E. Gabathuler,³⁹ R. Gamet,³⁹ K. A. George,³⁹ D. E. Hutchcroft,³⁹ D. J. Payne,³⁹ K. C. Schofield,³⁹ C. Touramanis,³⁹ A. J. Bevan,⁴⁰ C. K. Clarke,⁴⁰ F. Di Lodovico,⁴⁰ W. Menges,⁴⁰ R. Sacco,⁴⁰ G. Cowan,⁴¹ H. U. Flaecher,⁴¹ D. A. Hopkins,⁴¹ P. S. Jackson,⁴¹ T. R. McMahon,⁴¹ F. Salvatore,⁴¹ A. C. Wren,⁴¹ D. N. Brown,⁴² C. L. Davis,⁴² J. Allison,⁴³ N. R. Barlow,⁴³ R. J. Barlow,⁴³ Y. M. Chia,⁴³ C. L. Edgar,⁴³ G. D. Lafferty,⁴³ M. T. Naisbit,⁴³ J. C. Williams,⁴³ J. I. Yi,⁴³ C. Chen,⁴⁴ W. D. Hulsbergen,⁴⁴ A. Jawahery,⁴⁴ C. K. Lae,⁴⁴ D. A. Roberts,⁴⁴ G. Simi,⁴⁴ J. Tuggle,⁴⁴ G. Blaylock,⁴⁵ C. Dallapiccola,⁴⁵ S. S. Hertzbach,⁴⁵ X. Li,⁴⁵ T. B. Moore,⁴⁵ S. Saremi,⁴⁵ H. Staengle,⁴⁵ R. Cowan,⁴⁶ G. Sciolla,⁴⁶ S. J. Sekula,⁴⁶ M. Spitznagel,⁴⁶ F. Taylor,⁴⁶ R. K. Yamamoto,⁴⁶ H. Kim,⁴⁷ S. E. McLaughlin,⁴⁷ P. M. Patel,⁴⁷

