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A measurement of the branching fraction of the exclusive decay $B^0 \to K^{*0}\gamma$

The *BABAR* Collaboration

Abstract

The $b \to s\gamma$ transition proceeds by a loop "penguin" diagram. It may be used to measure precisely the couplings of the top quark and to search for the effects of any new particles appearing in the loop. We present a preliminary measurement of the branching fraction of the exclusive decay, $B^0 \to K^{*0}\gamma$. We use 8.6×10^6 $B\overline{B}$ decays to measure $\mathcal{B}(B^0 \to K^{*0}\gamma) = (5.4 \pm 0.8 \pm 0.5) \times 10^{-5}$.

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

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The *BABAR* Collaboration

B. Aubert, A. Boucham, D. Boutigny, I. De Bonis, J. Favier, J.-M. Gaillard, F. Galeazzi, A. Jeremie, Y. Karyotakis, J. P. Lees, P. Robbe, V. Tisserand, K. Zachariadou

Lab de Phys. des Particules, F-74941 Annecy-le-Vieux, CEDEX, France

A. Palano

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

G. P. Chen, J. C. Chen, N. D. Qi, G. Rong, P. Wang, Y. S. Zhu

Institute of High Energy Physics, Beijing 100039, China

G. Eigen, P. L. Reinertsen, B. Stugu

University of Bergen, Inst. of Physics, N-5007 Bergen, Norway

B. Abbott, G. S. Abrams, A. W. Borgland, A. B. Breon, D. N. Brown, J. Button-Shafer, R. N. Cahn, A. R. Clark, Q. Fan, M. S. Gill, S. J. Gowdy, Y. Groysman, R. G. Jacobsen, R. W. Kadel, J. Kadyk, L. T. Kerth, S. Kluth, J. F. Kral, C. Leclerc, M. E. Levi, T. Liu, G. Lynch, A. B. Meyer, M. Momayezi, P. J. Oddone, A. Perazzo, M. Pripstein, N. A. Roe, A. Romosan, M. T. Ronan, V. G. Shelkov, P. Strother, A. V. Telnov, W. A. Wenzel

Lawrence Berkeley National Lab, Berkeley, CA 94720, USA

P. G. Bright-Thomas, T. J. Champion, C. M. Hawkes, A. Kirk, S. W. O'Neale, A. T. Watson, N. K. Watson

University of Birmingham, Birmingham, B15 2TT, UK

T. Deppermann, H. Koch, J. Krug, M. Kunze, B. Lewandowski, K. Peters, H. Schmuecker, M. Steinke

Ruhr Universität Bochum, Inst. f. Experimentalphysik 1, D-44780 Bochum, Germany

J. C. Andress, N. Chevalier, P. J. Clark, N. Cottingham, N. De Groot, N. Dyce, B. Foster, A. Mass, J. D. McFall, D. Wallom, F. F. Wilson

University of Bristol, Bristol BS8 lTL, UK

K. Abe, C. Hearty, T. S. Mattison, J. A. McKenna, D. Thiessen

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

B. Camanzi, A. K. McKemey, J. Tinslay

Brunel University, Uxbridge, Middlesex UB8 3PH, UK

V. E. Blinov, A. D. Bukin, D. A. Bukin, A. R. Buzykaev, M. S. Dubrovin, V. B. Golubev, V. N. Ivanchenko, A. A. Korol, E. A. Kravchenko, A. P. Onuchin, A. A. Salnikov, S. I. Serednyakov, Yu. I. Skovpen, A. N. Yushkov

Budker Institute of Nuclear Physics, Siberian Branch of Russian Academy of Science, Novosibirsk 630090, Russia

A. J. Lankford, M. Mandelkern, D. P. Stoker

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

A. Ahsan, K. Arisaka, C. Buchanan, S. Chun

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

J. G. Branson, R. Faccini,[1] D. B. MacFarlane, Sh. Rahatlou, G. Raven, V. Sharma

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

C. Campagnari, B. Dahmes, P. A. Hart, N. Kuznetsova, S. L. Levy, O. Long, A. Lu, J. D. Richman, W. Verkerke, M. Witherell, S. Yellin

University of California at Santa Barbara, Santa Barbara, CA 93106, USA

J. Beringer, D. E. Dorfan, A. Eisner, A. Frey, A. A. Grillo, M. Grothe, C. A. Heusch, R. P. Johnson, W. Kroeger, W. S. Lockman, T. Pulliam, H. Sadrozinski, T. Schalk, R. E. Schmitz, B. A. Schumm, A. Seiden, M. Turri, D. C. Williams

University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA

E. Chen, G. P. Dubois-Felsmann, A. Dvoretskii, D. G. Hitlin, Yu. G. Kolomensky, S. Metzler, J. Oyang, F. C. Porter, A. Ryd, A. Samuel, M. Weaver, S. Yang, R. Y. Zhu

California Institute of Technology, Pasadena, CA 91125, USA

R. Aleksan, G. De Domenico, A. de Lesquen, S. Emery, A. Gaidot, S. F. Ganzhur, G. Hamel de Monchenault, W. Kozanecki, M. Langer, G. W. London, B. Mayer, B. Serfass, G. Vasseur, C. Yeche, M. Zito

Centre d'Etudes Nucléaires, Saclay, F-91191 Gif-sur-Yvette, France

S. Devmal, T. L. Geld, S. Jayatilleke, S. M. Jayatilleke, G. Mancinelli, B. T. Meadows, M. D. Sokoloff

University of Cincinnati, Cincinnati, OH 45221, USA

J. Blouw, J. L. Harton, M. Krishnamurthy, A. Soffer, W. H. Toki, R. J. Wilson, J. Zhang

Colorado State University, Fort Collins, CO 80523, USA

S. Fahey, W. T. Ford, F. Gaede, D. R. Johnson, A. K. Michael, U. Nauenberg, A. Olivas, H. Park, P. Rankin, J. Roy, S. Sen, J. G. Smith, D. L. Wagner

University of Colorado, Boulder, CO 80309, USA

T. Brandt, J. Brose, G. Dahlinger, M. Dickopp, R. S. Dubitzky, M. L. Kocian, R. Müller-Pfefferkorn, K. R. Schubert, R. Schwierz, B. Spaan, L. Wilden

Technische Universität Dresden, Inst. f. Kern- u. Teilchenphysik, D-01062 Dresden, Germany

L. Behr, D. Bernard, G. R. Bonneaud, F. Brochard, J. Cohen-Tanugi, S. Ferrag, E. Roussot, C. Thiebaux, G. Vasileiadis, M. Verderi

Ecole Polytechnique, Lab de Physique Nucléaire H. E., F-91128 Palaiseau, France

A. Anjomshoaa, R. Bernet, F. Di Lodovico, F. Muheim, S. Playfer, J. E. Swain

University of Edinburgh, Edinburgh EH9 3JZ, UK

C. Bozzi, S. Dittongo, M. Folegani, L. Piemontese

Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy

E. Treadwell

Florida A&M University, Tallahassee, FL 32307, USA

[1]Jointly appointed with Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

R. Baldini-Ferroli, A. Calcaterra, R. de Sangro, D. Falciai, G. Finocchiaro, P. Patteri, I. M. Peruzzi,[2] M. Piccolo, A. Zallo

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

S. Bagnasco, A. Buzzo, R. Contri, G. Crosetti, P. Fabbricatore, S. Farinon, M. Lo Vetere, M. Macri, M. R. Monge, R. Musenich, R. Parodi, S. Passaggio, F. C. Pastore, C. Patrignani, M. G. Pia, C. Priano, E. Robutti, A. Santroni

Università di Genova, Dipartimento di Fisica and INFN, I-16146 Genova, Italy

J. Cochran, H. B. Crawley, P.-A. Fischer, J. Lamsa, W. T. Meyer, E. I. Rosenberg

Iowa State University, Ames, IA 50011-3160, USA

R. Bartoldus, T. Dignan, R. Hamilton, U. Mallik

University of Iowa, Iowa City, IA 52242, USA

C. Angelini, G. Batignani, S. Bettarini, M. Bondioli, M. Carpinelli, F. Forti, M. A. Giorgi, A. Lusiani, M. Morganti, E. Paoloni, M. Rama, G. Rizzo, F. Sandrelli, G. Simi, G. Triggiani

Università di Pisa, Scuola Normale Superiore, and INFN, I-56010 Pisa, Italy

M. Benkebil, G. Grosdidier, C. Hast, A. Hoecker, V. LePeltier, A. M. Lutz, S. Plaszczynski, M. H. Schune, S. Trincaz-Duvoid, A. Valassi, G. Wormser

LAL, F-91898 ORSAY Cedex, France

R. M. Bionta, V. Brigljević, O. Fackler, D. Fujino, D. J. Lange, M. Mugge, X. Shi, T. J. Wenaus, D. M. Wright, C. R. Wuest

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

M. Carroll, J. R. Fry, E. Gabathuler, R. Gamet, M. George, M. Kay, S. McMahon, T. R. McMahon, D. J. Payne, C. Touramanis

University of Liverpool, Liverpool L69 3BX, UK

M. L. Aspinwall, P. D. Dauncey, I. Eschrich, N. J. W. Gunawardane, R. Martin, J. A. Nash, P. Sanders, D. Smith

University of London, Imperial College, London, SW7 2BW, UK

D. E. Azzopardi, J. J. Back, P. Dixon, P. F. Harrison, P. B. Vidal, M. I. Williams

University of London, Queen Mary and Westfield College, London, E1 4NS, UK

G. Cowan, M. G. Green, A. Kurup, P. McGrath, I. Scott

University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, UK

D. Brown, C. L. Davis, Y. Li, J. Pavlovich, A. Trunov

University of Louisville, Louisville, KY 40292, USA

J. Allison, R. J. Barlow, J. T. Boyd, J. Fullwood, A. Khan, G. D. Lafferty, N. Savvas, E. T. Simopoulos, R. J. Thompson, J. H. Weatherall

