Observation of B^0 Meson Decay to $a_1^{\pm}(1260)\pi^{\mp}$

B. Aubert,[1] R. Barate,[1] M. Bona,[1] D. Boutigny,[1] F. Couderc,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] V. Tisserand,[1] A. Zghiche,[1] E. Grauges,[2] A. Palano,[3] M. Pappagallo,[3] J. C. Chen,[4] N. D. Qi,[4] G. Rong,[4] P. Wang,[4] Y. S. Zhu,[4] G. Eigen,[5] I. Ofte,[5] B. Stugu,[5] G. S. Abrams,[6] M. Battaglia,[6] D. N. Brown,[6] J. Button-Shafer,[6] R. N. Cahn,[6] E. Charles,[6] C. T. Day,[6] M. S. Gill,[6] Y. Groysman,[6] R. G. Jacobsen,[6] J. A. Kadyk,[6] L. T. Kerth,[6] Yu. G. Kolomensky,[6] G. Kukartsev,[6] G. Lynch,[6] L. M. Mir,[6] P. J. Oddone,[6] T. J. Orimoto,[6] M. Pripstein,[6] N. A. Roe,[6] M. T. Ronan,[6] W. A. Wenzel,[6] M. Barrett,[7] K. E. Ford,[7] T. J. Harrison,[7] A. J. Hart,[7] C. M. Hawkes,[7] S. E. Morgan,[7] A. T. Watson,[7] K. Goetzen,[8] T. Held,[8] H. Koch,[8] B. Lewandowski,[8] M. Pelizaeus,[8] K. Peters,[8] T. Schroeder,[8] M. Steinke,[8] J. T. Boyd,[9] J. P. Burke,[9] W. N. Cottingham,[9] D. Walker,[9] T. Cuhadar-Donszelmann,[10] B. G. Fulsom,[10] C. Hearty,[10] N. S. Knecht,[10] T. S. Mattison,[10] J. A. McKenna,[10] A. Khan,[11] P. Kyberd,[11] M. Saleem,[11] L. Teodorescu,[11] V. E. Blinov,[12] A. D. Bukin,[12] V. P. Druzhinin,[12] V. B. Golubev,[12] A. P. Onuchin,[12] S. I. Serednyakov,[12] Yu. I. Skovpen,[12] E. P. Solodov,[12] K. Yu Todyshev,[12] D. S. Best,[13] M. Bondioli,[13] M. Bruinsma,[13] M. Chao,[13] S. Curry,[13] I. Eschrich,[13] D. Kirkby,[13] A. J. Lankford,[13] P. Lund,[13] M. Mandelkern,[13] R. K. Mommsen,[13] W. Roethel,[13] D. P. Stoker,[13] S. Abachi,[14] C. Buchanan,[14] S. D. Foulkes,[15] J. W. Gary,[15] O. Long,[15] B. C. Shen,[15] K. Wang,[15] L. Zhang,[15] H. K. Hadavand,[16] E. J. Hill,[16] H. P. Paar,[16] S. Rahatlou,[16] V. Sharma,[16] J. W. Berryhill,[17] C. Campagnari,[17] A. Cunha,[17] B. Dahmes,[17] T. M. Hong,[17] D. Kovalskyi,[17] J. D. Richman,[17] T. W. Beck,[18] A. M. Eisner,[18] C. J. Flacco,[18] C. A. Heusch,[18] J. Kroseberg,[18] W. S. Lockman,[18] G. Nesom,[18] T. Schalk,[18] B. A. Schumm,[18] A. Seiden,[18] P. Spradlin,[18] D. C. Williams,[18] M. G. Wilson,[18] J. Albert,[19] E. Chen,[19] A. Dvoretskii,[19] D. G. Hitlin,[19] I. Narsky,[19] T. Piatenko,[19] F. C. Porter,[19] A. Ryd,[19] A. Samuel,[19] R. Andreassen,[20] G. Mancinelli,[20] B. T. Meadows,[20] M. D. Sokoloff,[20] F. Blanc,[21] P. C. Bloom,[21] S. Chen,[21] W. T. Ford,[21] J. F. Hirschauer,[21] A. Kreisel,[21] U. Nauenberg,[21] A. Olivas,[21] W. O. Ruddick,[21] J. G. Smith,[21] K. A. Ulmer,[21] S. R. Wagner,[21] J. Zhang,[21] A. Chen,[22] E. A. Eckhart,[22] A. Soffer,[22] W. H. Toki,[22] R. J. Wilson,[22] F. Winklmeier,[22] Q. Zeng,[22] D. D. Altenburg,