S. H. Robertson,⁴⁷ A. Lazzaro,⁴⁸ V. Lombardo,⁴⁸ F. Palombo,⁴⁸ J. M. Bauer,⁴⁹ L. Cremaldi,⁴⁹ V. Eschenburg,⁴⁹ R. Godang,⁴⁹ R. Kroeger,⁴⁹ D. A. Sanders,⁴⁹ D. J. Summers,⁴⁹ H. W. Zhao,⁴⁹ S. Brunet,⁵⁰ D. Côté,⁵⁰ M. Simard,⁵⁰ P. Taras,⁵⁰ F. B. Viaud,⁵⁰ H. Nicholson,⁵¹ N. Cavallo,^{52,†} G. De Nardo,⁵² F. Fabozzi,^{52,†} C. Gatto,⁵² L. Lista,⁵² D. Monorchio,⁵² P. Paolucci,⁵² D. Piccolo,⁵² C. Sciacca,⁵² M. A. Baak,⁵³ G. Raven,⁵³ H. L. Snoek,⁵³ C. P. Jessop,⁵⁴ J. M. LoSecco,⁵⁴ G. Benelli,⁵⁵ L. A. Corwin,⁵⁵ K. K. Gan,⁵⁵ K. Honscheid,⁵⁵ D. Hufnagel,⁵⁵ P. D. Jackson,⁵⁵ H. Kagan,⁵⁵ R. Kass,⁵⁵ A. M. Rahimi,⁵⁵ J. J. Regensburger,⁵⁵ R. Ter-Antonyan,⁵⁵ Q. K. Wong,⁵⁵ N. L. Blount,⁵⁶ J. Brau,⁵⁶ R. Frey,⁵⁶ O. Igonkina,⁵⁶ J. A. Kolb,⁵⁶ M. Lu,⁵⁶ C. T. Potter,⁵⁶ R. Rahmat,⁵⁶ N. B. Sinev,⁵⁶ D. Strom,⁵⁶ J. Strube,⁵⁶ E. Torrence,⁵⁶ A. Gaz,⁵⁷ M. Margoni,⁵⁷ M. Morandin,⁵⁷ A. Pompili,⁵⁷ M. Posocco,⁵⁷ M. Rotondo,⁵⁷ F. Simonetto,⁵⁷ R. Stroili,⁵⁷ C. Voci,⁵⁷ M. Benayoun,⁵⁸ H. Briand,⁵⁸ J. Chauveau,⁵⁸ P. David,⁵⁸ L. Del Buono,⁵⁸ Ch. de la Vaissière,⁵⁸ O. Hamon,⁵⁸ B. L. Hartfel,⁵⁸ Ph. Leruste,⁵⁸ J. Malclès,⁵⁸ J. Ocariz,⁵⁸ L. Roos,⁵⁸ G. Therin,⁵⁸ L. Gladney,⁵⁹ M. Biasini,⁶⁰ R. Covarelli,⁶⁰ C. Angelini,⁶¹ G. Batignani,⁶¹ S. Bettarini,⁶¹ F. Bucci,⁶¹ G. Calderini,⁶¹ M. Carpinelli,⁶¹ R. Cenci,⁶¹ F. Forti,⁶¹ M. A. Giorgi,⁶¹ A. Lusiani,⁶¹ G. Marchiori,⁶¹ M. A. Mazur,⁶¹ M. Morganti,⁶¹ N. Neri,⁶¹ E. Paoloni,⁶¹ G. Rizzo,⁶¹ J. J. Walsh,⁶¹ M. Haire,⁶² D. Judd,⁶² D. E. Wagoner,⁶² J. Biesiada,⁶³ N. Danielson,⁶³ P. Elmer,⁶³ Y. P. Lau,⁶³ C. Lu,⁶³ J. Olsen,⁶³ A. J. S. Smith,⁶³ A. V. Telnov,⁶³ F. Bellini,⁶⁴ G. Cavoto,⁶⁴ A. D’Orazio,⁶⁴ D. del Re,⁶⁴ E. Di Marco,⁶⁴ R. Faccini,⁶⁴ F. Ferrarotto,⁶⁴ F. Ferroni,⁶⁴ M. Gaspero,⁶⁴ L. Li Gioi,⁶⁴ M. A. Mazzoni,⁶⁴ S. Morganti,⁶⁴ G. Piredda,⁶⁴ F. Polci,⁶⁴ F. Safai Tehrani,⁶⁴ C. Voena,⁶⁴ M. Ebert,⁶⁵ H. Schröder,⁶⁵ R. Waldi,⁶⁵ T. Adye,⁶⁶ B. Franek,⁶⁶ E. O. Olaiya,⁶⁶ S. Ricciardi,⁶⁶ F. F. Wilson,⁶⁶ R. Aleksan,⁶⁷ S. Emery,⁶⁷ A. Gaidot,⁶⁷ S. F. Ganzhur,⁶⁷ G. Hamel de Monchenault,⁶⁷ W. Kozanecki,⁶⁷ M. Legendre,⁶⁷ G. Vasseur,⁶⁷ Ch. Yèche,⁶⁷ M. Zito,⁶⁷ X. R. Chen,⁶⁸ H. Liu,⁶⁸ W. Park,⁶⁸ M. V. Purohit,⁶⁸ J. R. Wilson,⁶⁸ M. T. Allen,⁶⁹ D. Aston,⁶⁹ R. Bartoldus,⁶⁹ P. Bechtel,⁶⁹ N. Berger,⁶⁹ R. Claus,⁶⁹ J. P. Coleman,⁶⁹ M. R. Convery,⁶⁹ J. C. Dingfelder,⁶⁹ J. Dorfan,⁶⁹ G. P. Dubois-Felsmann,⁶⁹ D. Dujmic,⁶⁹ W. Dunwoodie,⁶⁹ R. C. Field,⁶⁹ T. Glanzman,⁶⁹ S. J. Gowdy,⁶⁹ M. T. Graham,⁶⁹ P. Grenier,⁶⁹ V. Halyo,⁶⁹ C. Hast,⁶⁹ T. Hryn’ova,⁶⁹ W. R. Innes,⁶⁹ M. H. Kelsey,⁶⁹ P. Kim,⁶⁹ D. W. G. S. Leith,⁶⁹ S. Li,⁶⁹ S. Luitz,⁶⁹ V. Luth,⁶⁹ H. L. Lynch,⁶⁹ D. B. MacFarlane,⁶⁹ H. Marsiske,⁶⁹ R. Messner,⁶⁹ D. R. Muller,⁶⁹ C. P. O’Grady,⁶⁹ V. E. Ozcan,⁶⁹ A. Perazzo,⁶⁹ M. Perl,⁶⁹ T. Pulliam,⁶⁹ B. N. Ratcliff,⁶⁹ A. Roodman,⁶⁹ A. A. Salnikov,⁶⁹ R. H. Schindler,⁶⁹ J. Schwiening,⁶⁹ A. Snyder,⁶⁹ J. Stelzer,⁶⁹ D. Su,⁶⁹ M. K. Sullivan,⁶⁹ K. Suzuki,⁶⁹ S. K. Swain,⁶⁹ J. M. Thompson,⁶⁹ J. Va’vra,⁶⁹ N. van Bakel,⁶⁹ A. P. Wagner,⁶⁹ M. Weaver,⁶⁹ A. J. R. Weinstein,⁶⁹ W. J. Wisniewski,⁶⁹ M. Wittgen,⁶⁹ D. H. Wright,⁶⁹ H. W. Wulsin,⁶⁹ A. K. Yarritu,⁶⁹ K. Yi,⁶⁹ C. C. Young,⁶⁹ P. R. Burchat,⁷⁰ A. J. Edwards,⁷⁰ S. A. Majewski,⁷⁰ B. A. Petersen,⁷⁰ L. Wilden,⁷⁰ S. Ahmed,⁷¹ M. S. Alam,⁷¹ R. Bula,⁷¹ J. A. Ernst,⁷¹ V. Jain,⁷¹ B. Pan,⁷¹ M. A. Saeed,⁷¹ F. R. Wappler,⁷¹ S. B. Zain,⁷¹ W. Bugg,⁷² M. Krishnamurthy,⁷² S. M. Spanier,⁷² R. Eckmann,⁷³ J. L. Ritchie,⁷³ A. Satpathy,⁷³ C. J. Schilling,⁷³ R. F. Schwitters,⁷³ J. M. Izen,⁷⁴ X. C. Lou,⁷⁴ S. Ye,⁷⁴ F. Bianchi,⁷⁵ F. Gallo,⁷⁵ D. Gamba,⁷⁵ M. Bomben,⁷⁶ L. Bosisio,⁷⁶ C. Cartaro,⁷⁶ F. Cossutti,⁷⁶ G. Della Ricca,⁷⁶ S. Dittongo,⁷⁶ L. Lanceri,⁷⁶ L. Vitale,⁷⁶ V. Azzolini,⁷⁷ N. Lopez-March,⁷⁷ F. Martinez-Vidal,⁷⁷ Sw. Banerjee,⁷⁸ B. Bhuyan,⁷⁸ C. M. Brown,⁷⁸ D. Fortin,⁷⁸ K. Hamano,⁷⁸ R. Kowalewski,⁷⁸ I. M. Nugent,⁷⁸ J. M. Roney,⁷⁸ R. J. Sobie,⁷⁸ J. J. Back,⁷⁹ P. F. Harrison,⁷⁹ T. E. Latham,⁷⁹ G. B. Mohanty,⁷⁹ M. Pappagallo,^{79,‡} H. R. Band,⁸⁰ X. Chen,⁸⁰ B. Cheng,⁸⁰ S. Dasu,⁸⁰ M. Datta,⁸⁰ K. T. Flood,⁸⁰ J. J. Hollar,⁸⁰ P. E. Kutter,⁸⁰ B. Mellado,⁸⁰ A. Mihalyi,⁸⁰ Y. Pan,⁸⁰ M. Pierini,⁸⁰ R. Prepost,⁸⁰ S. L. Wu,⁸⁰ Z. Yu,⁸⁰ and H. Neal⁸¹

(The BABAR Collaboration)

¹Laboratoire de Physique des Particules, IN2P3/CNRS et Université de Savoie, F-74941 Annecy-Le-Vieux, France

²Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain

³Università di Bari, Dipartimento di Fisica and INFN, I-70126 Bari, Italy

⁴Institute of High Energy Physics, Beijing 100039, China

⁵University of Bergen, Institute of Physics, N-5007 Bergen, Norway

⁶Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

⁷University of Birmingham, Birmingham, B15 2TT, United Kingdom

⁸Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

⁹University of Bristol, Bristol BS8 1TL, United Kingdom

¹⁰University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

¹¹Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

¹²Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

¹³University of California at Irvine, Irvine, California 92697, USA

¹⁴University of California at Los Angeles, Los Angeles, California 90024, USA

¹⁵University of California at Riverside, Riverside, California 92521, USA

¹⁶University of California at San Diego, La Jolla, California 92093, USA

- ¹⁷University of California at Santa Barbara, Santa Barbara, California 93106, USA
- ¹⁸University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
- ¹⁹California Institute of Technology, Pasadena, California 91125, USA
- ²⁰University of Cincinnati, Cincinnati, Ohio 45221, USA
- ²¹University of Colorado, Boulder, Colorado 80309, USA
- ²²Colorado State University, Fort Collins, Colorado 80523, USA
- ²³Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
- ²⁴Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
- ²⁵Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
- ²⁶University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
- ²⁷Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
- ²⁸Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
- ²⁹Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy
- ³⁰Harvard University, Cambridge, Massachusetts 02138, USA
- ³¹Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
- ³²Imperial College London, London, SW7 2AZ, United Kingdom
- ³³University of Iowa, Iowa City, Iowa 52242, USA
- ³⁴Iowa State University, Ames, Iowa 50011-3160, USA
- ³⁵Johns Hopkins University, Baltimore, Maryland 21218, USA
- ³⁶Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
- ³⁷Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B. P. 34, F-91898 ORSAY Cedex, France
- ³⁸Lawrence Livermore National Laboratory, Livermore, California 94550, USA
- ³⁹University of Liverpool, Liverpool L69 7ZE, United Kingdom
- ⁴⁰Queen Mary, University of London, E1 4NS, United Kingdom
- ⁴¹University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
- ⁴²University of Louisville, Louisville, Kentucky 40292, USA
- ⁴³University of Manchester, Manchester M13 9PL, United Kingdom
- ⁴⁴University of Maryland, College Park, Maryland 20742, USA
- ⁴⁵University of Massachusetts, Amherst, Massachusetts 01003, USA
- ⁴⁶Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
- ⁴⁷McGill University, Montréal, Québec, Canada H3A 2T8
- ⁴⁸Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
- ⁴⁹University of Mississippi, University, Mississippi 38677, USA
- ⁵⁰Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
- ⁵¹Mount Holyoke College, South Hadley, Massachusetts 01075, USA
- ⁵²Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
- ⁵³NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
- ⁵⁴University of Notre Dame, Notre Dame, Indiana 46556, USA
- ⁵⁵Ohio State University, Columbus, Ohio 43210, USA
- ⁵⁶University of Oregon, Eugene, Oregon 97403, USA
- ⁵⁷Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
- ⁵⁸Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
- ⁵⁹University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
- ⁶⁰Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
- ⁶¹Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
- ⁶²Prairie View A&M University, Prairie View, Texas 77446, USA
- ⁶³Princeton University, Princeton, New Jersey 08544, USA
- ⁶⁴Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
- ⁶⁵Universität Rostock, D-18051 Rostock, Germany
- ⁶⁶Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
- ⁶⁷DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
- ⁶⁸University of South Carolina, Columbia, South Carolina 29208, USA
- ⁶⁹Stanford Linear Accelerator Center, Stanford, California 94309, USA
- ⁷⁰Stanford University, Stanford, California 94305-4060, USA
- ⁷¹State University of New York, Albany, New York 12222, USA
- ⁷²University of Tennessee, Knoxville, Tennessee 37996, USA
- ⁷³University of Texas at Austin, Austin, Texas 78712, USA
- ⁷⁴University of Texas at Dallas, Richardson, Texas 75083, USA
- ⁷⁵Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
- ⁷⁶Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
- ⁷⁷IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain

⁷⁸University of Victoria, Victoria, British Columbia, Canada V8W 3P6

⁷⁹Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

⁸⁰University of Wisconsin, Madison, Wisconsin 53706, USA

⁸¹Yale University, New Haven, Connecticut 06511, USA

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We search for the decays $B^- \rightarrow \phi K^- \gamma$ and $\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma$ in a data sample of 228 million $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the BABAR detector. We measure the branching fraction $\mathcal{B}(B^- \rightarrow \phi K^- \gamma) = (3.5 \pm 0.6 \pm 0.4) \times 10^{-6}$ and set an upper limit $\mathcal{B}(\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma) < 2.7 \times 10^{-6}$ at the 90% confidence level. We also measure the direct CP asymmetry in $B^- \rightarrow \phi K^- \gamma$, $\mathcal{A}_{CP} = (-26 \pm 14 \pm 5)\%$. The uncertainties are statistical and systematic, respectively.

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Measurements of the branching fractions and CP asymmetries of $b \rightarrow s\gamma$ decays provide a sensitive probe of the standard model (SM), in which these decays are forbidden at tree level but allowed through electroweak penguin processes. They are sensitive to the possible effects of physics beyond the SM manifesting as new virtual particles contributing to loops. These additional contributions to the decay amplitudes could affect branching fractions and CP violation [1]. The SM theoretical prediction [2] and experimental measurements [3] of the $b \rightarrow s\gamma$ inclusive branching fraction have uncertainties of about 10% and are consistent with each other. Although exclusive $b \rightarrow s\gamma$ branching fractions are experimentally easier to determine than inclusive ones, calculations for the exclusive modes are theoretically challenging due to large nonperturbative quantum chromodynamic effects. The expected direct CP asymmetry between B^+ and B^- decay rates in the SM is $-(0.1 - 1)\%$ [4], while the time-dependent CP asymmetry in neutral CP eigenstates such as $B^0 \rightarrow \phi K_s^0 \gamma$ should be a few percent [5]. A significantly larger CP asymmetry of either type would be a sign of new physics.

There have already been results published for branching fraction and/or CP asymmetry measurements in several exclusive modes: $B \rightarrow K^* \gamma$ [6], $B^0 \rightarrow K_s^0 \pi^0 \gamma$ [7], $B \rightarrow \eta(\prime) K \gamma$ [8], and various $B \rightarrow K \pi \pi \gamma$ [9] modes. The Belle collaboration has measured $\mathcal{B}(B^- \rightarrow \phi K^- \gamma) = (3.4 \pm 0.9 \pm 0.4) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma) < 8.3 \times 10^{-6}$ at the 90% confidence level using 96 million $B\bar{B}$ pairs [10]. We present the first BABAR measurement of the branching fraction for the charged mode $B^- \rightarrow \phi K^- \gamma$ and a search for the neutral mode $\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma$ [21] using 228 million $B\bar{B}$ pairs. We also measure for the first time the direct CP asymmetry in the charged mode $\mathcal{A}_{CP} = [N(B^-) - N(B^+)]/[N(B^-) + N(B^+)]$, where the flavor of the B is determined by the charge of the kaon.

The data used in this analysis were recorded with the BABAR detector at the PEP-II asymmetric storage rings, in which 9.0 GeV electrons collide with 3.1 GeV positrons to produce $\Upsilon(4S)$ mesons. The BABAR detector is described in detail elsewhere [11]. Most important to this analysis are the tracking system composed of the silicon vertex tracker (SVT) and drift chamber (DCH) inside a

1.5 T magnetic field, the ring-imaging detector of internally reflected Cherenkov light (DIRC), and the electromagnetic calorimeter (EMC). The tracking system can reconstruct a B decay vertex with a resolution of 70 μm along the direction of the beam, and has a transverse momentum resolution of 0.52% at 500 MeV/c. The DIRC provides kaon-pion separation of at least 4σ significance for momenta up to 3 GeV/c. The EMC detects photons over an energy range from 20 MeV to 9 GeV, with a resolution of 2.6% at 2.5 GeV. A detailed Monte Carlo (MC) simulation of signal and background processes was performed using the EVTGEN generator [12] and the GEANT4 package [13].

