## Measurement of $\left|V_{c b}\right|$ and the Form-Factor Slope in $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ Decays in Events Tagged by a Fully Reconstructed $B$ Meson

B. Aubert, ${ }^{1}$ Y. Karyotakis, ${ }^{1}$ J. P. Lees, ${ }^{1}$ V. Poireau, ${ }^{1}$ E. Prencipe, ${ }^{1}$ X. Prudent, ${ }^{1}$ V. Tisserand, ${ }^{1}$ J. Garra Tico, ${ }^{2}$ E. Grauges, ${ }^{2}$ M. Martinelli ${ }^{a b},{ }^{3}$ A. Palano ${ }^{a b},{ }^{3}$ M. Pappagallo ${ }^{a b},{ }^{3}$ G. Eigen, ${ }^{4}$ B. Stugu, ${ }^{4}$ L. Sun, ${ }^{4}$ M. Battaglia, ${ }^{5}$ D. N. Brown, ${ }^{5}$ L. T. Kerth,,${ }^{5}$ Yu. G. Kolomensky, ${ }^{5}$ G. Lynch,,${ }^{5}$ I. L. Osipenkov, ${ }^{5}$ K. Tackmann, ${ }^{5}$ T. Tanabe, ${ }^{5}$ C. M. Hawkes, ${ }^{6}$ N. Soni, ${ }^{6}$ A. T. Watson, ${ }^{6}$ H. Koch, ${ }^{7}$ T. Schroeder, ${ }^{7}$ D. J. Asgeirsson, ${ }^{8}$ B. G. Fulsom, ${ }^{8}$ C. Hearty, ${ }^{8}$ T. S. Mattison, ${ }^{8}$ J. A. McKenna, ${ }^{8}$ M. Barrett, ${ }^{9}$ A. Khan, ${ }^{9}$ A. Randle-Conde, ${ }^{9}$ V. E. Blinov, ${ }^{10}$ A. D. Bukin, ${ }^{10,{ }^{*}}$ A. R. Buzykaev, ${ }^{10}$ V. P. Druzhinin, ${ }^{10}$ V. B. Golubev, ${ }^{10}$ A. P. Onuchin, ${ }^{10}$ S. I. Serednyakov, ${ }^{10}$ Yu. I. Skovpen, ${ }^{10}$ E. P. Solodov, ${ }^{10}$ K. Yu. Todyshev, ${ }^{10}$ M. Bondioli, ${ }^{11}$ S. Curry, ${ }^{11}$ I. Eschrich, ${ }^{11}$ D. Kirkby, ${ }^{11}$ A. J. Lankford, ${ }^{11}$ P. Lund, ${ }^{11}$ M. Mandelkern, ${ }^{11}$ E. C. Martin, ${ }^{11}$ D. P. Stoker, ${ }^{11}$ H. Atmacan, ${ }^{12}$ J. W. Gary, ${ }^{12}$ F. Liu, ${ }^{12}$ O. Long, ${ }^{12}$ G. M. Vitug, ${ }^{12}$ Z. Yasin, ${ }^{12}$ L. Zhang, ${ }^{12}$ V. Sharma, ${ }^{13}$ C. Campagnari, ${ }^{14}$ T. M. Hong, ${ }^{14}$ D. Kovalskyi, ${ }^{14}$ M. A. Mazur, ${ }^{14}$ J. D. Richman, ${ }^{14}$ T. W. Beck, ${ }^{15}$ A. M. Eisner, ${ }^{15}$ C. A. Heusch,,${ }^{15}$ J. Kroseberg, ${ }^{15}$ W. S. Lockman, ${ }^{15}$ A. J. Martinez, ${ }^{15}$ T. Schalk, ${ }^{15}$ B. A. Schumm, ${ }^{15}$ A. Seiden,,$^{15}$ L. Wang, ${ }^{15}$ L. O. Winstrom, ${ }^{15}$ C. H. Cheng, ${ }^{16}$ D. A. Doll, ${ }^{16}$ B. Echenard, ${ }^{16}$ F. Fang, ${ }^{16}$ D. G. Hitlin, ${ }^{16}$ I. Narsky, ${ }^{16}$ T. Piatenko, ${ }^{16}$ F. C. Porter, ${ }^{16}$ R. Andreassen, ${ }^{17}$ G. Mancinelli, ${ }^{17}$ B. T. Meadows, ${ }^{17}$ K. Mishra, ${ }^{17}$ M. D. Sokoloff, ${ }^{17}$ P. C. Bloom, ${ }^{18}$ W. T. Ford, ${ }^{18}$ A. Gaz, ${ }^{18}$ J. F. Hirschauer, ${ }^{18}$ M. Nagel, ${ }^{18}$ U. Nauenberg, ${ }^{18}$ J. G. Smith, ${ }^{18}$ S. R. Wagner, ${ }^{18}$ R. Ayad, ${ }^{19, \dagger}$ W. H. Toki, ${ }^{19}$ R. J. Wilson, ${ }^{19}$ E. Feltresi, ${ }^{20}$ A. Hauke, ${ }^{20}$ H. Jasper, ${ }^{20}$ T. M. Karbach, ${ }^{20}$ J. Merkel, ${ }^{20}$ A. Petzold, ${ }^{20}$ B. Spaan,,$^{20}$ K. Wacker, ${ }^{20}$ M. J. Kobel, ${ }^{21}$ R. Nogowski, ${ }^{21}$ K. R. Schubert, ${ }^{21}$ R. Schwierz, ${ }^{21}$ A. Volk, ${ }^{21}$ D. Bernard, ${ }^{22}$ E. Latour, ${ }^{22}$ M. Verderi, ${ }^{22}$ P. J. Clark, ${ }^{23}$ S. Playfer, ${ }^{23}$ J. E. Watson, ${ }^{23}$ M. Andreotti ${ }^{a b},{ }^{24}$ D. Bettoni ${ }^{a},{ }^{24}$ C. Bozzi ${ }^{a},{ }^{24}$ R. Calabrese ${ }^{a b},{ }^{24}$ A. Cecchi ${ }^{a b},{ }^{24}$ G. Cibinetto ${ }^{a b},{ }^{24}$ E. Fioravanti ${ }^{a b},{ }^{24}$ P. Franchini ${ }^{a b},{ }^{24}$ E. Luppi ${ }^{a b},{ }^{24}$ M. Munerato ${ }^{a b},{ }^{24}$ M. Negrini ${ }^{a b},{ }^{24}$ A. Petrella ${ }^{a b},{ }^{24}$ L. Piemontese ${ }^{a},{ }^{24}$ V. Santoro ${ }^{a b},{ }^{24}$ R. Baldini-Ferroli, ${ }^{25}$ A. Calcaterra, ${ }^{25}$ R. de Sangro, ${ }^{25}$ G. Finocchiaro, ${ }^{25}$ S. Pacetti, ${ }^{25}$ P. Patteri, ${ }^{25}$ I. M. Peruzzi, ${ }^{25,},{ }^{\dagger}$ M. Piccolo, ${ }^{25}$ M. Rama, ${ }^{25}$ A. Zallo, ${ }^{25}$ R. Contri ${ }^{a b},{ }^{26}$ E. Guido, ${ }^{26}$ M. Lo Vetere ${ }^{a b},{ }^{26}$ M. R. Monge ${ }^{a b},{ }^{26}$ S. Passaggio ${ }^{a},{ }^{26}$ C. Patrignani ${ }^{a b},{ }^{26}$ E. Robutti ${ }^{a},{ }^{26}$ S. Tosi ${ }^{a b},{ }^{26}$ K. S. Chaisanguanthum, ${ }^{27}$ M. Morii, ${ }^{27}$ A. Adametz, ${ }^{28}$ J. Marks, ${ }^{28}$ S. Schenk, ${ }^{28}$ U. Uwer, ${ }^{28}$ F. U. Bernlochner, ${ }^{29}$ V. Klose, ${ }^{29}$ H. M. Lacker, ${ }^{29}$ D. J. Bard, ${ }^{30}$ P. D. Dauncey, ${ }^{30}$ M. Tibbetts, ${ }^{30}$ P. K. Behera, ${ }^{31}$ M. J. Charles, ${ }^{31}$ U. Mallik, ${ }^{31}$ J. Cochran, ${ }^{32}$ H. B. Crawley, ${ }^{32}$ L. Dong, ${ }^{32}$ V. Eyges, ${ }^{32}$ W. T. Meyer, ${ }^{32}$ S. Prell, ${ }^{32}$ E. I. Rosenberg, ${ }^{32}$ A. E. Rubin,,${ }^{32}$ Y. Y. Gao, ${ }^{33}$ A. V. Gritsan, ${ }^{33}$ Z. J. Guo, ${ }^{33}$ N. Arnaud, ${ }^{34}$ J. Béquilleux, ${ }^{34}$ A. D'Orazio, ${ }^{34}$ M. Davier, ${ }^{34}$ D. Derkach, ${ }^{34}$ J. Firmino da Costa, ${ }^{34}$ G. Grosdidier, ${ }^{34}$ F. Le Diberder, ${ }^{34}$ V. Lepeltier, ${ }^{34}$ A. M. Lutz, ${ }^{34}$ B. Malaescu, ${ }^{34}$ S. Pruvot, ${ }^{34}$ P. Roudeau, ${ }^{34}$ M. H. Schune, ${ }^{34}$ J. Serrano, ${ }^{34}$ V. Sordini, ${ }^{34,}$ A. Stocchi, ${ }^{34}$ G. Wormser, ${ }^{34}$ D. J. Lange, ${ }^{35}$ D. M. Wright, ${ }^{35}$ I. Bingham, ${ }^{36}$ J. P. Burke, ${ }^{36}$ C. A. Chavez, ${ }^{36}$ J. R. Fry, ${ }^{36}$ E. Gabathuler, ${ }^{36}$ R. Gamet, ${ }^{36}$ D. E. Hutchcroft, ${ }^{36}$ D. J. Payne, ${ }^{36}$ C. Touramanis, ${ }^{36}$ A. J. Bevan, ${ }^{37}$ C. K. Clarke, ${ }^{37}$ F. Di Lodovico, ${ }^{37}$ R. Sacco, ${ }^{37}$ M. Sigamani, ${ }^{37}$ G. Cowan, ${ }^{38}$ S. Paramesvaran, ${ }^{38}$ A. C. Wren, ${ }^{38}$ D. N. Brown, ${ }^{39}$ C. L. Davis, ${ }^{39}$ A. G. Denig, ${ }^{40}$ M. Fritsch, ${ }^{40}$ W. Gradl, ${ }^{40}$ A. Hafner, ${ }^{40}$ K. E. Alwyn, ${ }^{41}$ D. Bailey, ${ }^{41}$ R. J. Barlow, ${ }^{41}$ G. Jackson, ${ }^{41}$ G. D. Lafferty, ${ }^{41}$ T. J. West, ${ }^{41}$ J. I. Yi, ${ }^{41}$ J. Anderson, ${ }^{42}$ C. Chen, ${ }^{42}$ A. Jawahery, ${ }^{42}$ D. A. Roberts, ${ }^{42}$ G. Simi, ${ }^{42}$ J. M. Tuggle, ${ }^{42}$ C. Dallapiccola, ${ }^{43}$ E. Salvati, ${ }^{43}$ S. Saremi, ${ }^{43}$ R. Cowan, ${ }^{44}$ D. Dujmic, ${ }^{44}$ P. H. Fisher, ${ }^{44}$ S. W. Henderson, ${ }^{44}$ G. Sciolla, ${ }^{44}$ M. Spitznagel, ${ }^{44}$ R. K. Yamamoto, ${ }^{44}$ M. Zhao, ${ }^{44}$ P. M. Patel,,${ }^{45}$ S. H. Robertson, ${ }^{45}$ M. Schram, ${ }^{45}$ A. Lazzaro ${ }^{a b},{ }^{46}$ V. Lombardo ${ }^{a},{ }^{46}$ F. Palombo ${ }^{a b},{ }^{46}$ S. Stracka ${ }^{a b},{ }^{46}$ J. M. Bauer, ${ }^{47}$ L. Cremaldi, ${ }^{47}$ R. Godang, ${ }^{47, ~(q)}$ R. Kroeger, ${ }^{47}$ P. Sonnek, ${ }^{47}$ D. J. Summers, ${ }^{47}$ H. W. Zhao, ${ }^{47}$ M. Simard, ${ }^{48}$ P. Taras, ${ }^{48}$ H. Nicholson, ${ }^{49}$ G. De Nardo ${ }^{a b},{ }^{50}$ L. Lista ${ }^{a},{ }^{50}$ D. Monorchio ${ }^{a b},{ }^{50}$ G. Onorato ${ }^{a b},{ }^{50}$ C. Sciacca ${ }^{a b},{ }^{50}$ G. Raven, ${ }^{51}$ H. L. Snoek, ${ }^{51}$ C. P. Jessop, ${ }^{52}$ K. J. Knoepfel,,${ }^{52}$ J. M. LoSecco, ${ }^{52}$ W. F. Wang, ${ }^{52}$ L. A. Corwin, ${ }^{53}$ K. Honscheid, ${ }^{53}$ H. Kagan, ${ }^{53}$ R. Kass, ${ }^{53}$ J. P. Morris, ${ }^{53}$ A. M. Rahimi, ${ }^{53}$ J. J. Regensburger, ${ }^{53}$ S. J. Sekula, ${ }^{53}$ Q. K. Wong, ${ }^{53}$ N. L. Blount, ${ }^{54}$ J. Brau, ${ }^{54}$ R. Frey, ${ }^{54}$ O. Igonkina, ${ }^{54}$ J. A. Kolb, ${ }^{54}$ M. Lu, ${ }^{54}$ R. Rahmat, ${ }^{54}$ N. B. Sinev, ${ }^{54}$ D. Strom, ${ }^{54}$ J. Strube, ${ }^{54}$ E. Torrence, ${ }^{54}$ G. Castelli ${ }^{a b},{ }^{55}$ N. Gagliardi ${ }^{a b},{ }^{55}$ M. Margoni ${ }^{a b},{ }^{55}$ M. Morandin ${ }^{a},{ }^{55}$ M. Posocco ${ }^{a},{ }^{55}$ M. Rotondo ${ }^{a}$, ${ }^{55}$ F. Simonetto ${ }^{a b},{ }^{55}$ R. Stroili ${ }^{a b},{ }^{55}$ C. Voci ${ }^{a b},{ }^{55}$ P. del Amo Sanchez, ${ }^{56}$ E. Ben-Haim, ${ }^{56}$ G. R. Bonneaud, ${ }^{56}$ H. Briand, ${ }^{56}$ J. Chauveau, ${ }^{56}$ O. Hamon, ${ }^{56}$ Ph. Leruste, ${ }^{56}$ G. Marchiori, ${ }^{56}$ J. Ocariz, ${ }^{56}$ A. Perez, ${ }^{56}$ J. Prendki, ${ }^{56}$ S. Sitt, ${ }^{56}$ L. Gladney, ${ }^{57}$ M. Biasini ${ }^{a b},{ }^{58}$ E. Manoni ${ }^{a b},{ }^{58}$ C. Angelini ${ }^{a b}$, ${ }^{59}$ G. Batignani ${ }^{a b},{ }^{59}$
 A. Lusiani ${ }^{a c},{ }^{59}$ M. Morgantia ${ }^{a b},{ }^{59}$ N. Neri ${ }^{a b},{ }^{59}$ E. Paoloni ${ }^{a b},{ }^{59}$ G. Rizzo ${ }^{a b},{ }^{59}$ J. J. Walsh ${ }^{a}{ }^{59}$ D. Lopes Pegna, ${ }^{60}$ C. Lu, ${ }^{60}$ J. Olsen, ${ }^{60}$ A. J. S. Smith,${ }^{60}$ A. V. Telnov, ${ }^{60}$ F. Anulli ${ }^{a},{ }^{61}$ E. Baracchini ${ }^{a b},{ }^{61}$ G. Cavoto ${ }^{a},{ }^{61}$ R. Faccini ${ }^{a b},{ }^{61}$ F. Ferrarotto ${ }^{a},{ }^{61}$ F. Ferroni ${ }^{a b}{ }^{a 61}$ M. Gaspero ${ }^{a b},{ }^{61}$ P. D. Jackson ${ }^{a},{ }^{61}$ L. Li Gioi ${ }^{a},{ }^{61}$ M. A. Mazzoni ${ }^{a}$, ${ }^{61}$ S. Morganti ${ }^{a},{ }^{61}$ G. Piredda ${ }^{a},{ }^{61}$ F. Renga ${ }^{a b},{ }^{61}$ C. Voena ${ }^{a},{ }^{61}$ M. Ebert, ${ }^{62}$ T. Hartmann, ${ }^{62}$ H. Schröder, ${ }^{62}$ R. Waldi, ${ }^{62}$ T. Adye, ${ }^{63}$ B. Franek, ${ }^{63}$ E. O. Olaiya, ${ }^{63}$ F. F. Wilson, ${ }^{63}$ S. Emery, ${ }^{64}$ L. Esteve, ${ }^{64}$ G. Hamel de Monchenault, ${ }^{64}$ W. Kozanecki, ${ }^{64}$ G. Vasseur, ${ }^{64}$ Ch. Yèche, ${ }^{64}$ M. Zito,,${ }^{64}$ M. T. Allen, ${ }^{65}$ D. Aston,,${ }^{65}$ R. Bartoldus, ${ }^{65}$ J. F. Benitez, ${ }^{65}$ R. Cenci,,${ }^{65}$ J. P. Coleman, ${ }^{65}$ M. R. Convery, ${ }^{65}$ J. C. Dingfelder, ${ }^{65}$ J. Dorfan, ${ }^{65}$ G. P. Dubois-Felsmann, ${ }^{65}$ W. Dunwoodie, ${ }^{65}$ R. C. Field, ${ }^{65}$ M. Franco Sevilla, ${ }^{65}$ A. M. Gabareen, ${ }^{65}$ M. T. Graham,,${ }^{65}$ P. Grenier, ${ }^{65}$ C. Hast, ${ }^{65}$ W. R. Innes,,${ }^{65}$ J. Kaminski, ${ }^{65}$ M. H. Kelsey, ${ }^{65}$ H. Kim,,${ }^{65}$ P. Kim, ${ }^{65}$ M. L. Kocian,,${ }^{65}$ D. W. G. S. Leith,,${ }^{65}$ S. Li, ${ }^{65}$ B. Lindquist, ${ }^{65}$ S. Luitz, ${ }^{65}$ V. Luth,,${ }^{65}$ H. L. Lynch, ${ }^{65}$ D. B. MacFarlane, ${ }^{65}$ H. Marsiske, ${ }^{65}$ R. Messner, ${ }^{65, *}$ D. R. Muller, ${ }^{65}$ H. Neal,,${ }^{65}$ S. Nelson, ${ }^{65}$ C. P. O'Grady, ${ }^{65}$ I. Ofte,,${ }^{65}$ M. Perl, ${ }^{65}$ B. N. Ratcliff, ${ }^{65}$ A. Roodman, ${ }^{65}$ A. A. Salnikov,,${ }^{65}$ R. H. Schindler, ${ }^{65}$ J. Schwiening, ${ }^{65}$ A. Snyder, ${ }^{65}$ D. Su, ${ }^{65}$ M. K. Sullivan, ${ }^{65}$ K. Suzuki, ${ }^{65}$ S. K. Swain, ${ }^{65}$ J. M. Thompson,,${ }^{65}$ J. Va'vra, ${ }^{65}$ A. P. Wagner, ${ }^{65}$ M. Weaver, ${ }^{65}$ C. A. West, ${ }^{65}$ W. J. Wisniewski, ${ }^{65}$ M. Wittgen, ${ }^{65}$ D. H. Wright,,${ }^{65}$ H. W. Wulsin, ${ }^{65}$ A. K. Yarritu, ${ }^{65}$ C. C. Young, ${ }^{65}$ V. Ziegler, ${ }^{65}$ X. R. Chen, ${ }^{66}$ H. Liu, ${ }^{66}$ W. Park, ${ }^{66}$ M. V. Purohit, ${ }^{66}$ R. M. White, ${ }^{66}$ J. R. Wilson, ${ }^{66}$ P. R. Burchat, ${ }^{67}$ A. J. Edwards, ${ }^{67}$ T. S. Miyashita,,${ }^{67}$ S. Ahmed, ${ }^{68}$ M. S. Alam, ${ }^{68}$ J. A. Ernst, ${ }^{68}$ B. Pan, ${ }^{68}$ M. A. Saeed, ${ }^{68}$ S. B. Zain,,${ }^{68}$ A. Soffer, ${ }^{69}$ S. M. Spanier, ${ }^{70}$ B. J. Wogsland, ${ }^{70}$ R. Eckmann, ${ }^{71}$ J. L. Ritchie, ${ }^{71}$ A. M. Ruland, ${ }^{71}$ C. J. Schilling, ${ }^{71}$ R. F. Schwitters, ${ }^{71}$ B. C. Wray, ${ }^{71}$ B. W. Drummond, ${ }^{72}$ J. M. Izen,,$^{72}$ X. C. Lou, ${ }^{72}$ F. Bianchi ${ }^{a b},{ }^{73}$ D. Gamba ${ }^{a b},{ }^{\text {, }}$, M3 M. Pelliccioni ${ }^{a b}{ }^{a b}{ }^{73}$ M. Bomben ${ }^{a b},{ }^{74}$ L. Bosisio ${ }^{a b},{ }^{74}$ C. Cartaro ${ }^{a b},{ }^{74}$ G. Della Ricca ${ }^{a b},{ }^{74}$ L. Lanceri ${ }^{a b},{ }^{74}$ L. Vitale ${ }^{a b},{ }^{74}$ V. Azzolini, ${ }^{75}$ N. Lopez-March, ${ }^{75}$ F. Martinez-Vidal, ${ }^{75}$ D. A. Milanes, ${ }^{75}$ A. Oyanguren, ${ }^{75}$ J. Albert, ${ }^{76}$ Sw. Banerjee, ${ }^{76}$ B. Bhuyan, ${ }^{76}$ H. H. F. Choi, ${ }^{76}$ K. Hamano, ${ }^{76}$ G. J. King, ${ }^{76}$ R. Kowalewski, ${ }^{76}$ M. J. Lewczuk, ${ }^{76}$ I. M. Nugent, ${ }^{76}$ J. M. Roney, ${ }^{76}$ R. J. Sobie, ${ }^{76}$ T. J. Gershon, ${ }^{77}$ P. F. Harrison, ${ }^{77}$ J. Ilic, ${ }^{77}$ T. E. Latham, ${ }^{77}$ G. B. Mohanty, ${ }^{77}$ E. M. T. Puccio, ${ }^{77}$
H. R. Band, ${ }^{78}$ X. Chen, ${ }^{78}$ S. Dasu, ${ }^{78}$ K. T. Flood, ${ }^{78}$ Y. Pan, ${ }^{78}$ R. Prepost, ${ }^{78}$ C. O. Vuosalo, ${ }^{78}$ and S. L. Wu ${ }^{78}$ (The BaBar Collaboration)
${ }^{1}$ Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
${ }^{2}$ Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
${ }^{3}$ INFN Sezione di Bari ${ }^{a}$; Dipartimento di Fisica, Università di Bari ${ }^{\text {b }}$, I-70126 Bari, Italy
${ }^{4}$ University of Bergen, Institute of Physics, N-5007 Bergen, Norway
${ }^{5}$ Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
${ }^{6}$ University of Birmingham, Birmingham, B15 2TT, United Kingdom
${ }^{7}$ Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
${ }^{8}$ University of British Columbia, Vancouver, British Columbia, Canada V6T $1 Z 1$
${ }^{9}$ Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
${ }^{10}$ Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
${ }^{11}$ University of California at Irvine, Irvine, California 92697, USA
${ }^{12}$ University of California at Riverside, Riverside, California 92521, USA
${ }^{13}$ University of California at San Diego, La Jolla, California 92093, USA
${ }^{14}$ University of California at Santa Barbara, Santa Barbara, California 93106, USA
${ }^{15}$ University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
${ }^{16}$ California Institute of Technology, Pasadena, California 91125, USA
${ }^{17}$ University of Cincinnati, Cincinnati, Ohio 45221, USA
${ }^{18}$ University of Colorado, Boulder, Colorado 80309, USA
${ }^{19}$ Colorado State University, Fort Collins, Colorado 80523, USA
${ }^{20}$ Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
${ }^{21}$ Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
${ }^{22}$ Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
${ }^{23}$ University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
${ }^{24}$ INFN Sezione di Ferrara ${ }^{a}$; Dipartimento di Fisica, Università di Ferrara ${ }^{b}$, I-44100 Ferrara, Italy
${ }^{25}$ INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
${ }^{26}$ INFN Sezione di Genova ${ }^{a}$; Dipartimento di Fisica, Università di Genova ${ }^{b}$, I-16146 Genova, Italy
${ }^{27}$ Harvard University, Cambridge, Massachusetts 02138, USA
${ }^{28}$ Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
${ }^{29}$ Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
${ }^{30}$ Imperial College London, London, SW7 2AZ, United Kingdom
${ }^{31}$ University of Iowa, Iowa City, Iowa 52242, USA