[23] E. Feltresi,[23] A. Hauke,[23] H. Jasper,[23] B. Spaan,[23] T. Brandt,[24] V. Klose,[24] H. M. Lacker,[24] W. F. Mader,[24] R. Nogowski,[24] A. Petzold,[24] J. Schubert,[24] K. R. Schubert,[24] R. Schwierz,[24] J. E. Sundermann,[24] A. Volk,[24] D. Bernard,[25] G. R. Bonneaud,[25] P. Grenier,[25,*] E. Latour,[25] Ch. Thiebaux,[25] M. Verderi,[25] D. J. Bard,[26] P. J. Clark,[26] W. Gradl,[26] F. Muheim,[26] S. Playfer,[26] A. I. Robertson,[26] Y. Xie,[26] M. Andreotti,[27] D. Bettoni,[27] C. Bozzi,[27] R. Calabrese,[27] G. Cibinetto,[27] E. Luppi,[27] M. Negrini,[27] A. Petrella,[27] L. Piemontese,[27] E. Prencipe,[27] F. Anulli,[28] R. Baldini-Ferroli,[28] A. Calcaterra,[28] R. de Sangro,[28] G. Finocchiaro,[28] S. Pacetti,[28] P. Patteri,[28] I. M. Peruzzi,[28,†] M. Piccolo,[28] M. Rama,[28] A. Zallo,[28] A. Buzzo,[29] R. Capra,[29] R. Contri,[29] M. Lo Vetere,[29] M. M. Macri,[29] M. R. Monge,[29] S. Passaggio,[29] C. Patrignani,[29] E. Robutti,[29] A. Santroni,[29] S. Tosi,[29] G. Brandenburg,[30] K. S. Chaisanguanthum,[30] M. Morii,[30] J. Wu,[30] R. S. Dubitzky,[31] J. Marks,[31] S. Schenk,[31] U. Uwer,[31] W. Bhimji,[32] D. A. Bowerman,[32] P. D. Dauncey,[32] U. Egede,[32] R. L. Flack,[32] J. R. Gaillard,[32] J . A. Nash,[32] M. B. Nikolich,[32] W. Panduro Vazquez,[32] X. Chai,[33] M. J. Charles,[33] U. Mallik,[33] N. T. Meyer,[33] V. Ziegler,[33] J. Cochran,[34] H. B. Crawley,[34] L. Dong,[34] V. Eyges,[34] W. T. Meyer,[34] S. Prell,[34] E. I. Rosenberg,[34] A. E. Rubin,[34] A. V. Gritsan,[35] M. Fritsch,[36] G. Schott,[36] N. Arnaud,[37] M. Davier,[37] G. Grosdidier,[37] A. Höcker,[37] F. Le Diberder,[37] V. Lepeltier,[37] A. M. Lutz,[37] A. Oyanguren,[37] S. Pruvot,[37] S. Rodier,[37] P. Roudeau,[37] M. H. Schune,[37] A. Stocchi,[37] W. F. Wang,[37] G. Wormser,[37] C. H. Cheng,[38] D. J. Lange,[38] D. M. Wright,[38] C. A. Chavez,[39] I. J. Forster,[39] J. R. Fry,[39] E. Gabathuler,[39] R. Gamet,[39] K. A. George,[39] D. E. Hutchcroft,[39] D. J. Payne,[39] K. C. Schofield,[39] C. Touramanis,[39] A. J. Bevan,[40] F. Di Lodovico,[40] W. Menges,[40] R. Sacco,[40] C. L. Brown,[41] G. Cowan,[41] H. U. Flaecher,[41] D. A. Hopkins,[41] P. S. Jackson,[41] T. R. McMahon,[41] S. Ricciardi,[41] F. Salvatore,[41] D. N. Brown,[42] C. L. Davis,[42] J. Allison,[43] N. R. Barlow,[43] R. J. Barlow,[43] Y. M. Chia,[43] C. L. Edgar,[43] M. P. Kelly,[43] G. D. Lafferty,[43] M. T. Naisbit,[43] J. C. Williams,[43] J. I. Yi,[43] C. Chen,[44] W. D. Hulsbergen,[44] A. Jawahery,[44] C. K. Lae,[44] D. A. Roberts,[44] G. Simi,[44] G. Blaylock,[45] C. Dallapiccola,[45] S. S. Hertzbach,[45] X. Li,[45] T. B. Moore,[45] S. Saremi,[45] H. Staengle,[45] S. Y. Willocq,[45] R. Cowan,[46] K. