Measurement of branching fractions and mass spectra of $B \to K\pi\pi\gamma$

B. Aubert, R. Barate, D. Boutigny, F. Couderc, Y. Karyotakis, J. P. Lees, V. Poirier, V. Tisserand, A. Zghiche, E. Grauges, A. Palano, M. Pappalardo, A. Pompli, J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu, G. Eigen, I. Ofte, B. Stugu, G. S. Abrams, M. Battaglia, A. B. Breon, D. N. Brown, J. Button-Shaffer, 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. Kukansev, G. Lynch, L. M. Mir, P. J. Oddone, T. J. Orimoto, M. Pripstein, N. A. Roe, M. T. Ronan, W. A. Wenzel, M. Barrett, K. E. Ford, T. J. Harrison, A. J. Hart, C. M. Hawkes, S. E. Morgan, A. T. Watson, M. Fritsch, K. Goetzen, T. Held, H. Koch, B. Lewandowski, M. Pelizzae, K. Peters, T. Schroeder, M. Steine, J. T. Boyd, J. P. Burke, N. Chevalier, W. N. Cottingham, M. P. Kelly, T. Cuhadar-Donszelmann, B. G. Fulsom, C. Heartly, N. S. Knecht, T. S. Mattison, J. A. McKenna, A. Khan, P. Kyberd, M. Saleem, L. Teodorescu, A. E. Blinov, V. E. Blinov, A. D. Bukin, V. P. Druzhinin, V. B. Golubev, E. A. Kravchenko, A. P. Omuchin, S. I. Serednyakov, Yu. I. Skovpen, E. P. Solodov, A. N. Yushkov, D. Best, M. Bondiolli, M. Bruinsma, M. Chao, I. Eschrich, D. Kirkby, A. J. Lankford, M. Mandelkern, R. K. Mommsen, W. Roethel, D. P. Stoker, C. Buchanan, B. L. Hartley, S. D. Foulkes, J. W. Gary, O. Long, B. C. Shen, K. Wang, Z. Zhang, D. de Re, H. K. Hadavand, E. J. Hill, B. MacFarlane, H. Long, S. A. Rahatlou, V. Sharma, J. W. Berryhill, C. Campagnari, A. Cunha, B. Dahmes, T. M. Hong, M. A. Mazur, J. D. Richman, W. Verkerke, T. W. Beck, A. M. Eisner, C. J. Flacco, C. A. Heusch, J. Kroeseberg, W. S. Lockman, G. Nesom, B. A. Schumm, A. Seiden, P. Spradlin, D. C. Williams, M. G. Wilson, J. Albert, E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, I. Narsky, T. Platenko, F. C. Porter, A. Ryd, A. Samuel, R. Andreassen, S. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff, F. Blanc, P. Bloom, W. Chen, W. T. Ford, U. Nauenberg, A. Olivas, P. Rankin, W. O. Ruddick, J. G. Smith, K. A. Ulmer, R. W. Wagner, J. Zhang, A. Chen, E. A. Eckhart, A. Soffer, W. H. Toki, R. J. Wilson, Q. Zeng, D. Altenburg, E. Feltrisi, A. Hauke, B. Spaan, T. Brandt, J. Brose, M. Dickopp, V. Klose, H. M. Lackner, R. Nagowski, S. Otto, A. Petzold, G. Schott, J. Schubert, B. Kubera, R. Schubert, M. Schierlaw, J. E. Sundermann, D. Bernard, G. R. Bonneau, P. Guerin, S. Schrenk, Ch. Thiebaux, G. Vasileiadis, M. Verdi, D. J. Bard, P. J. Clark, W. Gradl, F. Muheim, S. Playfer, Y. Xie, M. Andreotti, V. Azzolini, D. Bettoni, C. Bozzi, R. Calabrese, G. Cibinetto, E. Lupp, M. Negri, L. Piemontese, F. Anulli, R. Baldini-Ferroli, A. Calcacera, R. de Sangro, G. Finoccia, P. Patteri, I. M. Peruzzi, M. Piccolo, A. Zallo, A. Buzzo, J. Capra, R. Conti, M. Lo Vetere, M. Macri, R. M. Monge, P. Passaggio, C. Patrignani, E. Robutti, A. Santroni, S. Tosi, S. Bailey, G. Brandenburg, K. S. Chaisanguanthu, M. Morii, E. Won, J. Wu, R. S. Dubitzky, U. Langenegger, J. Marks, S. Schenk, U. Uwer, W. Bliumii, D. A. Bowerman, P. D. Dauncey, E. Ugedo, R. L. Flack, J. R. Gaillard, G. W. Morton, J. A. Nash, M. Nikolich, G. P. Taylor, W. P. Vazquez, M. J. Charles, W. F. Mader, U. Mallik, A. K. Mohapatra, J. Cochran, H. B. Crawley, V. Eyges, W. T. Meyer, S. Prell, I. E. Rosenberg, A. E. Rubin, J. Yi, N. Arnaud, M. Davier, X. Giroux, G. Grosdidier, A. Hocker, F. Le Diberder, V. Lepeltiet, A. M. Lutz, A. Oyanguren, T. C. Petersen, M. Pierini, S. Piascik, S. Rodier, P. Roudeau, M. H. Schune, A. S. Stocchi, G. Wormser, H. Cheng, D. J. Lange, C. M. Simani, D. M. Wright, A. J. Bevan, C. A. Chavez, J. P. Coleman, J. I. Forster, J. R. Fry, E. Gabathuler, R. Gamet, K. A. George, E. Hutchcroft, R. J. Parry, D. J. Payne, K. Schofield, C. Touramanis, C. M. Cormack, F. Di Lodovico, R. Sacco, C. L. Brown, G. Cowan, H. U. Fafcher, M. G. Green, D. A. Hopkins, P. S. Jackson, T. R. McMahon, S. Ricciardi, F. Salvatore, D. Brown, C. L. Davis, J. Allison, N. R. Barlow, R. J. Barlow, M. C. Hodgkinson, G. D. Lafferty, M. T. Naisbit, J. C. Williams, C. Chen, A. Farbin, W. D. Hulsbergen, A. Jawahery, D. Kovalskyi, C. K. Lae, V. Lillard, D. A. Roberts, G. Simi, G. Blaylock, C. Dallapiccola, S. S. Hertzbach, R. Kofler, V. B. Koptchev, X. Li, T. B. Moore, S. Saremi, H. Staengle, S. Willocq, R. Cowan,