${ }^{32}$ Iowa State University, Ames, Iowa 50011-3160, USA<br>${ }^{33}$ Johns Hopkins University, Baltimore, Maryland 21218, USA<br>${ }^{34}$ Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11,<br>Centre Scientifique d'Orsay, B. P. 34, F-91898 Orsay Cedex, France<br>${ }^{35}$ Lawrence Livermore National Laboratory, Livermore, California 94550, USA<br>${ }^{36}$ University of Liverpool, Liverpool L69 7ZE, United Kingdom<br>${ }^{37}$ Queen Mary, University of London, London, E1 4NS, United Kingdom<br>${ }^{38}$ University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom<br>${ }^{39}$ University of Louisville, Louisville, Kentucky 40292, USA<br>${ }^{40}$ Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany<br>${ }^{41}$ University of Manchester, Manchester M13 9PL, United Kingdom<br>${ }^{42}$ University of Maryland, College Park, Maryland 20742, USA<br>${ }^{43}$ University of Massachusetts, Amherst, Massachusetts 01003, USA<br>${ }^{44}$ Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA<br>${ }^{45} \mathrm{Mc}$ Gill University, Montréal, Québec, Canada H3A $2 T 8$<br>${ }^{46}$ INFN Sezione di Milano ${ }^{a}$; Dipartimento di Fisica, Università di Milano ${ }^{b}$, I-20133 Milano, Italy<br>${ }^{47}$ University of Mississippi, University, Mississippi 38677, USA<br>${ }^{48}$ Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7<br>${ }^{49}$ Mount Holyoke College, South Hadley, Massachusetts 01075, USA<br>${ }^{50}$ INFN Sezione di Napoli ${ }^{a}$; Dipartimento di Scienze Fisiche, Università di Napoli Federico $I I^{b}$, I-80126 Napoli, Italy<br>${ }^{51}$ NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands<br>${ }^{52}$ University of Notre Dame, Notre Dame, Indiana 46556, USA ${ }^{53}$ Ohio State University, Columbus, Ohio 43210, USA ${ }^{54}$ University of Oregon, Eugene, Oregon 97403, USA<br>${ }^{55}$ INFN Sezione di Padova ${ }^{a}$; Dipartimento di Fisica, Università di Padova ${ }^{b}$, I-35131 Padova, Italy<br>${ }^{56}$ Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France<br>${ }^{57}$ University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA<br>${ }^{58}$ INFN Sezione di Perugia ; Dipartimento di Fisica, Università di Perugia ${ }^{b}$, I-06100 Perugia, Italy<br>${ }^{59}$ INFN Sezione di Pisa ${ }^{a}$; Dipartimento di Fisica,<br>Università di Pisa ${ }^{b}$; Scuola Normale Superiore di Pisa ${ }^{c}$, I-56127 Pisa, Italy<br>${ }^{60}$ Princeton University, Princeton, New Jersey 08544, USA<br>${ }^{61}$ INFN Sezione di Roma ${ }^{a}$; Dipartimento di Fisica, Università di Roma La Sapienza ${ }^{b}$, I-00185 Roma, Italy ${ }^{62}$ Universität Rostock, D-18051 Rostock, Germany<br>${ }^{63}$ Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom<br>${ }^{64}$ CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France<br>${ }^{65}$ SLAC National Accelerator Laboratory, Stanford, California 94309 USA<br>${ }^{66}$ University of South Carolina, Columbia, South Carolina 29208, USA<br>${ }^{67}$ Stanford University, Stanford, California 94305-4060, USA<br>${ }^{68}$ State University of New York, Albany, New York 12222, USA<br>${ }^{69}$ Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel<br>${ }^{70}$ University of Tennessee, Knoxville, Tennessee 37996, USA<br>${ }^{71}$ University of Texas at Austin, Austin, Texas 78712, USA<br>${ }^{72}$ University of Texas at Dallas, Richardson, Texas 75083, USA<br>${ }^{73}$ INFN Sezione di Torino ${ }^{a}$; Dipartimento di Fisica Sperimentale, Università di Torino ${ }^{b}$, I-10125 Torino, Italy<br>${ }^{7}$ INFN Sezione di Trieste ${ }^{a}$; Dipartimento di Fisica, Università di Trieste ${ }^{b}$, I-34127 Trieste, Italy<br>${ }^{75}$ IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain<br>${ }^{76}$ University of Victoria, Victoria, British Columbia, Canada V8W 3P6<br>${ }^{77}$ Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom<br>${ }^{78}$ University of Wisconsin, Madison, Wisconsin 53706, USA