University of Manchester, Manchester M13 9PL, UK

[2]Jointly appointed with Univ. di Perugia, I-06100 Perugia, Italy

C. Dallapiccola, A. Farbin, A. Jawahery, V. Lillard, J. Olsen, D. A. Roberts
University of Maryland, College Park, MD 20742, USA

B. Brau, R. Cowan, F. Taylor, R. K. Yamamoto
Massachusetts Institute of Technology, Lab for Nuclear Science, Cambridge, MA 02139, USA

G. Blaylock, K. T. Flood, S. S. Hertzbach, R. Kofler, C. S. Lin, S. Willocq, J. Wittlin
University of Massachusetts, Amherst, MA 01003, USA

P. Bloom, D. I. Britton, M. Milek, P. M. Patel, J. Trischuk
McGill University, Montreal, PQ, Canada H3A 2T8

F. Lanni, F. Palombo
Università di Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy

J. M. Bauer, M. Booke, L. Cremaldi, R. Kroeger, J. Reidy, D. Sanders, D. J. Summers
University of Mississippi, University, MS 38677, USA

J. F. Arguin, J. P. Martin, J. Y. Nief, R. Seitz, P. Taras, A. Woch, V. Zacek
Université de Montreal, Lab. Rene J. A. Levesque, Montreal, QC, Canada, H3C 3J7

H. Nicholson, C. S. Sutton
Mount Holyoke College, South Hadley, MA 01075, USA

N. Cavallo, G. De Nardo, F. Fabozzi, C. Gatto, L. Lista, D. Piccolo, C. Sciacca
Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126 Napoli, Italy

M. Falbo
Northern Kentucky University, Highland Heights, KY 41076, USA

J. M. LoSecco
University of Notre Dame, Notre Dame, IN 46556, USA

J. R. G. Alsmiller, T. A. Gabriel, T. Handler
Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

F. Colecchia, F. Dal Corso, G. Michelon, M. Morandin, M. Posocco, R. Stroili, E. Torassa, C. Voci
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy

M. Benayoun, H. Briand, J. Chauveau, P. David, C. De la Vaissière, L. Del Buono, O. Hamon, F. Le Diberder, Ph. Leruste, J. Lory, F. Martinez-Vidal, L. Roos, J. Stark, S. Versillé
Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, Cedex 05, France

P. F. Manfredi, V. Re, V. Speziali
Università di Pavia, Dipartimento di Elettronica and INFN, I-27100 Pavia, Italy

E. D. Frank, L. Gladney, Q. H. Guo, J. H. Panetta
University of Pennsylvania, Philadelphia, PA 19104, USA

M. Haire, D. Judd, K. Paick, L. Turnbull, D. E. Wagoner
Prairie View A&M University, Prairie View, TX 77446, USA

J. Albert, C. Bula, M. H. Kelsey, C. Lu, K. T. McDonald, V. Miftakov, S. F. Schaffner, A. J. S. Smith, A. Tumanov, E. W. Varnes

Princeton University, Princeton, NJ 08544, USA

G. Cavoto, F. Ferrarotto, F. Ferroni, K. Fratini, E. Lamanna, E. Leonardi, M. A. Mazzoni, S. Morganti, G. Piredda, F. Safai Tehrani, M. Serra

Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy

R. Waldi

Universität Rostock, D-18051 Rostock, Germany

P. F. Jacques, M. Kalelkar, R. J. Plano

Rutgers University, New Brunswick, NJ 08903, USA

T. Adye, U. Egede, B. Franek, N. I. Geddes, G. P. Gopal

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., OX11 0QX, UK

N. Copty, M. V. Purohit, F. X. Yumiceva

University of South Carolina, Columbia, SC 29208, USA

I. Adam, P. L. Anthony, F. Anulli, D. Aston, K. Baird, E. Bloom, A. M. Boyarski, F. Bulos, G. Calderini, M. R. Convery, D. P. Coupal, D. H. Coward, J. Dorfan, M. Doser, W. Dunwoodie, T. Glanzman, G. L. Godfrey, P. Grosso, J. L. Hewett, T. Himel, M. E. Huffer, W. R. Innes, C. P. Jessop, P. Kim, U. Langenegger, D. W. G. S. Leith, S. Luitz, V. Luth, H. L. Lynch, G. Manzin, H. Marsiske, S. Menke, R. Messner, K. C. Moffeit, M. Morii, R. Mount, D. R. Muller, C. P. O'Grady, P. Paolucci, S. Petrak, H. Quinn, B. N. Ratcliff, S. H. Robertson, L. S. Rochester, A. Roodman, T. Schietinger, R. H. Schindler, J. Schwiening, G. Sciolla, V. V. Serbo, A. Snyder, A. Soha, S. M. Spanier, A. Stahl, D. Su, M. K. Sullivan, M. Talby, H. A. Tanaka, J. Va'vra, S. R. Wagner, A. J. R. Weinstein, W. J. Wisniewski, C. C. Young