| Institution                                                                                     |
|------------------------------------------------------------------------------------------------|
| University of California at Riverside, Riverside, California 92521, USA                        |
| University of California at San Diego, La Jolla, California 92093, USA                       |
| University of California at Santa Barbara, Santa Barbara, California 93106, USA              |
| University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA |
| California Institute of Technology, Pasadena, California 91125, USA                           |
| University of Cincinnati, Cincinnati, Ohio 45221, USA                                       |
| University of Colorado, Boulder, Colorado 80309, USA                                        |
| Colorado State University, Fort Collins, Colorado 80523, USA                                 |
| Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany                         |
| Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany |
| University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom                                   |
| Università di Ferrara, Dipartimento di Fisica e INFN, I-44100 Ferrara, Italy                 |
| Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy                         |
| Università di Genova, Dipartimento di Fisica e INFN, I-16146 Genova, Italy                   |
| Harvard University, Cambridge, Massachusetts 02138, USA                                     |
| Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany |
| Imperial College London, London, SW7 2AZ, United Kingdom                                     |
| University of Iowa, Iowa City, Iowa 52242, USA                                              |
| Iowa State University, Ames, Iowa 50011-3100, USA                                           |
| Laboratoire de l’Accélérateur Linéaire, F-91898 Orsay, France                              |
| Lawrence Livermore National Laboratory, Livermore, California 94550, USA                    |
| University of Liverpool, Liverpool L69 7E, United Kingdom                                    |
| Queen Mary, University of London, E1 4NS, United Kingdom                                     |
| University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom |
| University of Louisville, Louisville, Kentucky 40292, USA                                    |
| University of Manchester, Manchester M13 9PL, United Kingdom                                 |
| University of Maryland, College Park, Maryland 20742, USA                                    |
| University of Massachusetts, Amherst, Massachusetts 01003, USA                              |
| Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA |
| McGill University, Montréal, Quebec, Canada H3A 2T8                                        |
| Università di Milano, Dipartimento di Fisica e INFN, I-20133 Milano, Italy                   |
| University of Maryland, College Park, Maryland 20742, USA                                    |
| Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany |
| Imperial College London, London, SW7 2AZ, United Kingdom                                     |
| University of Iowa, Iowa City, Iowa 52242, USA                                              |
| Iowa State University, Ames, Iowa 50011-3100, USA                                           |
| Laboratoire de l’Accélérateur Linéaire, F-91898 Orsay, France                              |
| Lawrence Livermore National Laboratory, Livermore, California 94550, USA                    |
| University of Liverpool, Liverpool L69 7E, United Kingdom                                    |
| Queen Mary, University of London, E1 4NS, United Kingdom                                     |
| University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom |
| University of Louisville, Louisville, Kentucky 40292, USA                                    |
| University of Manchester, Manchester M13 9PL, United Kingdom                                 |
| University of Maryland, College Park, Maryland 20742, USA                                    |
| University of Massachusetts, Amherst, Massachusetts 01003, USA                              |
| Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA |
| McGill University, Montréal, Quebec, Canada H3A 2T8                                        |
| Università di Milano, Dipartimento di Fisica e INFN, I-20133 Milano, Italy                   |
| University of Mississippi, University Mississippi 38677, USA                                 |
| Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, Quebec, Canada H3C 3J7   |
| Mount Holyoke College, South Hadley, Massachusetts 01075, USA                               |
| Università di Napoli Federico II, Dipartimento di Scienze Fisiche e INFN, I-80126, Napoli, Italy |
| NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands |
| University of Notre Dame, Notre Dame, Indiana 46556, USA                                     |
| Ohio State University, Columbus, Ohio 43210, USA                                            |
| University of Oregon, Eugene, Oregon 97403, USA                                            |
| Università di Padova, Dipartimento di Fisica e INFN, I-35131 Padova, Italy                   |
| Universités Paris VI et VII, Laboratoire de Physique Nucléaire et de Hautes Energies, P-75252 Paris, France |
| University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA                           |
| Università di Perugia, Dipartimento di Fisica e INFN, I-06100 Perugia, Italy                 |
| Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore e INFN, I-56127 Pisa, Italy |
| Prairie View A&M University, Prairie View, Texas 77446, USA                                 |
| Princeton University, Princeton, New Jersey 08544, USA                                     |
| Università di Roma La Sapienza, Dipartimento di Fisica e INFN, I-00185 Roma, Italy           |
| Universität Rostock, D-18051 Rostock, Germany                                               |
| Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom              |
| DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France                                     |
| University of South Carolina, Columbia, South Carolina 29208, USA                           |
| Stanford Linear Accelerator Center, Stanford, California 94309, USA                       |
| Stanford University, Stanford, California 94305-4060, USA                                  |
| State University of New York, Albany, New York 12222, USA                                  |
| University of Tennessee, Knoxville, Tennessee 37996, USA                                  |
| University of Texas at Austin, Austin, Texas 78712, USA                                   |
| University of Texas at Dallas, Richardson, Texas 75083, USA                               |
| Università di Torino, Dipartimento di Fisica Sperimentale e INFN, I-10125 Torino, Italy     |
| Università di Trieste, Dipartimento di Fisica e INFN, I-34127 Trieste, Italy               |
| IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain                              |
| Vanderbilt University, Nashville, Tennessee 37235, USA                                    |
| University of Victoria, Victoria, British Columbia, Canada V8W 3P6                          |
| Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom             |
We present a measurement of the partial branching fractions and mass spectra of the exclusive radiative penguin processes $B \rightarrow K \pi \pi \gamma$ in the range $m_{K\pi\pi} < 1.8$ GeV/$c^2$. We reconstruct four final states: $K^+ \pi^- \pi^+ \gamma$, $K^- \pi^+ \pi^- \gamma$, $K_S^0 \pi^- \pi^+ \gamma$, and $K_S^0 \pi^+ \pi^- \gamma$, where $K_S^0 \rightarrow \pi^+ \pi^-$. Using 232 million $e^+e^- \rightarrow B \bar{B}$ events recorded by the BABAR experiment at the PEP-II asymmetric-energy storage ring, we measure the branching fractions $\mathcal{B}(B^+ \rightarrow K^+ \pi^- \pi^+ \gamma) = (2.05 \pm 0.13 \text{ (stat.)} \pm 0.20 \text{ (syst.)}) \times 10^{-3}$, $\mathcal{B}(B^0 \rightarrow K^+ \pi^+ \pi^- \gamma) = (4.07 \pm 0.22 \text{ (stat.)} \pm 0.31 \text{ (syst.)}) \times 10^{-3}$, $\mathcal{B}(B^0 \rightarrow K^0 \pi^+ \pi^- \gamma) = (1.95 \pm 0.21 \text{ (stat.)} \pm 0.12 \text{ (syst.)}) \times 10^{-3}$, and $\mathcal{B}(B^+ \rightarrow K^0 \pi^+ \pi^+ \gamma) = (4.56 \pm 0.42 \text{ (stat.)} \pm 0.31 \text{ (syst.)}) \times 10^{-3}$.

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In the standard model (SM) the radiative penguin decay $B \rightarrow X_s \gamma$, where $X_s$ is a hadronic system with unit strangeness, proceeds via weak-interaction loop diagrams. New physics, beyond the SM, may also contribute to the loop amplitude, and lead to differences from the SM. This possibility has been pursued in inclusive measurements, which are theoretically clean but experimentally challenging, and in exclusive measurements, such as $B \rightarrow K \pi \gamma$. We report measurements of the branching fractions and mass spectra for the decays $B \rightarrow K \pi \gamma$ in four channels. SM predictions of the rates and resonance structure of these decays have large uncertainties [1]. The $K^+ \pi^+ \pi^- \gamma$ and $K_S^0 \pi^- \pi^+ \gamma$ decay channels have previously been observed [2]. Throughout this Letter, stated decays include charge conjugate modes.

The decays $B \rightarrow K_S^0 \pi^0 \gamma$, which have not previously been observed, are of particular interest because these three-body hadronic states permit the measurement, given sufficient statistics, of the photon polarization [3]. The polarization measurement depends on the interference between processes such as $(K \pi \pi)\pi^0 \gamma$ and $(K \pi^0)\pi^+ \pi^- \gamma$, where () indicates resonant substructure. This measurement may be compared with the SM prediction of nearly complete left-handed polarization.

We use a sample of $(232 \pm 1.5) \times 10^6 B \bar{B}$ pairs in a 210.9 fb$^{-1}$ dataset collected at the $\Upsilon(4S)$ resonance with the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ collider. For background studies, we also use a 21.7 fb$^{-1}$ sample collected below the $B \bar{B}$ threshold. The measurement procedure was designed using simulated signal and background events, data in sideband kinematic regions, and reconstructed $B \rightarrow D \pi^\pm, D \rightarrow K \pi^\pm \pi^\mp$ decays. Only after we established the selection and fit procedures did we examine signal candidates in the data sample.

A description of the detector exists elsewhere [4]. For this measurement, the most important detector elements are the five-layer silicon microstrip tracking detector (SVT) and the forty-layer drift chamber (DCH), situated in a 1.5 T solenoidal magnetic field, which measure charged particle momenta; the CsI(Tl) electromagnetic calorimeter (EMC), which measures the energies and directions of the photons; and the detector of internally reflected Cherenkov light (DIRC). The DIRC response and energy loss ($dE/dx$) measured in the SVT and DCH are used to identify charged kaons and pions.