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We present a measurement of the Cabibbo-Kobayashi-Maskawa matrix element $\left|V_{c b}\right|$ and the form-factor slope $\rho^{2}$ in $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decays based on 460 million $B \bar{B}$ events recorded at the $\Upsilon(4 S)$ resonance with the $B A B A R$ detector. $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decays are selected in events in which a hadronic decay of the second $B$ meson is fully reconstructed. We measure the differential decay rate and determine $\mathcal{G}(1)\left|V_{c b}\right|=(43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$ and $\rho^{2}=1.20 \pm 0.09 \pm 0.04$, where $\mathcal{G}(1)$ is the hadronic form factor at the point of zero recoil. We also determine the exclusive branching fractions and find $\mathcal{B}\left(B^{-} \rightarrow D^{0} \ell^{-} \bar{\nu}_{\ell}\right)=(2.31 \pm 0.08 \pm 0.09) \%$ and $\mathcal{B}\left(\bar{B}^{0} \rightarrow D^{+} \ell^{-} \bar{\nu}_{\ell}\right)=(2.23 \pm 0.11 \pm 0.11) \%$.

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In the Standard Model (SM) of electroweak interactions, the rate of the semileptonic $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decay is proportional to the square of the Cabibbo-KobayashiMaskawa (CKM) 1] matrix element $\left|V_{c b}\right|$, which is a measure of the weak interaction coupling of the $b$ to the $c$ quark. The length of the side of the unitary triangle opposite to the well-measured angle $\beta$ is proportional to the ratio $\left|V_{u b} / V_{c b}\right|$, making the determination of $\left|V_{c b}\right|$ important to test the SM description of $C P$ symmetry violation. In addition, imprecise knowledge of $\left|V_{c b}\right|$ is an important uncertainty limiting comparison of measurements of $C P$ violation in $K$ meson decays with those in $B$ meson decays [2].

Measurements of $\left|V_{c b}\right|$ have been performed in inclusive semileptonic $B$ decays [3] and in the exclusive transitions $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ and $\bar{B} \rightarrow D^{*} \ell^{-} \bar{\nu}_{\ell}$ [4]. The most recent inclusive and exclusive determinations differ by more than two standard deviations, with the inclusive result more than twice as precise as the exclusive one [5]. Thus improvements in the measurements of exclusive decay rates are highly desirable, particularly for $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decays, where the experimental uncertainties dominate. Measurements of $\left|V_{c b}\right|$ based on studies of $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decays have previously been reported by the Belle 6], CLEO [7], ALEPH [8] and BABAR [4] Collaborations.

The $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decay rate [9] is proportional to the square of the hadronic matrix element that describes the effects of strong interactions in $\bar{B} \rightarrow D$ transitions. In the limit of very small lepton masses $(\ell=e$ or $\mu)$, their effect can be parameterized by a single form factor $\mathcal{G}(w)$ :

$$
\begin{align*}
& \frac{\mathrm{d} \Gamma(\bar{B} \rightarrow D \ell \nu)}{\mathrm{d} w}  \tag{1}\\
& =\frac{G_{F}^{2}}{48 \pi^{3} \hbar} M_{D}^{3}\left(M_{B}+M_{D}\right)^{2}\left(w^{2}-1\right)^{3 / 2}\left|V_{c b}\right|^{2} \mathcal{G}^{2}(w)
\end{align*}
$$

where $G_{F}$ is the Fermi coupling constant, and $M_{B}$ and $M_{D}$ are the masses of the $B$ and $D$ mesons, respectively. The variable $w$ denotes the product of the $B$ and $D$ meson four-velocities $V_{B}$ and $V_{D}, w=V_{B} \cdot V_{D}=$ $\left(M_{B}^{2}+M_{D}^{2}-q^{2}\right) /\left(2 M_{B} M_{D}\right)$, where $q^{2} \equiv\left(p_{B}-p_{D}\right)^{2}$, and $p_{B}$ and $p_{D}$ are the four-momenta of the $B$ and $D$ mesons.

In the limit of infinite quark masses, $\mathcal{G}(w)$ coincides with the Isgur-Wise function [10]. This function is normalized to unity at zero recoil, where $q^{2}$ is maximum. Corrections to the heavy quark limit have been calculated based on unquenched 11] and quenched lattice QCD 12]. Thus $\left|V_{c b}\right|$ can be extracted by extrapolating the differential decay rate to $w=1$. To reduce the uncertainties associated with this extrapolation, constraints on the shape of the form factor are necessary. Several functional forms have been proposed 13]. We adopt the parameterization suggested in Ref. [14], where the non-linear dependence
of the form factor on $w$ is expressed in terms of a single shape parameter, the form-factor slope $\rho^{2}$.

In this letter, we present a measurement of the differential decay rates for $\bar{B}^{0} \rightarrow D^{+} \ell^{-} \bar{\nu}_{\ell}$ and $B^{-} \rightarrow D^{0} \ell^{-} \bar{\nu}_{\ell}$ decays. The analysis is based on data collected with the $B A B A R$ detector [15] at the PEP-II asymmetric-energy $e^{+} e^{-}$storage rings. The data consist of $417 \mathrm{fb}^{-1}$ recorded at the $\Upsilon(4 S)$ resonance, corresponding to approximately 460 million $B \bar{B}$ pairs. An additional sample of $40 \mathrm{fb}^{-1}$, collected at a center-of-mass (CM) energy 40 MeV below the $\Upsilon(4 S)$ resonance, is used to study background from $e^{+} e^{-} \rightarrow f \bar{f}(f=u, d, s, c, \tau)$ continuum events. We also use samples of GEANT4 Monte Carlo (MC) simulated events that correspond to about three times the data sample size. The simulation models $\bar{B} \rightarrow D^{(*)} \ell^{-} \bar{\nu}_{\ell}$ decays using calculations based on Heavy Quark Effective Theory (HQET) [14], $\bar{B} \rightarrow D^{* *}\left(\rightarrow D^{(*)} \pi\right) \ell^{-} \bar{\nu}_{\ell}$ decays using the ISGW2 model [16], and non-resonant $\bar{B} \rightarrow$ $D^{(*)} \pi \ell^{-} \bar{\nu}_{\ell}$ decays using the Goity-Roberts model [17]. The MC simulation includes radiative effects such as bremsstrahlung in the detector material. QED final-state radiation is modeled by PHOTOS [18].