We search for $B \rightarrow \phi K \gamma$ candidates based on charged track combinations and the presence of a high-energy photon using a kinematic fitter [14] to reconstruct the intermediate mesons and the B . Each decay vertex is required to have a χ^2 probability greater than 0.1%. Candidates for $\phi \rightarrow K^+ K^-$ are selected from pairs of oppositely charged tracks that have been distinguished from pions based on a particle identification (PID) likelihood selection algorithm that uses dE/dx and Cherenkov light measurements. The same PID algorithm is used for the single K^- from the B^- in the charged mode. We keep ϕ candidates with masses within a ± 10 MeV/ c^2 window of the nominal ϕ mass [15]. In the neutral mode, pairs of oppositely charged tracks are accepted as K_s^0 candidates if they have a combined invariant mass within ± 10 MeV/ c^2 of the K_s^0 mass and if the K_s^0 flight length is greater than three times its uncertainty. We require the combined ϕK invariant mass to be less than 3.0 GeV/ c^2 . In the neutral mode a D^0 veto is applied by removing candidates with combined ϕK invariant mass within ± 10 MeV/ c^2 of the D^0 mass. Photon candidates are reconstructed from EMC clusters that are not associated with charged tracks, are isolated from other clusters, and have the expected photon lateral shower shape. We require an energy of 1.5–2.6 GeV in the e^+e^- rest frame (CM frame) and we veto photon candidates that form a π^0 (η) candidate with invariant mass between 115–155 MeV/ c^2 (470–620 MeV/ c^2) when combined with another photon of energy greater than 50 MeV (250 MeV).

We identify signal B decays through the distributions

of two quantities, missing mass and reconstructed mass, that peak around the nominal B mass. The missing mass is $m_{\text{miss}} = \sqrt{|p_{\mathcal{T}(4S)} - p_B|^2}$, where $p_{\mathcal{T}(4S)}$ is the $\mathcal{T}(4S)$ four-momentum and p_B is the four-momentum of the $B \rightarrow \phi K \gamma$ candidate after a mass constraint on the B is applied. The reconstructed mass m_{rec} is the B candidate invariant mass calculated from the reconstructed energy and momentum. We require $5.12 < m_{\text{miss}} < 5.32 \text{ GeV}/c^2$ and $4.98 < m_{\text{rec}} < 5.48 \text{ GeV}/c^2$. To further discriminate B decays from continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) background we use two topological quantities: the ratio of Legendre moments L_2/L_0 and the cosine of the angle between the B candidate and the e^- direction in the CM frame $|\cos\theta_B^*|$. We require $L_2/L_0 < 0.55$, where $L_i = \sum_j |p_j^*| |\cos\theta_j^*|^i$, p_j^* is the CM momentum of each particle j not used in the B candidate, and θ_j^* is the CM angle between the particle's momentum and the thrust axis of the B candidate. We also require $|\cos\theta_B^*| < 0.9$.

The selection criteria described above are chosen to optimize $N_S/\sqrt{N_S + N_B}$ in the signal region, where N_S and N_B are the MC simulated signal and background yields, respectively, and the signal region is defined by $5.05 < m_{\text{rec}} < 5.4 \text{ GeV}/c^2$, $5.27 < m_{\text{miss}} < 5.29 \text{ GeV}/c^2$, $|\cos\theta_B^*| < 0.8$, and $L_2/L_0 < 0.48$. Signal MC is based on inclusive $B \rightarrow X_s \gamma$ events generated according to the model of Kagan and Neubert [16], using $m_b = 4.62 \text{ GeV}/c^2$ for the effective b quark mass. Only the part of the hadronic mass spectrum above the ϕK threshold of $1.52 \text{ GeV}/c^2$ is used, with X_s forced to decay to ϕK . This model does not take resonances into account.

After all criteria are applied, the average candidate multiplicity in events with at least one candidate are 1.01 and 1.07 in the neutral and charged modes respectively. If multiple B candidates are found in an event, we select the best one based on a χ^2 formed from the value and uncertainty of the mass of the ϕ candidate and, in the neutral mode, the K_s^0 candidate. The remaining background comes from continuum combinatorics, nonresonant $B \rightarrow KK^+K^-\gamma$, $B \rightarrow \phi K \pi^0$, and $B \rightarrow \phi K \eta$.