We reconstruct the photon candidate in the $K \pi \pi \gamma$ decay from an EMC shower not associated with a charged track. The photon must be in the fiducial region of the EMC, have a shower-profile consistent with a single photon, and be well-separated from other showers. To remove photons from $\pi^0 (\eta)$ decays, we combine the candidate with other photons having energies of at least 50 (250) MeV/$c^2$, and reject it if the invariant mass of any combination is within 25 (40) MeV/$c^2$ of the $\pi^0 (\eta)$ mass.

We select $K^\pm$ and $\pi^\pm$ candidates from charged tracks consistent with a kaon or pion mass hypothesis in the DIRC and in the $dE/dx$ in the SVT and DCH. We reconstruct $K_S^0$ candidates from pairs of oppositely-charged tracks, and determine the decay vertex with a fit. We require that the invariant mass falls within 11 MeV/$c^2$ of the $K_S^0$ mass; that the distance between the $B$ decay vertex and the $K_S^0$ vertex exceeds 450 MeV; this last selection is about 83% efficient.

The dominant source of background is continuum production of light quark-antiquark pairs, in which a high-energy photon typically is produced either by initial state radiation, or from the decay of a $\pi^0$ or $\eta$ in which one photon is not detected. To reject these backgrounds, we construct a Fisher discriminant [5] from the polar angle of the $B$ candidate in the CM frame, the angle between the thrust axis of the $B$ and the thrust axis of the remaining charged and neutral particles, and the ratio of the second to zeroth angular moments of the remaining charged and neutral particles around the thrust axis of the $B$. We optimize the coefficients independently in each channel to discriminate between simulated signal and continuum.

We perform a geometric fit to the reconstructed $B$ candidate, with production vertex constrained to the nominal beam spot, rejecting the candidate if the final state is inconsistent with decay from a single vertex. We define
\( \Delta E^* \equiv E_B - E_{beam} \) and \( m_{ES} \equiv \sqrt{E_{beam}^2 - \mathbf{p}_B^2} \), where \( E_B \) and \( \mathbf{p}_B \) are the CM energy and momentum of the \( B \) candidate, and \( E_{beam} \) is the CM energy of each beam. We require \( m_{ES} > 5.2 \text{GeV}/c^2 \) and \( |\Delta E^*| < 0.15 \text{GeV} \). We also require that the invariant mass of the \( K\pi\pi \) system, \( m_{K\pi\pi} \), fall below 1.8 \text{GeV}/c^2; this eliminates much of a rising continuum background with very little expected signal loss. It also removes \( K\pi\pi \) combinations from \( D \) decays, in \( B \rightarrow D\pi^0 \) and \( B \rightarrow D\eta \) where the \( \pi^0 \) or \( \eta \) are mis-reconstructed as a photon. In an event in which we reconstruct multiple candidates in one channel that pass the selection requirements (occurring in 11-27\% of selected signal events, depending on the channel), we keep the candidate with the largest vertex probability (with the best \( \pi^0 \) mass in the \( K^0\pi^+\pi^-\gamma \) channel; with the \( \pi^0 \) mass as a tie breaker in the \( K^+\pi^-\pi^0\gamma \) channel) and reject the others. Candidates reconstructed in different channels are allowed in the same event. The dependence of the efficiency of our selection requirements on intermediate resonance and on \( m_{K\pi\pi} \) has been checked and found to be small; systematic uncertainties are discussed later.

The dominant backgrounds from \( B\Bar{B} \) events after the selection criteria have been applied are \( b \rightarrow s\gamma \) processes. We categorize these backgrounds: (i) “crossfeed” from mis-reconstructed \( K\pi\pi\gamma \) decays, such as by choosing incorrectly a particle from the other \( B \); (ii) \( B \rightarrow K\pi\gamma \) decays that combine with a track from the other \( B \) to form a \( K\pi\gamma \) candidate; and (iii) backgrounds from all other \( b \rightarrow s\gamma \) decays. A crossfeed candidate may be reconstructed in the same decay channel in which it is produced, or in a different channel, and can also be produced in a \( B \rightarrow K\pi\pi\gamma \) decay that is not used in this analysis (such as \( B^+ \rightarrow K^+\pi^0\pi^0\gamma \)). We model our signal as well as crossfeed backgrounds with simulated \( B \rightarrow K\pi\gamma \) decays, where \( K\pi \) is any of the five lowest-lying \( J > 0 \) kaon resonances above the \( K^*(892) \). We study backgrounds from \( K\pi\gamma \) using simulated \( B \rightarrow K^*(892)\gamma \) and \( B \rightarrow K^*_2(1430)\gamma \) decays. We study backgrounds from other \( b \rightarrow s\gamma \) decays using an inclusive simulation according to the model of Kagan and Neubert [8] with \( m_b = 4.8 \text{GeV}/c^2 \), tuned to match multiplicity distributions measured in inclusive \( b \rightarrow s\gamma \) decays [7]. The largest final background contributions from \( b \rightarrow s\gamma \) processes are crossfeed backgrounds, for which we obtain yields ranging from 55\% to 95\% of the signal yields.

