Measurement of the $B \to X_s \ell^+ \ell^-$ Branching Fraction
with a Sum over Exclusive Modes

B. Aubert,1 R. Barate,1 D. Boutigny,1 F. Couderc,1 J.-M. Gaillard,1 A. Hickeur,1 Y. Karyotakis,1 J. P. Lees,1 V. Tisserand,1 A. Zghiche,1 A. Palano,2 A. Pompili,2 J. C. Chen,3 N. D. Qi,3 G. Rong,3 P. Wang,3 Y. S. Zhu,3 G. Eigen,4 I. Ofte,4 B. Stigli,4 G. S. Abrams,5 A. W. Borgland,5 A. B. Brevan,5 D. N. Brown,5 J. Button-Shaffer,5 R. N. Cahn,5 E. Charles,5 C. T. Day,5 M. S. Gill,5 A. V. Gritsan,5 Y. Groysman,5 R. G. Jacobsen,5 R. W. Kadel,5 J. Kadyk,5 L. T. Kerth,5 Yu. G. Kolomensky,5 G. Kukartsev,5 C. Le Clerc,5 G. Lynch,5 A. M. Merchant,5 L. M. Mir,5 P. J. Oddone,5 T. J. Orihoto,5 M. Pripstein,5 N. A. Roe,5 M. T. Ronan,5 V. G. Sehik,5 W. A. Wenzel,5 K. Ford,6 T. J. Harrison,6 C. M. Hawkes,6 S. E. Morgan,6 A. T. Watson,6 M. Fritsch,7 K. Goetz,7 T. Held,7 H. Koch,7 B. Lewandowski,7 M. Pelizaeus,7 M. Steinke,7 J. T. Boyd,8 N. Chevalier,8 W. N. Cottingham,8 M. P. Kelly,8 T. E. Latham,8 F. F. Wilson,8 T. Cuhadar-Donszelman,9 C. Hearty,9 N. S. Knecht,9 T. S. Mattison,9 J. A. McKenna,9 D. Thiessen,9 A. Khan,10 P. Kyberd,10 L. Teodorescu,10 V. E. Blinov,11 A. D. Bukan,11 V. P. Druzhinin,11 V. B. Golubev,11 V. N. Ivanchenko,11 E. A. Kravchenko,11 A. P. Omuchin,11 S. I. Serdyukov,11 Yu. I. Skovpen,11 E. P. Solodov,11 A. N. Yushkov,11 D. Best,12 M. Bruinsma,12 M. Chao,12 I. Esrich,12 D. Kirkby,12 A. J. Lankford,13 M. Mandelkern,12 R. K. Monnmsen,12 W. Roethel,12 D. P. Stoker,12 C. Buchanan,13 B. L. Hartt13 J. W. Gary,14 B. C. Shen,14 K. Wang,14 D. del Re,15 H. K. Hadavand,15 E. J. Hill,15 D. B. MacFarlane,15 H. P. Paar,15 Sh. Rahatlou,15 V. Sharma,15 J. W. Berryhill,16 C. Campagnari,16 B. Dahmes,16 S. L. Levy,16 O. Long,16 A. Lu,16 M. A. Mazur,16 J. D. Richman,16 W. Verkerke,16 T. W. Beck,17 A. M. Eisner,17 C. A. Heusch,17 W. S. Lockman,17 T. Schalk,17 R. E. Schmitz,17 B. A. Schumm,17 A. Seiden,17 P. Spradlin,17 D. C. Williams,17 M. G. Wilson,17 J. Albert,18 E. Chen,18 G. P. Dubois-Felsmann,18 A. Dvoretski,18 D. G. Hitlin,18 I. Narsky,18 T. Piatenko,18 F. C. Porter,18 A. Ryd,18 A. Samuel,18 S. Yang,18 S. Jayatilleke,19 G. Mancinelli,19 B. T. Meadows,19 M. D. Sokoloff,19 T. Abe,20 F. Blanc,20 P. Bloom,20 S. Chen,20 W. T. Ford,20 U. Naunberg,20 A. Olivas,20 P. Rankin,20 J. G. Smith,20 J. Zhang,20 A. Chen,21 J. L. Harton,21 A. Soffer,21 W. H. Toki,21 R. J. Wilson,21 Q. L. Zeng,21 D. Altenburg,22 T. Brandt,22 J. Brose,22 T. Colberg,22 M. Dickopp,22 E. Feltresi,22 A. Hauke,22 H. M. Lackner,22 E. Maly,22 R. Müller-Pfefferkorn,22 R. Novogowski,22 S. Ott,22 A. Petzold,22 J. Schubert,22 K. R. Schubert,22 R. Schierz,22 B. Spaan,22 J. E. Sundermann,22 D. Bernard,23 G. R. Bonneau,23 F. Brochard,23 P. Grenier,23 S. Schrenk,23 Ch. Thiebaux,23 G. Vasileiadis,23 M. Verderi,23 D. J. Bard,24 P. J. Clark,24 D. Lavin,24 F. Muheim,24 S. Playfer,24 Y. Xie,25 M. Andreotti,25 V. Azzolini,25 D. Bettoni,25 C. Bozzi,25 R. Calabrese,25 G. Cibinetto,25 E. Luppi,25 M. Negrisi,25 L. Piemontese,25 A. Sarti,25 E. Treadwell,26 R. Baldini-Ferroli,27 A. Calcaterra,27 R. de Sangro,27 G. Finocchiaro,27 P. Pattier,27 M. Piccolo,27 A. Zallo,27 A. Bugno,28 R. Capra,28 R. Contri,28 G. Crosetti,28 M. Lo Vetere,28 M. Macri,28 R. Monge,28 S. Passaggio,28 C. Patrignani,28 E. Robutti,28 A. Santroni,28 S. Tosi,28 S. Bailey,29 G. Brandenburg,29 M. Morii,29 E. Won,29 R. S. Dubitzky,30 U. Langenegger,30 W. Bhimji,31 D. A. Bowerman,31 P. D. Dauncey,31 U. Egede,31 J. R. Gaillard,31 G. W. Morton,31 J. A. Nash,31 G. P. Taylor,31 G. J. Grenier,32 U. Mallick,32 J. Cochran,33 H. B. Crawley,33 J. Lamsa,33 W. T. Meyer,33 S. Prell,33 E. I. Rosenberg,33 J. Yi,33 M. Davier,34 G. Grosseidig,34 A. Höcker,34 S. Laplace,34 F. Le Diberder,34 V. Lepeltier,34 A. M. Lutz,34 T. C. Petersen,34 S. Placzek,34 M. H. Schune,34 L. Tantot,34 G. Wormser,34 C. H. Cheng,35 D. J. Lange,35 M. C. Simani,35 D. M. Wright,35 A. J. Bevan,36 J. P. Coleman,36 J. R. Fry,36 E. Gabathuler,36 R. Gamet,36 R. J. Parry,36 D. J. Payne,37 R. J. Sloane,36 C. Touramanis,36 J. J. Back,37 C. M. Cormack,38 P. F. Harrison,37 M. B. Mohanty,37 C. L. Brown,38 G. Cowan,38 R. L. Flack,38 H. U. Flecher,38 M. G. Green,38 C. E. Marker,38 T. R. McMahon,38 S. Ricciardi,38 F. Salvatore,38 G. Vaitasas,38 M. A. Winter,38 D. Brown,39 C. L. Davis,39 J. Allison,40 N. R. Barlow,40 R. J. Barlow,40 P. A. Hart,40 M. Hodgkinson,40 G. D. Lafferty,40 A. J. Lyon,40 J. C. Williams,40 A. Farbin,41 W. D. Hulsbergen,41 A. Jawahery,41 D. Kovalskyi,41 C. K. Lee,41 V. Lillard,41 D. A. Roberts,41 G. Blaylock,42 C. Dallapiccola,42 K. T. Flood,42 S. S. Hertzbach,42 R. Kofler,42 V. B. Koptchev,42 T. B. Moore,42 S. Saremli,42 H. Staengle,42 S. Willoq,42 R. Cowan,43 G. Sciolla,43 F. Taylor,43 R. K. Yamamoto,43 D. J. J. Mangeol,44