Stanford Linear Accelerator Center, Stanford, CA 94309, USA

P. R. Burchat, C. H. Cheng, D. Kirkby, T. I. Meyer, C. Roat

Stanford University, Stanford, CA 94305-4060, USA

A. De Silva, R. Henderson

TRIUMF, Vancouver, BC, Canada V6T 2A3

W. Bugg, H. Cohn, E. Hart, A. W. Weidemann

University of Tennessee, Knoxville, TN 37996, USA

T. Benninger, J. M. Izen, I. Kitayama, X. C. Lou, M. Turcotte

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

F. Bianchi, M. Bona, B. Di Girolamo, D. Gamba, A. Smol, D. Zanin

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

L. Bosisio, G. Della Ricca, L. Lanceri, A. Pompili, P. Poropat, M. Prest, E. Vallazza, G. Vuagnin

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

R. S. Panvini

Vanderbilt University, Nashville, TN 37235, USA

C. M. Brown, P. D. Jackson, R. Kowalewski, J. M. Roney

University of Victoria, Victoria, BC, Canada V8W 3P6

H. R. Band, E. Charles, S. Dasu, P. Elmer, J. R. Johnson, J. Nielsen, W. Orejudos, Y. Pan, R. Prepost, I. J. Scott, J. Walsh, S. L. Wu, Z. Yu, H. Zobernig

University of Wisconsin, Madison, WI 53706, USA

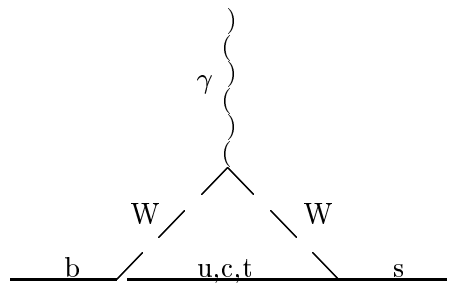

Figure 1: The leading order Feynman diagram for the $B^0 \to K^{*0}\gamma$ decay

In the Standard Model the exclusive decay $B^0 \to K^{*0}\gamma$ proceeds by the $b \to s\gamma$ loop "penguin" diagram shown in Fig. 1. Precise measurements of decay modes involving these transitions and modes with the related $b \to d\gamma$ transition such as $B^0 \to \rho\gamma$ will allow measurements of the top quark couplings V_{ts} and V_{td}. The strength of these transitions may also be enhanced by the presence of non-Standard Model contributions [1]. In minimal supersymmetric models, for example, the W can be replaced by a charged Higgs leading to significant enhancements in the branching fraction. In the first year of running the *BABAR* experiment has accumulated a dataset comparable to the world's largest to date, and this will increase by an order of magnitude over the next few years. The large dataset available and the state of the art detection systems employed at *BABAR* will allow measurements and searches of unprecedented precision. A comprehensive program to study these decays is now underway. The first step in this program is the preliminary measurement of the branching fraction of the exclusive decay mode $B^0 \to K^{*0}\gamma$ using the leading decay mode, $K^{*0} \to K^+\pi^-$. Here K^{*0} refers to the $K^{*0}(892)$ resonance, and charge conjugate channels are assumed throughout. The most precise measurement of the branching fraction to date, $\mathcal{B}(B^0 \to K^{*0}\gamma) = (4.55^{+0.72}_{-0.68} \pm 0.34) \times 10^{-5}$, is from the CLEO collaboration [2] and is in agreement with Standard Model predictions of $(3.3 - 6.3) \times 10^{-5}$ [3].

The data were collected with the *BABAR* detector [4] at the PEP-II asymmetric e^+e^- storage ring [5]. The results presented in this paper are based upon an integrated luminosity of $7.5\,\mathrm{fb}^{-1}$ of data corresponding to 8.6×10^6 $B\overline{B}$ meson pairs recorded at the $\Upsilon(4S)$ energy ("on-resonance") and $1.1\,\mathrm{fb}^{-1}$ below the $\Upsilon(4S)$ energy ("off-resonance"). The *BABAR* detector simulation is based upon GEANT [6] and tuned with data. Events taken from random triggers are used to measure the beam backgrounds. They are mixed into the simulated events, so that small changes in detector conditions, including dead channels, are also simulated. The simulated events are processed in the same manner as data.

The selection criteria for this analysis have been optimized to maximize $S^2/(S+B)$ where S is the number of signal candidates expected, assuming $\mathcal{B}(B^0 \to K^{*0}\gamma) = 4.55 \times 10^{-5}$, and B is the expected number of background candidates determined from Monte Carlo. We compute quantities in both the laboratory frame and the rest frame of the $\Upsilon(4S)$. Quantities computed in the rest frame are denoted by an asterisk; e.g. E_b^* is the energy of the e^+ and e^- beams which are symmetric in the $\Upsilon(4S)$ rest frame.

We begin the selection by requiring a high energy photon candidate in the calorimeter. The calorimeter consists of 6580 thallium doped CsI crystals arranged in a non-projective barrel and forward endcap geometry. We require the photon candidate to have an energy, measured in the laboratory frame, between 1.5 and 4.5 GeV and further require $2.20 < E^*_\gamma < 2.85$ GeV. A photon candidate is defined as a calorimeter cluster [4] in a region of good calorimetry ($-0.74 < \cos\theta < 0.93$), where θ is the polar angle to the beam axis. The cluster must be isolated from any track. The distribution of individual crystal energies in the cluster is required to have only one maximum and a lateral profile consistent with a photon shower. These requirements remove backgrounds from high energy π^0 and η mesons where the two photons from the decay have merged into one cluster. In addition we form the combination of the high energy photon candidate with all other photons in the event with energy greater than 50 (250) MeV and require the invariant mass of the combination not to lie within two standard deviations of the known $\pi^0(\eta)$ mass.

We next reconstruct the K^{*0} from K^+ and π^- candidates, by considering all pairs of tracks in the event. The tracks are required to be well reconstructed in the tracking detectors and to originate from a vertex consistent with the e^+e^- interaction point. The tracking detector consists of a five layer double-sided silicon vertex tracker plus a forty layer stereo-axial drift chamber. A track is identified as a kaon if it is projected to pass through the fiducial volume of the particle identification detector. This detector is a novel ring imaging Cherenkov detector (DIRC) in which the radiating medium, an elongated quartz bar, also acts as a light guide to project the light cone onto an array of photo-multiplier tubes at the backward end of the detector. The high light yield and low mass of this detector are a significant advance in particle identification over previous experiments. We require a cone of Cherenkov light consistent in time and angle with a kaon of the measured track momentum. The K^{*0} reconstruction is completed by requiring the invariant mass of the candidate pairs to be within 90 MeV/c^2 of the K^{*0} mass: $806 < M_{K^+\pi^-} < 986$ MeV/c^2.

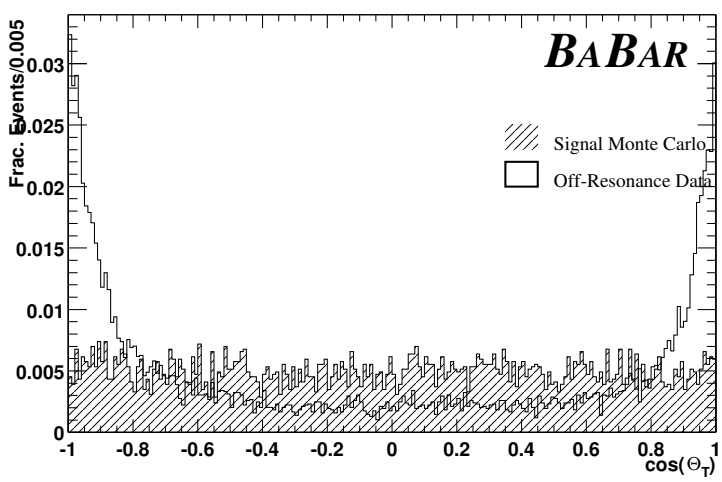

Figure 2: The event shape variable $\cos\theta^*_T$ for $B^0 \to K^{*0}\gamma$, $K^{*0} \to K^+\pi^-$ Monte Carlo and off resonance data.

The B^0 candidates are reconstructed from the K^{*0} and γ candidates. There are backgrounds from continuum $q\overline{q}$ production with the high energy photon originating from initial state radiation

or from a π^0 or η. We exploit event topology differences between signal and background to reduce the continuum contribution. The thrust vector $\vec{T}^*$ of the event is computed, excluding the B^0 daughter candidates. Fig. 2 shows the distribution of $\cos\theta_T^*$ for signal Monte Carlo events and off resonance data, where θ_T^* is the angle between the high energy photon candidate and $\vec{T}^*$. In this frame the $B\overline{B}$ pairs are produced approximately at rest and therefore decay isotropically with a flat distribution in $\cos\theta_T^*$. The $q\overline{q}$ pair is produced above threshold recoiling against each other in a jet-like topology, which results in a $\cos\theta_T^*$ distribution peaking at ± 1 . We require $|\cos\theta_T^*| < 0.78$. Backgrounds are further suppressed by constructing two additional event shape variables which are uncorrelated to $\cos\theta_T^*$. The angle of the B^0 candidate direction with respect to the beam axis, θ_B^* follows a $1-\cos^2\theta_B$ distribution and is flat for $q\overline{q}$ production. We require $|\cos\theta_B^*| < 0.76$. The helicity of the K^{*0} decay, θ_H^*, is defined as the angle of the K^+ in the K^{*0} rest frame with respect to the flight direction of the K^{*0} in the $\Upsilon(4S)$ rest frame. This follows a $1-\cos^2\theta_H^*$ distribution in $B^0 \to K^{*0}\gamma$, $K^{*0} \to K^+\pi^-$, whereas the $q\overline{q}$ background is flat. We require $|\cos\theta_H^*| < 0.7$.

Since the B^0 mesons are produced via $e^+e^- \to \Upsilon(4S) \to B\overline{B}$, the energy of the B^0 is given by the beam energy, E_b^*. The beam energy is measured much more precisely than the energy of the B^0 candidate daughter particles. In particular for the decay $B^0 \to K^{*0}\gamma$ the energy resolution of the high energy photon dominates the measured B^0 candidate energy. We reconstruct the B^0 candidate substituting E_b^* for the measured energy of the candidate daughters. We define the difference of the beam energy and energy of the B^0 daughters, $\Delta E^* = E_{K^*}^* + E_\gamma^* - E_b^*$. The B^0 mass is given by $m_{\rm ES} = \sqrt{E_b^{*2} - |p_B^{*2}|}$, where $|p_B^*|$ is the momentum of the B^0 candidate calculated using the measured momenta of the charged daughters and the energy of the photon. In the calculation of $m_{\rm ES}$ we rescale the measured photon energy, E_γ^* by a factor κ so that $E_b^* = E_{K^*}^* + \kappa E_\gamma^*$. This procedure corrects for the low energy tail in the E_γ^* distribution due to the incomplete containment of showers in the calorimeter. Using $m_{\rm ES}$ is an order of magnitude more precise than using the invariant mass. In addition the rescaling of E_γ^* enhances the resolution on $m_{\rm ES}$ by 20%. The resolution of $3.0\,{\rm MeV}/c^2$ is dominated by the beam energy spread. We select candidates with $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$.

Figure 3 shows the ΔE^* versus $m_{\rm ES}$ distribution for on-resonance data. Figure 4 shows the projection onto the $m_{\rm ES}$ axis, requiring $-200 < \Delta E^* < 100\,{\rm MeV}$. The $m_{\rm ES}$ distribution is fitted using an unbinned maximum likelihood fit. The background is empirically described by a function [7]:

$$\frac{dN}{dm_{\rm ES}} \propto m_{\rm ES}.\sqrt{1-\frac{{m_{\rm ES}}^2}{E_b^{*2}}}.\exp\left[-\zeta\left(1-\frac{{m_{\rm ES}}^2}{E_b^{*2}}\right)\right]$$

where the parameter ζ is measured from the off-resonance data sample which is required to pass the same selection criteria as the on-resonance data sample except that we remove the $\cos\theta_H^*$ cut, and relax the selection requirements to $|\cos\theta_T^*| < 0.95$ and $|\Delta E^*| < 500\,{\rm MeV}$ to gain statistics. We measure $\zeta = 22 \pm 13$. The fit to the on-resonance data uses this fixed value of ζ and adds a signal Gaussian whose mean and width are allowed to vary. We find a signal of 48.4 ± 7.3 events with the error coming from the statistical error of the fit.

As a consistency check we plot in Fig. 5 the ΔE^* projection by requiring $5.274 < m_{\rm ES} < 5.285\,{\rm GeV}/c^2$. The ΔE^* distribution is fitted using a fixed shape determined from the Monte Carlo sample which is in good agreement with the data. We also plot $M_{K^+\pi^-}$ in Fig. 6 by requiring $5.274 < m_{\rm ES} < 5.285\,{\rm GeV}/c^2$ and $-200 < \Delta E^* < 100\,{\rm MeV}$. We fit using a Breit-Wigner shape and determine that the signal is consistent with coming from a K^{*0}.

The efficiency for the selection of $B^0 \to K^{*0}\gamma$ candidates is $(15.5 \pm 0.3)\%$. The branching fraction is determined using the yield, the efficiency and the total number of $B\overline{B}$ events in the

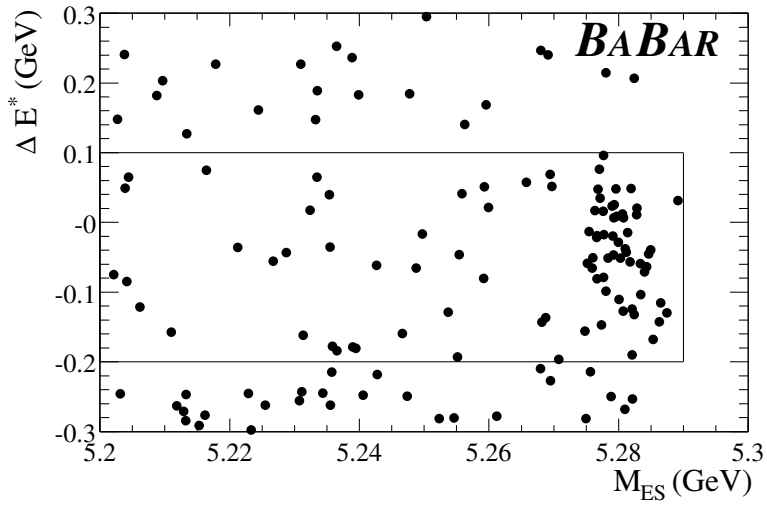

Figure 3: ΔE^* versus $m_{\rm ES}$ for $B^0 \to K^{*0}\gamma$,$K^{*0} \to K^+\pi^-$ candidates from $(8.6 \pm 0.3) \times 10^6$ $B\overline{B}$ decays. The box indicates the boundaries used to make the projection of the ΔE^*–$m_{\rm ES}$ plane onto the $m_{\rm ES}$ axis in Fig. 4.

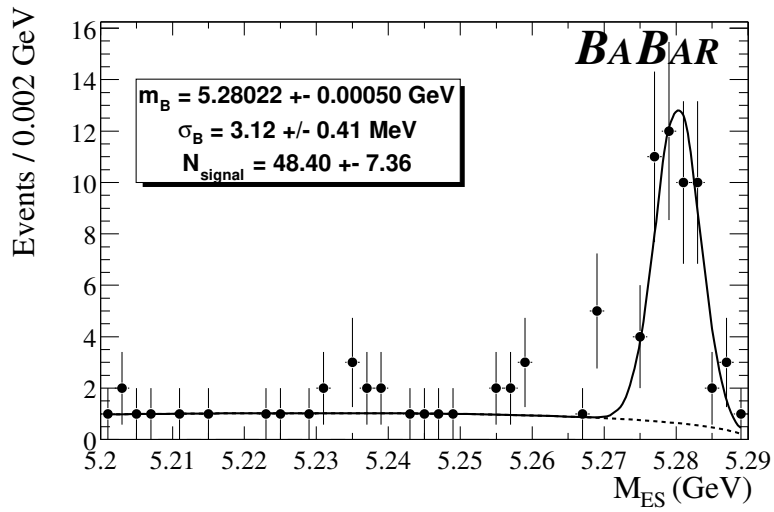

Figure 4: The $m_{\rm ES}$ projection for $B^0 \to K^{*0}\gamma$, $K^{*0} \to K^+\pi^-$ candidates from $(8.6 \pm 0.3) \times 10^6$ $B\overline{B}$ decays. The fit uses a parameterized background function, described in the text, and a Gaussian for the signal.

sample. The number of $B\overline{B}$ events is determined by counting the number of events passing a loose generic hadron requirement and subtracting the non-$B\overline{B}$ component estimated by scaling off-resonance data. We measure the number of $B\overline{B}$ events in the sample to be $(8.6 \pm 0.3) \times 10^6$. The branching fraction is measured to be $\mathcal{B}(B^0 \to K^{*0}\gamma) = (5.4 \pm 0.8 \pm 0.5) \times 10^{-5}$ consistent both with previous measurements and with the Standard Model expectations. The first error is

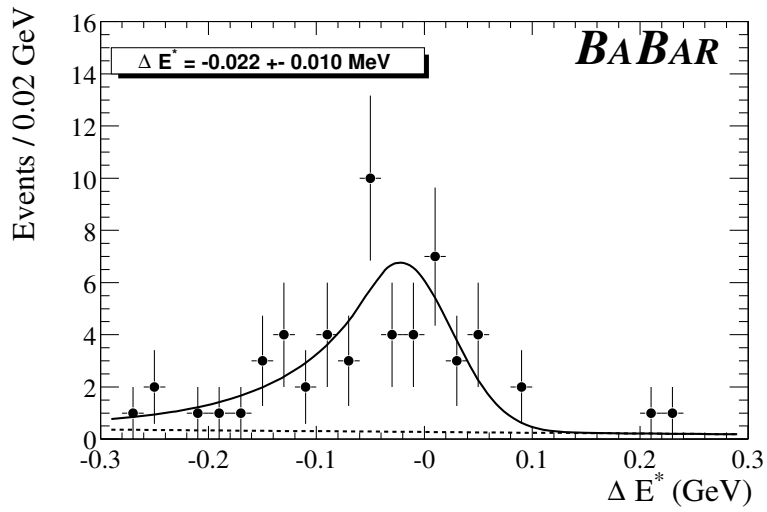

Figure 5: The ΔE^* projection for $B^0 \to K^{*0}\gamma$, $K^{*0} \to K^+\pi^-$ candidates from $(8.6 \pm 0.3) \times 10^6$ $B\overline{B}$ decays.