We estimate other sources of background candidates from \( B \) decays other than \( b \rightarrow s\gamma \) processes by simulating generic \( B \) decays. We pay special attention to \( B \) decays with \( K\pi\pi\pi^0 \) and \( K\pi\pi\eta \) final states; if the \( \pi^0 \) or \( \eta \) decays asymmetrically and we don’t detect the lower-energy photon, the kinematic properties of the resulting \( B \) candidate may resemble a signal candidate. We study these decays using high-statistics simulated samples, and look for signal candidates that are reconstructed from a single \( B \rightarrow K\pi\pi\pi^0 \) or \( B \rightarrow K\pi\pi\eta \) decay. We expect to reconstruct fewer than two such candidates per channel.

We perform a maximum likelihood fit to the joint \( m_{ES}-\Delta E^* \) distribution of our selected candidates. We fit all four channels simultaneously to account for crossfeed backgrounds between channels. The likelihood function contains terms for correctly reconstructed signal candidates, crossfeed background candidates between all 16 combinations of the production and reconstruction channels, backgrounds from \( B \rightarrow K\pi\gamma \) and from other \( b \rightarrow s\gamma \) decays, and backgrounds from continuum events. We have determined from simulations that the dominant continuum background component adequately accounts for combinatoric backgrounds from other \( B\Bar{B} \) decays, which do not show strong peaks in \( m_{ES} \) and \( \Delta E^* \).

The likelihood function for a candidate reconstructed in decay channel \( i \) with kinematic variables \( y \equiv (m_{ES}, \Delta E^*) \) is given by,

\[
\mathcal{L}(y) = N_{B\Bar{B}}\prod \left( \mathcal{B}^i e^{\epsilon_i f_i(y)} + \sum_j \mathcal{B}^j e^{\epsilon_j f_j(y)} \right) + n_i^s f_i^s(y) + n_i^b f_i^b(y),
\]

where \( N_{B\Bar{B}} \) is the number of \( B\Bar{B} \) pairs in our dataset; \( \mathcal{B}^i \) is the branching fraction for decay channel \( i \); \( \epsilon_i \) and \( f_i \) are the efficiency and probability density function (PDF) for correctly reconstructed signal candidates in decay channel \( i \); \( \epsilon_j \) and \( f_j \) are the efficiency and PDF for crossfeed background candidates produced in channel \( j \) and reconstructed in channel \( i \); \( n_i^s \) and \( f_i^s \) are the yield and PDF for backgrounds from continuum and generic \( B\Bar{B} \) decay events in channel \( i \); and \( n_i^b \) and \( f_i^b \) are the yield and PDF for backgrounds from other \( b \rightarrow s\gamma \) processes in channel \( i \). We further parameterize the likelihood function by the four data-taking runs during which data were collected, accounting for slight changes in experimental conditions.