Signal and background yields are extracted from a fit to an unbinned extended maximum likelihood function defined by

$$\mathcal{L}(N_S, N_B, \vec{\alpha}) = e^{-(N_S + N_B)} \times \prod_i^N [N_S \mathcal{P}_S(\vec{x}_i) + N_B \mathcal{P}_B(\vec{x}_i; \vec{\alpha})]; \quad (1)$$

N_S and N_B are the number of signal and background events respectively, the index i labels each event in the data set, and N is the total number of events used in the fit. \mathcal{P}_S and \mathcal{P}_B are products of the one-dimensional signal and background probability density functions (PDFs) for each of the observables $\vec{x} = \{m_{\text{miss}}, m_{\text{rec}}, L_2/L_0, \cos\theta_B^*\}$. The signal shape parameters are fixed in the fit while the background parameters $\vec{\alpha}$ are allowed to vary. In order to

fit the CP asymmetries of signal and background in the charged mode, the number of B^+ and B^- events is determined separately: $N_j^\pm = \frac{1}{2}(1 \mp \mathcal{A}_{CP}^j)n_j$, where $j = S$ or B , n_j and \mathcal{A}_{CP}^j are the total yield and CP asymmetry of species j , respectively, and the upper (lower) signs correspond to the positively (negatively) charged B mesons.

The signal PDFs for m_{miss} and m_{rec} are parametrized by

$$f(x) = \exp \left[\frac{-x^2}{2\sigma_{L,R}^2 + \alpha_{L,R}x^2} \right], \quad (2)$$

where the parameters $\sigma_{L,R}$ and $\alpha_{L,R}$ determine the core width and variation of the width on either side of $x = 0$, x being the difference from the nominal B mass of m_{miss} or m_{rec} . The m_{miss} background PDF is an ARGUS function [17], with the endpoint calculated event-by-event from the beam energy. The m_{rec} background PDF is modeled as a 2nd degree polynomial. The signal and background models for L_2/L_0 both use a binned PDF with eight bins. The $\cos\theta_B^*$ distribution is modeled as a 2nd degree polynomial in both signal and background; true B candidates follow a $1 - \cos^2\theta_B^*$ distribution if the detector efficiency is flat in $\cos\theta_B^*$.

To determine the signal PDF parameters we use a high-statistics $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\gamma$ sample. Once determined, these parameters are fixed for the fit to $B \rightarrow \phi K \gamma$ data. We determine the selection efficiency by performing a fit of the yields on signal MC.

We apply several corrections to the signal yield and efficiency before determining the branching fractions. Studies of simulated events show that the main sources of signal-like (peaking) backgrounds are nonresonant $B \rightarrow KK^+K^-\gamma$ events, and $B \rightarrow \phi K \pi^0$ or $B \rightarrow \phi K \eta$, where one of the photons from the π^0 or η decay is lost and the other is picked up as the signal high-energy photon. We estimate the amount of $B \rightarrow KK^+K^-\gamma$ contamination by fitting for the yield in ϕ mass sideband regions defined by $989 < m_\phi < 1009 \text{ MeV}/c^2$ and $1029 < m_\phi < 1049 \text{ MeV}/c^2$. By interpolating into the signal region, we find and correct for 0.0 ± 1.5 and 5 ± 4 events for the neutral and charged modes respectively. These contributions are subtracted from the event yields determined in the fit. From the known branching fraction [18] of $B \rightarrow \phi K^*(\rightarrow K\pi^0)$ we correct for a contamination of 0.27 ± 0.16 neutral and 1.98 ± 0.32 charged events. There have been no branching fraction measurements of $B \rightarrow \phi K \pi^0$ or $B \rightarrow \phi K \eta$. We assume that the branching fraction of the first is no more than one-third that of $B \rightarrow \phi K^*$ and that of the latter is no more than $B \rightarrow \phi K^*$. Based on this we assign an uncertainty of 0.5 neutral and 2.9 charged events due to nonresonant $B \rightarrow \phi K(\pi^0/\eta)$ background. To correct for any fit bias, we generate 1000 simulated experiments using PDFs with separate components for $B\bar{B}$ and continuum, and embedding signal events from the full simulation.

The background components are generated using shape parameters determined from the full MC simulation. We correct for a bias of $+4.1 \pm 0.5$ events in the charged mode, due to correlations among the observables in signal MC events that are not accounted for in the fit. In the neutral mode we find a bias of -0.06 ± 0.20 , so we apply no correction but include 0.20 events in the systematic uncertainty of the yield. We correct for efficiency differences between data and MC in charged track, single photon, and K_s^0 reconstruction. These multiplicative efficiency corrections are 0.956 in the neutral mode and 0.975 in the charged mode. The corrected efficiencies are $(15.3 \pm 0.8)\%$ in the neutral mode and $(21.9 \pm 1.6)\%$ in the charged mode, where the uncertainties are systematic (discussed below).