Semileptonic decays are selected in $B \bar{B}$ events in which a hadronic decay of the second $B$ meson $\left(B_{\mathrm{tag}}\right)$ is fully reconstructed. This leads to a very clean sample of events and also provides a precise measurement of $q^{2}$ and hence $w$. We first reconstruct the semileptonic $B$ decay, selecting a lepton with momentum in the CM frame $p_{\ell}^{*}$ larger than 0.6 GeV . For electrons, we search for a vertex formed in conjunction with a track of opposite charge and remove those with an invariant mass consistent with a photon conversion or a $\pi^{0}$ Dalitz decay. Candidate $D^{0}$ mesons that have the correct charge correlation with the lepton are reconstructed in the $K^{-} \pi^{+}$, $K^{-} \pi^{+} \pi^{0}, K^{-} \pi^{+} \pi^{+} \pi^{-}, K_{S}^{0} \pi^{+} \pi^{-}, K_{S}^{0} \pi^{+} \pi^{-} \pi^{0}, K_{S}^{0} \pi^{0}$, $K^{+} K^{-}, \pi^{+} \pi^{-}$, and $K_{S}^{0} K_{S}^{0}$ channels, and $D^{+}$mesons in the $K^{-} \pi^{+} \pi^{+}, K^{-} \pi^{+} \pi^{+} \pi^{0}, K_{S}^{0} \pi^{+}, K_{S}^{0} \pi^{+} \pi^{0}, K^{+} K^{-} \pi^{+}$, $K_{S}^{0} K^{+}$, and $K_{S}^{0} \pi^{+} \pi^{+} \pi^{-}$channels. $D^{0}\left(D^{+}\right)$candidates are required to be within $2 \sigma$ of the nominal $D^{0}\left(D^{+}\right)$ mass, where $\sigma$ is approximately $8 \mathrm{MeV} / c^{2}$. In events with multiple $D \ell^{-}$combinations, the candidate with the largest $D \ell^{-}$vertex probability is selected. Events with more than one reconstructed lepton with $p_{\ell}^{*}>0.6 \mathrm{GeV}$ are vetoed.

We reconstruct $B_{\text {tag }}$ decays [19] in charmed hadronic modes $\bar{B} \rightarrow D^{(*)} Y$, where $Y$ represents a collection of hadrons, composed of $n_{1} \pi^{ \pm}+n_{2} K^{ \pm}+n_{3} K_{S}^{0}+n_{4} \pi^{0}$, where $n_{1}+n_{2}=1,3,5, n_{3} \leq 2$, and $n_{4} \leq 2$. Using $D^{0}\left(D^{+}\right)$and $D^{* 0}\left(D^{*+}\right)$ as seeds for $B^{-}\left(\bar{B}^{0}\right)$ decays, we reconstruct about 1000 different decay modes. The kinematic consistency of a $B_{\mathrm{tag}}$ candidate with a $B$ meson decay is evaluated using two variables: the beam-energy substituted mass $m_{E S} \equiv \sqrt{s / 4-\left(p_{B}^{*}\right)^{2}}$, and the energy difference $\Delta E \equiv E_{B}^{*}-\sqrt{s} / 2$. Here $\sqrt{s}$ is the total CM energy, and $p_{B}^{*}$ and $E_{B}^{*}$ denote the momentum and energy of the $B_{\mathrm{tag}}$ candidate in the CM frame. For correctly
identified $B_{\text {tag }}$ decays, $m_{E S}$ peaks at the $B$-meson mass, while $\Delta E$ is consistent with zero. We select $B_{\text {tag }}$ candidates in the signal region defined as $5.27 \mathrm{GeV}<m_{E S}<$ 5.29 GeV , excluding those that have daughters in common with the $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decay. In the case of multiple $B_{\text {tag }}$ candidates in an event, we select the one with the smallest $|\Delta E|$ value. The $B_{\text {tag }}$ and the $D \ell^{-}$candidates are required to have the correct charge-flavor correlation. Cross-feed events, i.e., $B_{\mathrm{tag}}^{-}\left(\bar{B}_{\mathrm{tag}}^{0}\right)$ candidates erroneously reconstructed as a neutral (charged) $B$ meson, are subtracted using estimates from the simulation.

Semileptonic $B$ decays are identified by their missing-mass squared value, $m_{\text {miss }}^{2}=$ $\left[p(\Upsilon(4 S))-p\left(B_{\mathrm{tag}}\right)-p(D)-p(\ell)\right]^{2}$, defined in terms of the measured particle four-momenta. For correctly reconstructed signal events, the only missing particle is the neutrino and $m_{\text {miss }}^{2}$ peaks at zero. Other semileptonic $B$ decays, like $\bar{B} \rightarrow D^{(*, * *)} \ell^{-} \bar{\nu}_{\ell}$, where at least one particle is not reconstructed (feed-down), yield larger values of $m_{\text {miss }}^{2}$.

We measure $\left|V_{c b}\right|$ and the form-factor slope $\rho^{2}$ by a fit to the $w$ distribution. We examine the data and MC events in ten equal-size $w$ bins in the interval $1<w<$ 1.6. Since the $B$ momentum is known from the fully reconstructed $B_{\text {tag }}$ in the same event, $w$ can be reconstructed with good precision, namely to $\sim 0.01$, which corresponds to about $2 \%$ of the full kinematic range.

To obtain the $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ signal yield in each bin of $w$, we perform a one-dimensional extended binned maximum likelihood fit [20] to the corresponding $m_{\text {miss }}^{2}$ distribution. The fitted data samples are assumed to contain four different types of events: $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ signal events, feed-down from other semileptonic $B$ decays, combinatorial $B \bar{B}$ and continuum background, and fake lepton events (mostly from hadronic $B$ decays with hadrons misidentified as leptons). The Probability Density Functions (PDFs) are derived from the MC predictions for the different semileptonic $B$ decay $m_{\text {miss }}^{2}$ distributions. We use the off-peak data to provide the continuum background normalization. The shape of the continuum background distribution predicted by the MC simulation is consistent with that obtained from the off-peak data.

The measured $m_{\text {miss }}^{2}$ distributions are compared with the results of the fits for two different $w$ intervals in Fig. 1.

We perform a least-squares fit to the observed signal yields in the ten bins of $w$. We minimize a $\chi^{2}$ defined as

$$
\begin{equation*}
\chi^{2}=\sum_{i=1}^{10} \frac{\left(N_{\text {data }}^{i}-\sum_{j=1}^{N_{\text {MC }}^{i}} W_{j}^{i}\right)^{2}}{\left(\sigma_{\text {data }}^{i}\right)^{2}+\sum_{j=1}^{N_{\text {Mc }}^{i}{ }^{\text {med }}} W_{j}^{i}}, \tag{2}
\end{equation*}
$$

where the index $i$ refers to the $w$ bin and the index $j$ runs over all MC events in bin $i ; N_{\text {data }}^{i}$ is the observed number of signal events found in the $i^{\text {th }}$ bin and $\sigma_{\text {data }}^{i}$ the corresponding uncertainty. The expected signal yields are calculated at each step of the minimization from the


FIG. 1: (Color online) Fit to the $m_{\text {miss }}^{2}$ distribution, in two different $w$ intervals, for $B^{-} \rightarrow D^{0} \ell^{-} \bar{\nu}_{\ell}$ : the data (points with error bars) are compared to the results of the overall fit (sum of the solid histograms). The PDFs for the different fit components are stacked in the order shown in the legend.
reweighted sum of $N_{\mathrm{MC}}^{i}$ simulated events. Each weight is the product of two terms, $W_{j}^{i}=W^{\mathcal{L}} \times W_{j}^{i \text {,theo }}$ where $W^{\mathcal{L}}$ is an overall fixed scale factor, which accounts for the relative integrated luminosity of the data and signal MC events, and $W_{j}^{i, \text { theo }}$ is computed using the true $w$ value of the event $j$ and depends on $\mathcal{G}(1)\left|V_{c b}\right|$ and $\rho^{2}$, which are free parameters determined in the fit that are recalculated at each step of the minimization.