The branching fractions \( \mathcal{B}^i \), yields \( n_i \), and shape parameters of \( f_i \) are varied in the fit; other efficiencies, yields, and PDF shapes are fixed from simulation studies. We parameterize \( f_i^s \) as the product of Crystal Ball functions [8] of \( m_{ES} \) and of \( \Delta E^* \), \( f_i^b \) as the product of a Crystal Ball function of \( m_{ES} \) and a linear function of \( \Delta E^* \), and \( f_i^s \) as the product of an Argus function [9] of \( m_{ES} \) and an exponential function of \( \Delta E^* \). We use a binned parameterization for \( f_i^b \). As the signal and crossfeed terms are both scaled by the parameters \( \mathcal{B}^i \), the crossfeed background yields vary with the signal branching fractions, and we measure the branching fractions from yields of both signal and crossfeed candidates.

Table I shows the fit results. Projections in \( m_{ES} \), along with the fit results, are displayed in Fig. I. The fit probability (P-value) is evaluated with a likelihood ratio statistic [10], assuming Poisson-distributed bin contents, to be 10\%. The distribution of the test statistic under the null hypothesis is evaluated by simulation.

Figure 2 shows background-subtracted \( m_{K\pi\pi} \) mass spectra. Background subtraction is achieved using the
results of the fits to calculate event-by-event weights to extract the signal component. We present branching fractions in bins of $m_{K\pi\pi}$, which are largely model-independent, instead of extracting $B \to K\chi$ branching fractions for specific $K\chi$ resonances. Disentangling the resonance structure requires careful modeling of amplitudes and relative phases of interfering processes, including in the decays of the $K\chi$ resonances, not all of which are well measured. A partial wave analysis to extract the resonance structure and measure the photon polarization should be possible with future datasets.

**Table I:** Results of the fit for $B \to K\pi\pi\gamma$, for $m_{K\pi\pi} < 1.8$ GeV/$c^2$. The first error is statistical, the second systematic. The yields do not include the channel crossfeeds, which are included in the fit to obtain the branching fractions.

| Channel     | Yield      | Branching Fraction (10^−5) |
|-------------|------------|----------------------------|
| $K^+\pi^-\pi^0\gamma$ | 899 ± 38   | 2.95 ± 0.13 ± 0.20         |
| $K^+\pi^-\pi^0\gamma$ | 572 ± 31   | 4.07 ± 0.22 ± 0.31         |
| $K^0\pi^+\pi^-\gamma$ | 176 ± 20   | 1.85 ± 0.21 ± 0.12         |
| $K^0\pi^+\pi^-\gamma$ | 164 ± 15   | 4.56 ± 0.42 ± 0.31         |

We validate the procedure for extracting branching fractions and $m_{K\pi\pi}$ distributions using fits to simulated samples. We verify that the branching fractions and mass spectra obtained from these toy fits reproduce on average the simulation inputs. We use the same procedure to extract the $m_{K\pi\pi}$ distributions for continuum and generic $B\bar{B}$ backgrounds and for backgrounds from $b \to s\gamma$ decays; these are consistent with the expected distributions.

Systematic uncertainties arise from various sources, shown in Table I. The largest sources are: (i) The $T(4S)$ branching fractions to $B^+B^-$ and $B^0\bar{B}^0$ are each assumed to be 0.5. We assign a 2.6% systematic uncertainty to this, based on current information. (ii) The uncertainty on the photon selection efficiency determined from simulated events is estimated to be 2.7%. (iii) From studies of $B \to D\pi^\pm$, $D \to K\pi\pi$ events, we assign an uncertainty of 4.2% to the charged kaon identification efficiency. (iv) The uncertainty of the $\pi^0$ selection efficiency is estimated at 3.0%. (v) There is considerable uncertainty in the models we use to estimate backgrounds, including cross-feed dependence, from $b \to s\gamma$ processes. We estimate the effect of this uncertainty on both the branching fractions and mass spectra by simulating these backgrounds with substantially different models. The largest effect is in the $K^0\pi^-\pi^+\gamma$ channel, where the uncertainty is 4.0%. (vi) We measure a shift in the beam...
energy in $B \to D\pi^\mp$ decays, on average 0.6 MeV; we estimate the effect of this on our fits. (vii) We estimate bias in the fit due to uncertain parameterization of the signal and background PDFs. The largest effect is in the $K^0\pi^+\pi^0\gamma$ channel, where the uncertainty is 3.5%.