The signal yields, efficiencies, branching fractions, and charged-mode CP asymmetry are reported in Table I. We calculate the central value of the branching fractions by

$$\mathcal{B}_i = \frac{N_S^i}{N_{B\bar{B}} \cdot \varepsilon_i \cdot b_i} \quad (3)$$

where i labels either the neutral or charged mode, N_S^i is the corrected signal yield, $N_{B\bar{B}} = (228.3 \pm 2.5) \times 10^6$ is the number of $B\bar{B}$ pairs recorded, ε_i is the corrected efficiency, and b_i is $\mathcal{B}(\phi \rightarrow K^+K^-)[\frac{1}{2}\mathcal{B}(K_s^0 \rightarrow \pi^+\pi^-)]$ in the neutral mode and $\mathcal{B}(\phi \rightarrow K^+K^-)$ in the charged mode. The world average branching fractions are taken from Ref. [15]. We measure $\mathcal{B}(B^- \rightarrow \phi K^- \gamma) = (3.5 \pm 0.6 \pm 0.4) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma) = (1.3 \pm 1.0 \pm 0.3) \times 10^{-6}$. In the charged mode we measure $\mathcal{A}_{CP} = (-26 \pm 14 \pm 5)\%$. In Fig. 1 we show fits to the data projected onto m_{miss} and m_{rec} . In all cases, the displayed distribution is created with the signal region selection applied to all other fit variables. We determine the consistency of the branching fraction measurements with the assumption of isospin symmetry using 1000 simulated experiments in each mode with the number of signal events determined by the average branching fraction, $\mathcal{B}_{\text{av}} = 2.8 \times 10^{-6}$. From the distribution of the differences in branching fraction between the modes we find an 8.9% probability to measure a difference greater than or equal to that observed in data.

For the neutral mode we compute the 90% confidence level upper limit on the branching fraction. We use a Bayesian approach with a flat prior probability for the branching fraction in the physical region $0 \leq \mathcal{B} \leq 1$ and zero elsewhere. As the likelihood (Eq. 1) is a function of several parameters, we determine its dependence on N_S by fixing N_S to a series of values and recomputing the likelihood at each one, allowing N_B and $\bar{\alpha}$ to be reoptimized to obtain the maximum likelihood at each point. We convolve this function with a Gaussian distribution of width equal to the systematic uncertainty of the yield. Similarly, for the efficiency uncertainty we also use a Gaussian distribution of width equal to the efficiency sys-

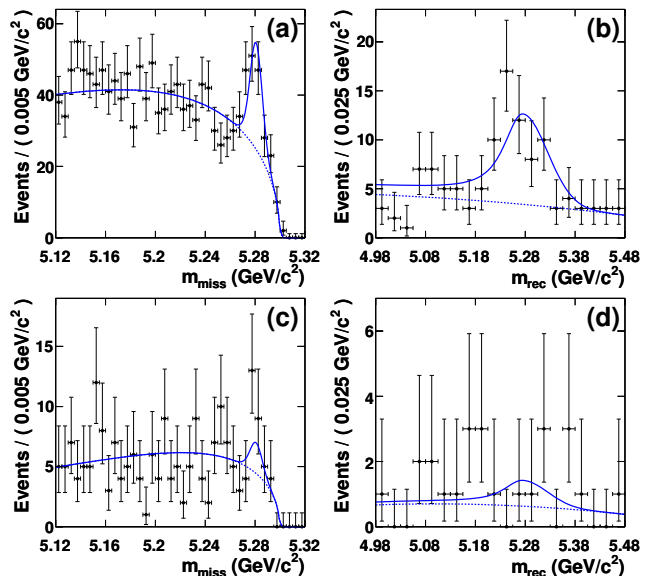


FIG. 1: Missing mass (a) and reconstructed mass (b) fits in the signal region for the charged mode and the neutral mode (c,d). The dotted curves show the background contribution while the solid curves show the sum of signal and background.

tematic uncertainty. We determine the branching fraction upper bound \mathcal{B}_{UB} from the following expression:

$$\int_0^{\mathcal{B}_{\text{UB}}} \mathcal{L}(\mathcal{B}) d\mathcal{B} / \int_0^1 \mathcal{L}(\mathcal{B}) d\mathcal{B} = 90\%. \quad (4)$$

After applying the previously discussed corrections to the yield and efficiency, and including systematic uncertainties, we obtain $\mathcal{B}(\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma) < 2.7 \times 10^{-6}$.

We assign a systematic uncertainty to the yield due to the fixed signal parameters in the fit. We vary these parameters within the ranges allowed by the $K^* \gamma$ sample to determine the total uncertainty of the yields. We account for other systematic uncertainties due to efficiency differences between data and MC in charged kaon tracking, kaon PID, and K_s^0 , ϕ , and photon selection. There are small uncertainties assigned to the L_2/L_0 selection and the π^0/η veto, also due to data-MC efficiency differences.

Figure 2 shows the efficiency-corrected ϕK invariant mass distributions, using the background subtraction technique described in Ref. [20]. In the charged mode, we find that no more than 50% of the spectrum in the 1.6 – 3.0 GeV/c^2 range can come from the $K_2(1770)$ resonance, and we use this information to bound the uncertainty due to the assumed MC ϕK mass spectrum. We determine what the efficiency would have been if half of the mass spectrum came from resonant $K_2(1770) \rightarrow \phi K$ production, while the other half came from the signal MC model. We assign the relative efficiency difference between this and the nominal model as an uncertainty.

TABLE I: Summary of the branching fractions and direct CP asymmetry. In $\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma$ the 90% confidence level upper limit is also given.