We first fit the $w$ distributions for the charged and neutral $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ samples separately, and then perform a fit to the combined $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ sample. In Fig. 2 we show the comparison between the data and the fit results for the combined sample. The measured values of $\mathcal{G}(1)\left|V_{c b}\right|$ and $\rho^{2}$, with the corresponding correlation $\rho_{\text {corr }}$ obtained from the fit, are reported in Table T. The value of the branching fraction is computed by integrating the differential expression in Eq. 1 and dividing by the appropriate $B$-meson lifetime.

In order to reduce the systematic uncertainty on the measurement of $\mathcal{G}(1)\left|V_{c b}\right|$ and the branching fractions, we normalize the exclusive signal yield to the yield of inclusive semileptonic decays, $\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$, in events tagged by a fully reconstructed hadronic $B$ decay. The inclusive $\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$ decays are selected by identifying one charged lepton with $p_{\ell}^{*}>0.6 \mathrm{GeV}$ and the charge expected based on the $B_{\mathrm{tag}}$ decay. In the case of multiple $B_{\text {tag }}$ candidates in an event, we select the decay mode with the highest purity, estimated from the MC prediction for the fraction of true decays in the $m_{E S}$ signal re-

TABLE I: Fit results for each sample. In the last column we report the results for the $\bar{B}^{0}$ and $B^{-}$combined fit, where the branching fraction refers to $\bar{B}^{0}$ decays. We also report the signal yields and the reconstruction efficiencies, integrated over the full $w$ range. For $\mathcal{G}(1)\left|V_{c b}\right|$ and $\rho^{2}$, we report both the statistical and systematic uncertainties.

|  | $B^{-} \rightarrow D^{0} \ell^{-} \bar{\nu}_{\ell}$ | $\bar{B}^{0} \rightarrow D^{+} \ell^{-} \bar{\nu}_{\ell}$ | $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ |
| :--- | :---: | :---: | :---: |
| $\mathcal{G}(1)\left\|V_{c b}\right\| \cdot 10^{3}$ | $41.7 \pm 2.1 \pm 1.3$ | $45.6 \pm 3.3 \pm 1.6$ | $43.0 \pm 1.9 \pm 1.4$ |
| $\rho^{2}$ | $1.14 \pm 0.11 \pm 0.04$ | $1.29 \pm 0.14 \pm 0.05$ | $1.20 \pm 0.09 \pm 0.04$ |
| $\rho_{\text {corr }}$ | 0.943 | 0.950 | 0.952 |
| $\chi^{2} / n d f$ | $3.4 / 8$ | $5.6 / 8$ | $9.9 / 18$ |
| Signal Yield | $2147 \pm 69$ | $1108 \pm 45$ | - |
| Recon. efficiency | $(1.99 \pm 0.02) \times 10^{-4}$ | $(1.09 \pm 0.02) \times 10^{-4}$ | - |
| $\mathcal{B}$ | $(2.31 \pm 0.08 \pm 0.09) \%$ | $(2.23 \pm 0.11 \pm 0.11) \%$ | $(2.17 \pm 0.06 \pm 0.09) \%$ |



FIG. 2: (a) $w$ distribution obtained summing $B^{-} \rightarrow D^{0} \ell^{-} \bar{\nu}_{\ell}$ and $\bar{B}^{0} \rightarrow D^{+} \ell^{-} \bar{\nu}_{\ell}$ yields. The data (points with error bars) are compared to the results of the overall fit (solid histogram). (b) $\mathcal{G}(w)\left|V_{c b}\right|$ distribution corrected for the reconstruction efficiency, with the fit result superimposed.
gion. Background components that peak in the $m_{E S}$ signal region include cascade $B$ meson decays, for which the lepton does not come directly from the $B$, and hadronic decays, and are subtracted using the corresponding MC predictions. The inclusive $\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$ yield is obtained from a maximum likelihood fit to the $m_{E S}$ distribution of the $B_{\text {tag }}$ candidates, as described in Ref. [21]. The fit yields $(198.9 \pm 1.6) \times 10^{3}$ events for the $B^{-} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$ sample and $(116.3 \pm 1.0) \times 10^{3}$ events for the $\bar{B}^{0} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$ sample. The corresponding reconstruction efficiencies, including the $B_{\text {tag }}$ reconstruction, are $0.39 \%$ and $0.25 \%$, respectively.

Numerous sources of systematic uncertainty are investigated. The largest uncertainties are due to differences in the efficiency of the $B_{t a g}$ selection between the exclusive $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ and inclusive $\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$ decays
(a relative $1.5 \%$ systematic uncertainty on $\left|V_{c b}\right|$ ), the $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ fit procedure ( $1.3 \%$ ), and the uncertainties on the branching fractions of the reconstructed $D$ decay modes and $\bar{B} \rightarrow D^{* *} \ell^{-} \bar{\nu}_{\ell}$ decays $(1.1 \%)$. The uncertainties due to the detector simulation are established by varying, within bounds given by data control samples, the tracking efficiency of all charged tracks ( $0.7 \%$ ), the calorimeter efficiency ( $0.9 \%$ ), and the lepton identification efficiency ( $0.9 \%$ ). We evaluate the systematic uncertainties associated with the MC simulation of various signal and background processes: photon conversion and $\pi^{0}$ Dalitz decay, $B$ cascade decay contamination ( $0.8 \%$ ), and flavor cross-feed ( $0.2 \%$ ). The uncertainty arising from radiative corrections $(0.1 \%)$ is studied by comparing the standard results with those obtained when PHOTOS is not used. We take $30 \%$ of the difference as a conservative systematic uncertainty. We vary the $\bar{B} \rightarrow D^{*} \ell^{-} \bar{\nu}_{\ell}$ form factors ( $0.4 \%$ ) within their measured uncertainties [4] and use an HQET parameterization 22] to describe $\bar{B} \rightarrow D^{* *} \ell^{-} \bar{\nu}_{\ell}$ decays ( $0.3 \%$ ). We evaluate an uncertainty associated with the $\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$ fitting procedure ( $0.8 \%$ ), and with the absolute branching fraction $\mathcal{B}\left(\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}\right)$ used for the normalization ( $0.8 \%$ ). The complete set of systematic uncertainties is given in Ref. [23].

From the fit to the combined $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ sample, we measure $\mathcal{G}(1)\left|V_{c b}\right|=(43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$. Using an unquenched lattice calculation 11], corrected by a factor of 1.007 for QED effects, we obtain $\left|V_{c b}\right|=$ $\left(39.8 \pm 1.8 \pm 1.3 \pm 0.9_{F F}\right) \times 10^{-3}$, where the third error is due to the theoretical uncertainty in $\mathcal{G}(1)$. As an alternative, we use a quenched lattice calculation based on the Step Scaling Method (SSM) 12], and obtain $\left|V_{c b}\right|=\left(41.6 \pm 1.8 \pm 1.4 \pm 0.7_{F F}\right) \times 10^{-3}$. The authors of [12] report the lattice determination of $\mathcal{G}(w)$ for finite momentum transfer. Although quenched, this new calculation allows the extraction of $\left|V_{c b}\right|$ with relatively small model dependence avoiding the large extrapolation to $w=1$. For example, from a linear interpolation around $w=1.2$, we obtain $\left|V_{c b}\right|=\left(41.4 \pm 1.3 \pm 1.4 \pm 1.0_{F F}\right) \times 10^{-3}$. We report our measurements of $\mathcal{G}(w)\left|V_{c b}\right|$ for $w>1$ in Ref. [23].