We have measured branching fractions for $B \to K\pi\pi\gamma$ in four decay channels for $m_{K\pi\pi} < 1.8$ GeV/$c^2$. The $K\pi^+\pi^-$ channels are consistent with the previous measurement. We present first observations of decays in the $K\pi^+\pi^0\gamma$ channels that are important to measuring the photon polarization. The branching fractions are relatively large in the context of $B \to X_s\gamma$ decays, providing encouragement that a polarization measurement may be possible with future datasets. Mass spectra for the $K\pi\pi$ system are also presented. We observe an enhancement near 1.3 GeV/$c^2$ and substantial branching fractions at higher masses. Untangling the resonant contributions presents a challenge for the polarization measurement.

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TABLE II: Estimated systematic uncertainties in the branching fractions, in percent, by source and decay channel.

| Source        | $K^+\pi^-\pi^+$ | $K^+\pi^-\pi^0$ | $K^0\pi^+\pi^+$ | $K^0\pi^-\pi^0$ |
|---------------|-----------------|-----------------|-----------------|-----------------|
| $B\bar{B}$ count | 1.1             | 1.1             | 1.1             | 1.1             |
| $\Upsilon(4S)$ BF | 2.6             | 2.6             | 2.6             | 2.6             |
| Efficiencies: Photon selection | 2.7             | 2.7             | 2.7             | 2.7             |
| $\pi^0$ and $\eta$ veto | 1.0             | 1.0             | 1.0             | 1.0             |
| Tracking | 1.4             | 1.1             | 1.1             | 0.8             |
| $\pi^\pm$ selection | 4.2             | 4.2             | 1.6             | 1.6             |
| $\pi^0$ selection | 1.4             | 1.0             | 1.4             | 1.0             |
| Fisher cut | 3.0             | 3.0             | 3.0             | 3.0             |
| Vertex probability | 0.7             | 0.7             | 0.7             | 0.7             |
| MC statistics | 0.5             | 0.7             | 0.8             | 1.1             |
| Backgrounds: $b \to s\gamma$ model | 1.4             | 1.0             | 4.0             | 1.3             |
| $B \to K\pi\pi^0/\eta$ | 0.2             | 0.1             | 0.0             | 0.6             |
| Beam energy shift | 1.0             | 0.5             | 1.6             | 0.6             |
| PDF shape | 0.1             | 2.9             | 0.9             | 0.2             |
| Fit bias | 1.6             | 1.3             | 1.3             | 3.5             |
| Total | 6.7             | 7.6             | 6.7             | 6.8             |

* Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
† Also with Università della Basilicata, Potenza, Italy
‡ Deceased
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We present a measurement of the partial branching fractions and mass spectra of the exclusive radiative penguin processes $B \to K\pi\pi\gamma$ in the range $m_{K\pi\pi} < 1.8\text{GeV}/c^2$. We reconstruct four final states: $K^+\pi^−\pi^+\gamma$, $K^+\pi^-\pi^0\gamma$, $K^0_S\pi^-\pi^+\gamma$, and $K^0_S\pi^+\pi^-\gamma$, where $K^0_S \to \pi^+\pi^-$. Using 232 million $e^+e^- \to BB$ events recorded by the BaBar experiment at the PEP-II asymmetric-energy storage ring, we measure the branching fractions $B(B^+ \to K^+\pi^−\pi^+\gamma) = (2.95 \pm 0.13 \text{ (stat.)} \pm 0.20 \text{ (syst.)}) \times 10^{-5}$, $B(B^0 \to K^+\pi^-\pi^0\gamma) = (4.07 \pm 0.22 \text{ (stat.)} \pm 0.31 \text{ (syst.)}) \times 10^{-5}$, $B(B^0 \to K^0_S\pi^-\pi^+\gamma) = (1.85 \pm 0.21 \text{ (stat.)} \pm 0.12 \text{ (syst.)}) \times 10^{-5}$, and $B(B^+ \to K^0_S\pi^+\pi^0\gamma) = (4.56 \pm 0.42 \text{ (stat.)} \pm 0.31 \text{ (syst.)}) \times 10^{-5}$. 