16 University of California at Santa Barbara, Santa Barbara, CA 93106, USA
17 University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, CA 95064, USA
18 California Institute of Technology, Pasadena, CA 91125, USA
19 University of Cincinnati, Cincinnati, OH 45221, USA
20 University of Colorado, Boulder, CO 80309, USA
21 Colorado State University, Fort Collins, CO 80523, USA
22 Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
23 Ecole Polytechnique, LLR, F-91128 Palaiseau, France
24 University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
25 Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
26 Florida A&M University, Tallahassee, FL 32307, USA
27 Laboratori Nazionali di Frascati dell’INFN, I-00044 Frascati, Italy
28 Università di Genova, Dipartimento di Fisica e INFN, I-16146 Genova, Italy
29 Harvard University, Cambridge, MA 02138, USA
30 Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
31 Imperial College London, London, SW7 2AZ, United Kingdom
32 University of Iowa, Iowa City, IA 52242, USA
33 Iowa State University, Ames, IA 50011-3160, USA
34 Laboratoire de l’Accélérateur Linéaire, F-91898 Orsay, France
35 Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
36 University of Liverpool, Liverpool L69 72E, United Kingdom
37 Queen Mary, University of London, E1 4NS, United Kingdom
38 University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
39 University of Louisville, Louisville, KY 40292, USA
40 University of Manchester, Manchester M13 9PL, United Kingdom
41 University of Maryland, College Park, MD 20742, USA
42 University of Massachusetts, Amherst, MA 01003, USA
43 Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, MA 02139, USA
44 McGill University, Montréal, QC, Canada H3A 2T8
45 Università di Milano, Dipartimento di Fisica e INFN, I-20133 Milano, Italy
46 University of Mississippi, University, MS 38677, USA
47 Université de Montréal, Laboratoire René J. A. Lévesque, Montréal, QC, Canada H3C 3J7
48 Mount Holyoke College, South Hadley, MA 01075, USA
49 Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
50 NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
51 University of Notre Dame, Notre Dame, IN 46556, USA
52 Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
53 Ohio State University, Columbus, OH 43210, USA
54 University of Oregon, Eugene, OR 97403, USA
55 Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
56 Universités Paris VI et VII, Lab de Physique Nucléaire H. E., F-75252 Paris, France
57 Università di Pavia, Dipartimento di Fisica and INFN, I-27100 Pavia, Italy
58 University of Pennsylvania, Philadelphia, PA 19104, USA
59 Università di Perugia, Dipartimento di Fisica and INFN, I-06100 Perugia, Italy
60 Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
61 Prairie View A&M University, Prairie View, TX 77446, USA
62 Princeton University, Princeton, NJ 08544, USA
63 Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
64 Universität Rostock, D-18051 Rostock, Germany
65 Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
66 DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
67 University of South Carolina, Columbia, SC 29208, USA
68 Stanford Linear Accelerator Center, Stanford, CA 94309, USA
69 Stanford University, Stanford, CA 94305-4060, USA
70 State Univ. of New York, Albany, NY 12222, USA
71 University of Tennessee, Knoxville, TN 37996, USA
72 University of Texas at Austin, Austin, TX 78712, USA
73 University of Texas at Dallas, Richardson, TX 75083, USA
74 Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
75 Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
76 Vanderbilt University, Nashville, TN 37235, USA
77 University of Victoria, Victoria, BC, Canada V8W 3P6
78 University of Wisconsin, Madison, WI 53706, USA
79 Yale University, New Haven, CT 06511, USA
We measure the branching fraction for the flavor-changing neutral-current process $B \rightarrow X_s \ell^+ \ell^-$ with a sample of $89 \times 10^6 \ T(4S) \rightarrow B \bar{B}$ events recorded with the BABAR detector at the PEP-II $e^+e^-$ storage ring. The final state is reconstructed from $\ell^+\ell^-$ or $\mu^+\mu^-$ pairs and a hadronic system $X_s$ consisting of one $K^\pm$ or $K_s^0$ and up to two pions, with at most one $\pi^0$. We observe a signal of $40 \pm 10 \text{(stat)} \pm 2 \text{(syst)}$ events and extract the inclusive branching fraction $B(B \rightarrow X_s \ell^+ \ell^-) = (5.6 \pm 1.5 \text{(stat)} \pm 0.6 \text{(exp syst)} \pm 1.1 \text{(model syst)}) \times 10^{-6}$ for $m_{\ell^+\ell^-} > 0.2 \text{ GeV}/c^2$.

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The rare decay $B \rightarrow X_s \ell^+ \ell^-$, which proceeds through the $b \rightarrow s\ell^+\ell^-$ transition, is interesting because the study of its rate and charge asymmetry could lead to indirect observation of physics beyond the Standard Model (SM). This transition is forbidden at lowest order in the SM but is allowed at higher order via electroweak penguin and $W$-box diagrams. This implies that non-SM physics in these loops would contribute at the same order as the SM $\text{I} \text{I} \text{I}$. Recent SM calculations of the inclusive branching fractions predict $B(B \rightarrow X_s \ell^+ \ell^-) = (6.9 \pm 1.0) \times 10^{-6}$ [$4.2 \pm 0.7) \times 10^{-6}$ for $m_{\ell^+\ell^-} < 0.2 \gev/c^2$] and $B(B \rightarrow X_s \mu^+ \mu^-) = (4.2 \pm 0.7) \times 10^{-6}$ $\text{I} \text{I} \text{I}$. Although the branching fraction measurement for inclusive decays is more challenging than for exclusive decays, it is motivated by smaller theoretical uncertainties. Exclusive $B \rightarrow K^{(*)}\ell^+ \ell^- (\ell = e, \mu)$ decays have been observed by Belle and BABAR $\text{I} \text{I} \text{I}$. Belle has also reported a measurement of the inclusive $B \rightarrow X_s \ell^+ \ell^-$ branching fraction $\text{I} \text{I} \text{I}$.