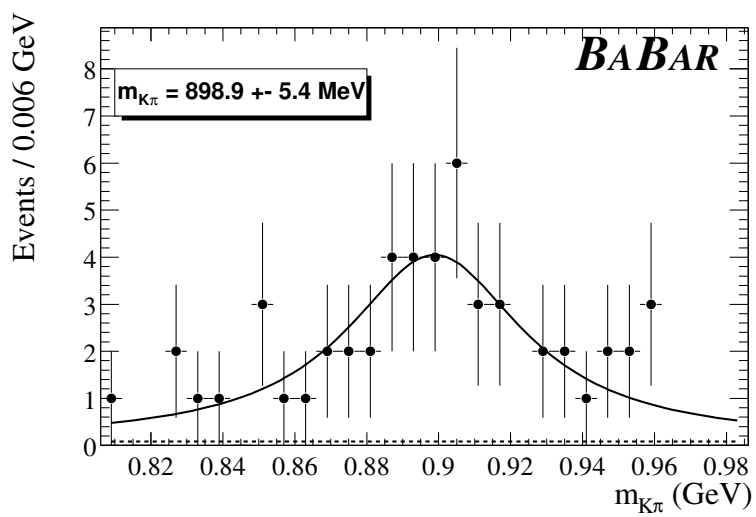

Figure 6: The $M_{K^+\pi^-}$ distribution for $B^0 \to K^{*0}\gamma$, $K^{*0} \to K^+\pi^-$ candidates from $(8.6 \pm 0.3) \times 10^6$ $B\overline{B}$ decays. The fit is to a Breit-Wigner shape

the statistical uncertainty in the yield. The second error is the systematic uncertainty.

The total systematic error of 8.6% is a quadratic sum of several uncorrelated components tabulated in Table 1. The systematic uncertainty in the background shape is obtained from varying the parameter ζ within the allowed range from the off-resonance data.

The primary check on track efficiency is obtained by studying the probability for observing drift chamber versus silicon detector-only tracks in inclusive $D^0 \to K^-\pi^+\pi^+\pi^-$. This is compared with the rate for finding the third track in one-versus-three topology tau-pair decays. A final check is

the observed multiplicity distribution in $\Upsilon(4S)$ events. A systematic error of 2.5% per track with $p_T > 1\,\mathrm{GeV}/c$ on the overall efficiency scale is determined by comparing the three methods. In addition we measure the tracking resolution with $e^+e^- \to \mu^+\mu^-$ events and compare to Monte Carlo expectations. We find a difference in the tail of this distribution which leads to a systematic uncertainty in the K^{*0} selection efficiency.

The kaon identification efficiency in the DIRC is derived from a sample of $D^{*+} \to D^0\pi^+$ in which the charge of the associated slow pion tags the flavor of the D meson and hence the charge of the kaon in the subsequent $D^0 \to K^-\pi^+$. The errors on this measured value are taken as a systematic uncertainty in the efficiency for kaon identification.

The calorimeter energy resolution is measured in data using π^0 and η meson decays, and $e^+e^- \to e^+e^-\gamma$ events. These are compared to Monte Carlo simulated events of the same processes. The differences result in a systematic uncertainty in the energy resolution which can broaden the ΔE^* distribution causing an uncertainty in the efficiency of the ΔE^* requirement. An overall energy scale uncertainty is estimated by using a data sample of η meson decays with symmetric energy photons. The deviation in the reconstructed η mass from the nominal η mass estimates the uncertainty in the measured single photon energy. This resultant deviation in the central value of the ΔE^* distribution causes a systematic uncertainty in the efficiency of the ΔE^* requirement. The photon efficiency uncertainty is estimated using a sample of $e^+e^- \to e^+e^-\gamma$ events compared to Monte Carlo simulated $e^+e^- \to e^+e^-\gamma$ events. The expected energy and position of the photon can be derived from a fit to the beam energy and the measured track momenta for the e^+e^-. We apply the photon selection cuts and compare the efficiency in the data and the Monte Carlo sample to derive the systematic uncertainty. The π^0/η veto efficiency is tested by "embedding" a Monte Carlo generated photon into both off-resonance data and off-resonance Monte Carlo events. The difference in the measured efficiency is used as the systematic uncertainty. The merged π^0 modeling is tested by comparing a sample of merged π^0 in $\tau^- \to \rho^-\nu, \rho^- \to \pi^-\pi^0$ data and Monte Carlo. We assign a systematic in the photon selection efficiency by comparing the fraction of merged π^0 removed in the two samples.

Table 1: The fractional systematic uncertainties in the measurement of $\mathcal{B}(B^0 \to K^{*0}\gamma)$.

Uncertainty	% of $\mathcal{B}(B^0 \to K^{*0}\gamma)$
Tracking efficiency	5.0
B counting	3.6
Kaon identification efficiency	3.0
Track resolution	3.0
Calorimeter energy resolution	2.5
Background shape	2.3
Monte Carlo Statistics	1.9
Calorimeter energy scale	1.0
Calorimeter efficiency	1.0
π^0/η veto	1.0
Merged π^0 modeling	1.0
Total	8.6

In conclusion, we report a preliminary measurement of the branching fraction of the rare decay

$\mathcal{B}(B^0 \to K^{*0}\gamma) = (5.4 \pm 0.8 \pm 0.5) \times 10^{-5}$ with a precision comparable to previous experiments and consistent with Standard Model expectations.

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