The resulting value of $\left|V_{c b}\right|$ extrapolated to $w=1$ is
largely independent of previous $B A B A R$ results [4] and significantly more precise than previous measurements from $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decays. It is also consistent with the measurement obtained from $\bar{B} \rightarrow D^{*} \ell^{-} \bar{\nu}_{\ell}$ decays and with the inclusive determination of $\left|V_{c b}\right|=(41.6 \pm 0.6) \times$ $10^{-3}$ (5].

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* Deceased
${ }^{\dagger}$ Now at Temple University, Philadelphia, Pennsylvania 19122, USA
$\ddagger$ Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
§ Also with Università di Roma La Sapienza, I-00185 Roma, Italy
« Now at University of South Alabama, Mobile, Alabama 36688, USA
** Also with Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F75252 Paris, France
${ }^{\dagger \dagger}$ Also with Università di Sassari, Sassari, Italy
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TABLE II: Systematic uncertainties in the measurement of $\mathcal{G}(1)\left|V_{c b}\right|, \rho^{2}$ and the branching fraction for $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ decays. We report the relative error (in \%) for $\mathcal{G}(1)\left|V_{c b}\right|$ and branching fraction, and the absolute error on $\rho^{2}$.

|  | Systematic uncertainty on $\left\|V_{c b}\right\|, \rho^{2}$ and BF |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | $D^{0} \ell^{-} \bar{\nu}^{\prime}$ |  |  | $D^{+} \ell^{-} \bar{\nu}^{\prime}$ |  |  | $D \ell^{-} \bar{\nu}_{\ell}$ |  |
|  | $\left\|V_{c b}\right\|$ (\%) | $\rho^{2}$ | $B F(\%)$ | $\left\|V_{c b}\right\|(\%)$ | $\rho^{2}$ | BF (\%) | $\left\|V_{c b}\right\|(\%)$ | $\rho^{2}$ | BF (\%) |
| Tracking efficiency | 0.5 | 0.008 | 0.7 | 1.1 | 0.003 | 1.4 | 0.7 | 0.004 | 1.0 |
| Neutral reconstruction | 1.0 | 0.003 | 1.2 | 0.8 | 0.006 | 0.9 | 0.9 | 0.004 | 1.2 |
| Lepton ID | 1.0 | 0.009 | 1.0 | 0.9 | 0.009 | 0.8 | 0.9 | 0.009 | 0.9 |
| Final State Radiation | 0.1 | 0.005 | 0.2 | 0.1 | 0.005 | 0.2 | 0.1 | 0.005 | 0.2 |
| Cascade $\bar{B} \rightarrow X \rightarrow \ell^{-}$decay background | 0.6 | - | 1.2 | 1.0 | - | 2.0 | 0.8 | - | 1.5 |
| $B^{0}-B^{ \pm}$cross-feed | 0.2 | 0.003 | 0.2 | 0.2 | 0.003 | 0.2 | 0.2 | 0.003 | 0.2 |
| $\bar{B} \rightarrow D^{*} \ell^{-} \bar{\nu}_{\ell}$ form factors | 0.6 | 0.008 | 0.5 | 0.2 | 0.003 | 0.2 | 0.4 | 0.006 | 0.3 |
| $\bar{B} \rightarrow D^{* *} \ell^{-} \bar{\nu}_{\ell}$ form factors | 0.2 | 0.007 | 0.2 | 0.3 | 0.006 | 0.2 | 0.3 | 0.007 | 0.1 |
| $D$ branching fractions | 1.0 | - | 2.0 | 1.4 | - | 2.7 | 1.1 | - | 2.2 |
| $\mathcal{B}\left(\bar{B} \rightarrow D^{* *} \ell^{-} \bar{\nu}_{\ell}\right)$ | 1.2 | 0.023 | 0.6 | 1.0 | 0.011 | 0.9 | 1.1 | 0.019 | 0.6 |
| $\mathcal{B}\left(\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}\right)$ | 0.9 | - | 1.9 | 0.9 | - | 1.9 | 0.8 | - | 1.7 |
| $B_{\text {tag }}$ selection | 1.1 | 0.021 | 0.6 | 1.8 | 0.036 | 0.8 | 1.5 | 0.028 | 0.8 |
| $\bar{B} \rightarrow X \ell^{-} \bar{\nu}_{\ell}$ fit | 0.7 | - | 1.4 | 1.1 | - | 2.2 | 0.8 | - | 1.7 |
| $\bar{B} \rightarrow D \ell^{-} \bar{\nu}_{\ell}$ fit | 1.3 | 0.018 | 1.1 | 1.1 | 0.027 | 0.6 | 1.3 | 0.020 | 0.8 |
| $B$ meson lifetime | - | - | 0.7 | - | - | 0.6 | - | - | 0.6 |
| Total systematic error | 3.1 | 0.04 | 4.1 | 3.6 | 0.05 | 5.0 | 3.3 | 0.04 | 4.3 |

TABLE III: Fit results for $\left|V_{c b}\right| \mathcal{G}(w)$ extracted at different value of $w$. In order to reduce any fit model dependence, we fit the data interpolating few bins around $w$. In particular we use 4 bins between $w=1.00$ and $w=1.24$ to extract $\left|V_{c b}\right| \mathcal{G}(w)$ at $w=1.03,1.05$ and 1.10 , and 4 bins between $w=1.06$ and $w=1.30$ to extract $\left|V_{c b}\right| \mathcal{G}(w=1.20)$. The statistical correlation between the measurement at $w=1.20$ and the others is $\rho_{\text {corr }}=0.57$, instead the systematic uncertainties can be assumed correlated at $100 \%$. In the last column we report the results for $\left|V_{c b}\right|$ obtained using the results for the $\mathcal{G}(w)$ computed in G.M. de Divitiis et al., Phys. Lett. B655, 45 (2007).

| $w$ | $\left\|V_{c b}\right\| \cdot \mathcal{G}(w) \cdot 10^{3}$ | $\mathcal{G}(w)$ | $\left\|V_{c b}\right\| \cdot 10^{3}$ |
| :--- | :---: | :---: | :---: |
| 1.03 | $40.9 \pm 5.7 \pm 1.3$ | $1.001 \pm 0.019$ | $40.9 \pm 5.7 \pm 1.3 \pm 0.8$ |
| 1.05 | $40.2 \pm 5.0 \pm 1.3$ | $0.987 \pm 0.015$ | $40.7 \pm 5.1 \pm 1.3 \pm 0.6$ |
| 1.10 | $38.3 \pm 3.3 \pm 1.3$ | $0.943 \pm 0.011$ | $40.6 \pm 3.5 \pm 1.4 \pm 0.5$ |
| 1.20 | $35.3 \pm 1.1 \pm 1.2$ | $0.853 \pm 0.021$ | $41.4 \pm 1.3 \pm 1.4 \pm 1.0$ |