The data sample used in this analysis was collected with the BABAR detector $\text{I}$ at the PEP-II asymmetric-energy $e^+e^-$ storage ring at the Stanford Linear Accelerator Center. The sample consists of $89 \times 10^6 \ B \bar{B}$ events recorded at the $T(4S)$, corresponding to an integrated luminosity of $81.9 \ \text{fb}^{-1}$.

We study the $B \rightarrow X_s \ell^+ \ell^-$ process by fully reconstructing a subset of all possible final states. The reconstructed hadronic systems $X_s$ consist of one $K^\pm$ or $K_s^0$ and up to two pions, with at most one $\pi^0$. This approach allows approximately half of the total inclusive rate to be reconstructed. If the fraction of modes containing a $K_s^0$ is assumed equal to that containing a $K^0$, the missing states represent $\sim 30\%$ of the total rate. To compute the inclusive branching fraction, we account for missing modes and selection efficiencies using a $B \rightarrow X_s \ell^+ \ell^-$ decay model constructed as follows. For $m_{X_s} < 1.1 \ \text{GeV}/c^2$, exclusive $B \rightarrow K^{(*)}\ell^+ \ell^-$ decays are generated with a $b \rightarrow s\ell^+\ell^-$ decay model according to $\text{I} \text{I} \text{I} \text{I}$. The remaining decays, for $m_{X_s} > 1.1 \ \text{GeV}/c^2$, are generated according to a quark-level calculation $\text{I} \text{I} \text{I} \text{I}$ and the $b$-quark Fermi motion model of $\text{I} \text{I} \text{I}$.

JETSET $\text{I} \text{I} \text{I}$ is then used to hadronize the system consisting of a strange quark and a spectator quark.

The full reconstruction method exploits the strong kinematic discrimination provided by $m_{ES} = \sqrt{E_{\text{beam}}^2 - p_B^2}$ and $\Delta E = E_B - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy and $E_B (p_B)$ is the reconstructed $B$-meson energy (three-momentum). These quantities are evaluated in the $e^+e^-$ center-of-mass (CM) frame.