Decay Mode	Yield	Efficiency (%)	$\mathcal{B}(10^{-6})$	\mathcal{A}_{CP} (%)
$B^- \rightarrow \phi K^- \gamma$	$85 \pm 15 \pm 7$	$21.9 \pm 1.6(\text{syst})$	$3.5 \pm 0.6 \pm 0.4$	$-26 \pm 14 \pm 5$
$\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma$	$8 \pm 6 \pm 2$ < 16	$15.3 \pm 0.8(\text{syst})$	$1.3 \pm 1.0 \pm 0.3$ < 2.7	

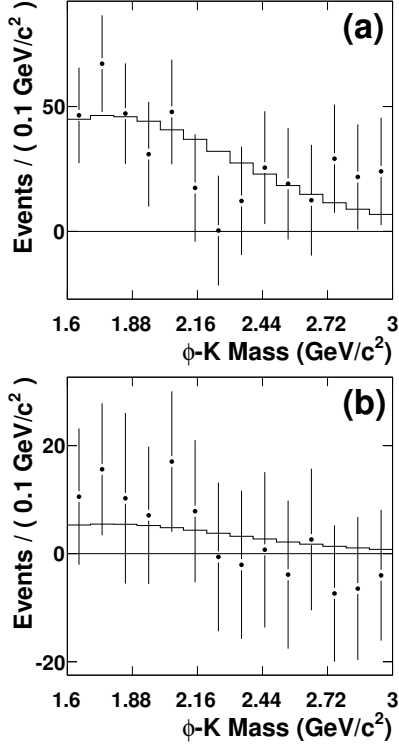


FIG. 2: The background-subtracted and efficiency-corrected ϕK mass distributions (points with uncertainties) for the charged mode (a) and the neutral mode (b). The signal MC model for the mass spectrum, based on Ref. [16], is shown as a histogram without uncertainties and is normalized to the efficiency-corrected signal yield obtained in data.

Adding all of the previously discussed uncertainties in quadrature, we find a total multiplicative uncertainty of 5.2% in the neutral mode and 7.1% in the charged mode. The complete systematic uncertainties for each mode are summarized in Table II.

For the direct CP asymmetry measurement we bound the K^+/K^- efficiency asymmetry of the detector by using the measured combinatoric background asymmetry, which is consistent with zero within an uncertainty of 1.8%. To account for uncertainty due to various peaking background sources we assume that each source can have a CP asymmetry of up to $\pm 58\%$, which is the root mean square width of a flat distribution between -1 and 1 . We multiply this by the expected fractional contamination in

TABLE II: Summary of the systematic uncertainties. Except where noted, all uncertainties are given as percentages.

Source	Uncertainty (%)	
	$\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma$	$B^- \rightarrow \phi K^- \gamma$
$K K^+ K^- \gamma$ Subtraction	19.7	5.2
Peaking Background	6.4	3.4
Fit Bias	2.6	0.6
Fit PDF Parameters	+7.0 -5.9	+5.9 -5.2
Yield Uncertainty	+1.8 -1.7 events	+7.3 -6.9 events
Kaon Tracking	2.8	4.2
K_S^0 Efficiency	1.5	0
ϕ Efficiency	1.7	1.7
Particle ID	2.8	4.2
Single Photon Efficiency	1.8	1.8
Photon Spectrum Model	0.4	2.6
L_2/L_0 Cut	1.2	1.2
π^0/η Veto	1.0	1.0
Efficiency Uncertainty	5.2	7.1
$B\bar{B}$ Counting	1.1	1.1
Total	+23 -22	± 11

the data sample to obtain the systematic uncertainty. For $B^- \rightarrow \phi K^- (\pi^0/\eta)$ we assign 1.8% uncertainty, while for $B^- \rightarrow K^- K^+ K^- \gamma$ we assign 3.5% uncertainty. For resonant $B \rightarrow \phi K^* (\rightarrow K \pi^0)$ events, the previous *BABAR* and *Belle* measurements [19] show that the CP asymmetry is consistent with zero to within 15%. We therefore consider it to be negligible. As was done with the branching fraction measurement, we vary the fixed signal parameters of the fit to obtain a 2.2% uncertainty for the signal CP asymmetry. Adding the uncertainties in quadrature we find a total \mathcal{A}_{CP} systematic uncertainty of 5%.

In summary, we have performed the first *BABAR* studies of $B \rightarrow \phi K \gamma$ decay modes. We measure $\mathcal{B}(B^- \rightarrow \phi K^- \gamma) = (3.5 \pm 0.6 \pm 0.4) \times 10^{-6}$, consistent with the result from *Belle*. We have set a limit $\mathcal{B}(\bar{B}^0 \rightarrow \phi \bar{K}^0 \gamma) < 2.7 \times 10^{-6}$ at the 90% confidence level. Lastly, we have made the first measurement of the direct CP asymmetry in $B^- \rightarrow \phi K^- \gamma$: $\mathcal{A}_{CP} = (-26 \pm 14 \pm 5)\%$.

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* Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

† Also with Università della Basilicata, Potenza, Italy

‡ Also with IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom

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