Clean identification of the $B$ decay products is important for minimizing the backgrounds. Electron candidates are required to have a laboratory-frame momentum $p_\ell > 0.5 \ \text{GeV}/c$ and are identified with measurements from the tracking systems and the electromagnetic calorimeter. Bremsstrahlung photons are recovered by combining an electron with up to three photons within a small angular region around the electron direction $\text{I} \text{I} \text{I} \text{I}$. Muon candidates are required to have $p_\mu > 1.0 \ \text{GeV}/c$ and are identified as penetrating charged particles in the instrumented flux return. Charged kaon identification relies on measurements performed with the Cherenkov ring-imaging detector and the tracking systems. The $K_0^0$ candidates are required to have $|m_{\pi^+\pi^-} - m_{K_0^0}| < 11.2 \ \text{MeV}/c^2$, a decay length greater than 2 mm, and $\cos \delta > 0.99$, where $\delta$ is the angle between the $K_0^0$ momentum vector and a line that connects the primary vertex with the $K_0^0$ vertex. Charged tracks that do not satisfy tight $e^\pm$ or $K^\pm$ identification are considered to be pions. Neutral pions are required to have a laboratory-frame energy greater than 400 MeV, a photon daughter energy greater than 50 MeV, and $|m_{\pi^\pm} - m_{\pi^0}| < 0.1 \ \text{MeV}/c^2$.

The candidates are reconstructed by first selecting the $e^+e^- \mu^+\mu^-$ or $e^+e^- \pi^+\pi^-$ pair with the largest value of $|p_{\ell^+}| + |p_{\ell^-}|$. Then, $B \rightarrow X_s \ell^+ \ell^-$ candidates are formed by adding any of the following hadronic topologies: $K^+$, $K^+\pi^0$, $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+$, $K_0^0$, $K_0^0\pi^0$, $K_0^0\pi^+$, $K_0^0\pi^-\pi^+$, and $K_0^0\pi^-\pi^-$. (We name one member of a pair of charge-conjugate states to refer to both, unless we specify otherwise.) A limit is imposed on the number of pions because the expected signal-to-background ratio drops significantly with increasing multiplicity.

With loose selection criteria, the average number of $B$ candidates per event is five in the signal simulation. A likelihood function for the signal is constructed based on the simulated distributions of $\Delta E$, $\log(P_{\text{Bjettz}})$, and $\cos \theta_B$, where $P_{\text{Bjettz}}$ is the fit probability for the $B$ vertex constructed from charged daughter particles and $\theta_B$ is the angle between $\vec{p}_B$ and the $e^-$ beam axis. We select the candidate with the largest signal likelihood before further cuts are applied. This approach entails a loss of 8% in signal efficiency but reduces the overall background.
Combinatorial backgrounds from nonsignal $B\bar{B}$ and continuum $e^+e^- \rightarrow q\bar{q}$ (with $q = u,d,s,c$) events are reduced by requiring $m_{X_c} < 1.8$ GeV/$c^2$, $5.20 < m_{ES} < 5.29$ GeV/$c^2$, and $-0.2 < \Delta E < 0.1$ GeV. We impose a limit on $m_{X_c}$ because the signal-to-background ratio drops as $m_{X_c}$ increases.

The dominant background producing a peak in $m_{ES}$ at the $B$ mass originates from $B \rightarrow J/\psi X, \psi(2S)X$ decays with $J/\psi \rightarrow \ell^+\ell^-$ and $\psi(2S) \rightarrow \ell^+\ell^-$. This charm- 
numion background is suppressed by vetoing $B$ candidates with dilepton mass in the ranges $2.70 < m_{e^+e^-} < 3.25$, $2.80 < m_{\mu^+\mu^-} < 3.20$, $2.61 < m_{e^+e^-} < 3.80$, and $3.55 < m_{\mu^+\mu^-} < 3.80$ GeV/$c^2$. In the electron channel, the veto is applied before and after bremsstrahlung recovery to allow for imperfect recovery. The potential peaking background from $B \rightarrow X_s\gamma$ decays with conversion of the photon into an $e^+e^-$ pair in the detector material is removed by requiring $m_{e^+e^-} > 0.2$ GeV/$c^2$. This cut also serves to reduce contributions from $b \rightarrow s e^+e^-$ transitions in which the $e^+e^-$ pair originates from a photon.

The final suppression of the combinatorial background is achieved with a likelihood based on nine variables: (i) $\Delta E$, (ii) $\Delta E_{ROE}$, (iii) $m_{ES}^{ROE}$, where $ROE$ refers to the rest of the event (all charged tracks and photon candidates not included in the $B$ candidate), (iv) the separation $\Delta z$ between the two leptons along the beam direction measured at their closest approach to the beam axis, (v) $\log_2(P_{B\text{vtx}})$, (vi) $\cos\theta_{\text{miss}}$, where $\theta_{\text{miss}}$ is the angle between the missing momentum vector for the whole event and the $z$ axis in the CM frame, (vii) $\cos\theta_B$, (viii) $|\cos\theta_T|$, where $\theta_T$ is the angle between the thrust axes of the $B$ candidate and the ROE in the CM frame, and (ix) the ratio $R_2$ of the second and zeroth-order Fox-Wolfram moments [13]. The variables $\Delta E$, $\Delta E_{ROE}$, and $m_{ES}^{ROE}$ are most effective at rejecting $B\bar{B}$ background, especially for events with two semi-leptonic decays that have large missing energy. The event-shape variables $|\cos\theta_T|$ and $R_2$ are most effective at suppressing continuum events. A likelihood value is computed as the product of nine independent probability density functions (PDF) for the signal, $B\bar{B}$, and continuum background components. Using simulated $B \rightarrow X_s\ell^+\ell^-$ decays, we choose cuts on the ratio $L_R = L_{\text{signal}}/(L_{\text{signal}} + L_{B\bar{B}} + L_{\text{cont}})$ to maximize the statistical significance of the signal. This optimization is performed separately for electron and muon channels in the regions $m_{X_c} < 0.6$, $0.6 < m_{X_c} < 1.1$, and $1.1 < m_{X_c} < 1.8$ GeV/$c^2$, and results in progressively harder $L_R$ cuts for increasing $m_{X_c}$.

After applying all selection criteria, we obtain a sample of 349 (222) events in the electron (muon) channel. According to the simulation, the remaining background consists mostly of $B\bar{B}$ events.

We perform an extended unbinned maximum-likelihood fit to the $m_{ES}$ distribution to extract the signal yield $N_{\text{sig}}$ as well as the combinatorial background shape and yield. The likelihood function consists of four components: signal, charm- 
numion background peaking, hadronic peaking background (see below), and combinatorial background.

The shapes of the signal and charm- 
numion peaking background are described by the same Gaussian PDF, with a width of 2.80, 2.61, and 2.74 MeV/$c^2$ in the electron, muon, and electron+muon channels, respectively. The Gaussian mean and width are determined from signal-like $B \rightarrow J/\psi X, \psi(2S)X$ decay candidates satisfying all selection criteria but failing the charmonium veto (charmonium-veto sample). The charm- 
numion peaking background is estimated from the simulation to contribute $0.4\pm0.2 (1.4\pm0.5)$ events in the electron (muon) channel. The size and shape of the hadronic peaking background component arising from $B \rightarrow D^{(*)}\pi n (n > 0)$ decays with misidentification of two charged pions as leptons, are derived directly from data by performing the analysis without the lepton identification requirements.

Taking the $\pi \rightarrow \ell$ misidentification rates into account, we estimate the hadronic peaking background to be $<0.1$ and $2.4\pm0.8$ events in the electron and muon channels, respectively. The error on the misidentification rates derived from data control samples dominates the uncertainty. The PDF for the combinatorial background arising from continuum and $B\bar{B}$ events is an ARGUS function [14] with an endpoint equal to $E_{beam}$.

The fit results are presented in Fig. (a) and Table 1. The statistical significance is $S = \sqrt{2 \ln(L_{\text{max}}/L_{0\text{max}})}$, where $L_{\text{max}}$ is the maximum likelihood for the fit and $L_{0\text{max}}$ is that for a fit with signal yield fixed to zero. The $B \rightarrow X_s\ell^+\ell^-$ signal yield is obtained from a fit to the combined electron and muon data. Figure (b) shows the $m_{ES}$ distribution of $B \rightarrow X_s\ell^+\ell^-$ muon candidates selected using the nominal criteria but requiring leptons of different flavor. An ARGUS function fits this distribution well, consistent with that sample being pure combinatorial background.
TABLE I: Signal yield, significance, efficiency, and branching fraction in the electron and muon channels, as well as for the electron+muon average (first, second, and third rows, respectively). For the signal yield, the first error is statistical and the second error is systematic. For the signal efficiency, the first error corresponds to the experimental systematic uncertainty arising from detector modeling, hadronization, and Monte Carlo statistics, whereas the second error corresponds to the uncertainties in the signal model. For the branching fraction, the errors correspond to statistical, experimental systematic, and signal model systematic uncertainties.

| $N_{\text{sig}}$ | $S$ | $\epsilon$ (%) | $B$ ($10^{-6}$) |
|------------------|-----|----------------|---------------|
| 29.2 ± 8.5 ± 1.3 | 4.0 | 2.74 ± 0.27 ± 0.49 | 6.0 ± 1.7 ± 0.7 ± 1.1 |
| 11.2 ± 6.2 ± 0.9 | 2.0 | 1.26 ± 0.12 ± 0.25 | 5.0 ± 2.8 ± 0.6 ± 1.0 |
| 40.1 ± 10.4 ± 1.7 | 4.3 | 2.00 ± 0.19 ± 0.37 | 5.6 ± 1.5 ± 0.6 ± 1.1 |

The branching fraction is $B = N_{\text{sig}} / (2N_{b\overline{b}}\epsilon)$, where $N_{b\overline{b}} = (88.9 ± 1.0) \times 10^6$ is the number of $B\overline{B}$ pairs and $\epsilon$ is the signal efficiency. The yield $N_{\text{sig}}$ includes a contribution from events containing a true $B \rightarrow X_s\ell^+\ell^-$ decay but having a selected $B$ candidate with incomplete or wrong decay products (cross-feed events). We estimate the cross-feed contribution to the signal yield to be $1.5 ± 1.5 (0.6 ± 0.6)$ events in the electron (muon) channel by including in the fit a component whose shape and normalization are taken from simulation. The corresponding uncertainties are estimated with an ensemble of simulated data-sized experiments. The signal efficiency is adjusted to reflect this contribution. Figure 2 shows the $B \rightarrow X_s\ell^+\ell^-$ differential branching fraction as a function of $m_{X_s}$ and $m_{\ell^+\ell^-}$, obtained by applying the nominal likelihood fit procedure to the data in bins of $m_{X_s}$ and $m_{\ell^+\ell^-}$. We use the nominal Gaussian shape for all bins, as we found no significant shape dependence on $m_{X_s}$ or $m_{\ell^+\ell^-}$.

We evaluate the systematic uncertainties in the signal yield by varying the signal Gaussian parameters (mean and width) and the signal shape (using asymmetric signal shapes) within the constraints allowed by the charmonium-veto sample. The amount of charmonium and hadronic peaking background is varied, as well as the shape of the latter.

Uncertainties in the signal efficiency originate from the detector modeling and from the simulation of signal decays. From control data samples we find uncertainties of 1.3% per track (0.8% per $\pi^+$) in the tracking efficiency; 0.85% per electron, 1.55% per muon, 1.0% per $K^+$, and 1.4% per $\pi^+$ in the charged-particle identification efficiency; 1.5% per $K_0^0$ and 5.6% per $\pi^0$ in the reconstruction efficiency. We check the efficiency of the cut in $L_R$ with the charmonium-veto sample and take the discrepancy with the simulation (3.7%) as the uncertainty. The fraction of signal cross feed included in the signal Gaussian is varied by $±100\%$. Altogether, the uncertainty from detector modeling is 8.3%.

The dominant source of uncertainty (18%) arises from the decay model. The fractions of $B \rightarrow K\ell^+\ell^-$ and $B \rightarrow K^*\ell^+\ell^-$ decays are both increased (or decreased) together by the theoretical uncertainties [1], resulting in the largest contribution (16%). Parameters of the Fermi motion model are varied within limits allowed by measurements of hadronic moments in semileptonic $B$ decays [12] and the photon spectrum in inclusive $B \rightarrow X_s\gamma$ decays [10]. The transition point (in $m_{X_s}$) between the $B \rightarrow K^*\ell^+\ell^-$ and $b \rightarrow s\ell^+\ell^-$ decay modes is varied by $±0.1$ GeV/$c^2$.

Hadronization uncertainties affecting the region $m_{X_s} > 1.1$ GeV/$c^2$ total 4.9% and are evaluated as follows. The ratio between the generator yield for decay modes containing a $K_0^0$ and that for modes containing a charged kaon is varied within the range $0.50 ± 0.05$, to allow for isospin violation. Similarly, the ratio between modes with one and no $\pi^0$ is varied within the range $1.0 ± 0.5$, and the ratio between two-body and three-body hadronic systems is varied within the range $0.5 ± 0.3$. Uncertainties in the last two ratios are set by the level of discrepancy between data and simulation as measured in [17]. The uncertainty in the fraction of modes with pion or kaon multiplicities different from those used in this analysis, or with photons that do not originate from $\pi^0$ decays but rather from $\eta$, $\eta'$, $\omega$, etc, is estimated by varying these different fractions by $±50\%$.

Table II summarizes the results of the analysis. For the combined $B \rightarrow X_s\ell^+\ell^-$ branching fraction we assume equal branching fractions in the electron and muon channels, and average over both channels. Table III shows the partial branching fractions in several dilepton and hadronic mass ranges.

We search for $CP$ violation in the $B \rightarrow X_s\ell^+\ell^-$ decay by performing separate fits to $B$ and $\overline{B}$ final states, where the final state flavor is determined by the kaon and pion charges (modes with $X_s = K_0^0$, $K_0^{*0}$, or $K_0^{*+}\pi^0\pi^-$ are not...
used). We find $N_{sig}^B = 14.7 \pm 6.5$(stat) and $N_{sig}^{\bar{B}} = 22.9 \pm 7.4$(stat), corresponding to an asymmetry $A_{CP} = (N_{sig}^B - N_{sig}^{\bar{B}})/(N_{sig}^B + N_{sig}^{\bar{B}}) = -0.22 \pm 0.26$(stat). The systematic uncertainty is taken to be the statistical uncertainty in the asymmetry measured in the charmonium-veto sample $A_{CP}^{sig} = -0.005 \pm 0.016$(stat).

In summary, we observe a signal of $40 \pm 10$(stat) $\pm 2$(syst) $B \rightarrow X_s \ell^+ \ell^-$ events with a statistical significance of $4.3 \sigma$. The corresponding branching fraction $B(B \rightarrow X_s \ell^+ \ell^-) = (5.6 \pm 1.5$(stat) $\pm 0.6$(exp syst) $\pm 1.1$(model syst)) $\times 10^{-6}$ for $m_{\ell^+\ell^-} > 0.2$ GeV/$c^2$ agrees well with predictions \cite{1} and a previous measurement \cite{2}. In restricted dilepton mass ranges below and above the charmonium region (see bottom of Table \ref{tab1}), the partial branching fractions also agree with predictions \cite{3,4,5,6,7,8,9}. At low hadronic mass, the partial branching fractions are consistent with existing $B \rightarrow K^{(*)}\ell^+\ell^-$ measurements \cite{10,11,12,13,14,15}. We determine the direct $CP$ asymmetry to be $A_{CP} = -0.22 \pm 0.26$(stat) $\pm 0.02$(syst), in agreement with a predicted asymmetry of $(0.19^{+0.17}_{-0.15}) \times 10^{-2}$ in the SM \cite{10}. Overall, we find no evidence for contributions from physics beyond the SM.

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* Now at Department of Physics, University of Warwick, Coventry, United Kingdom
† Also with Università della Basilicata, Potenza, Italy
‡ Also with IFIC, Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Valencia, Spain.
§ Deceased.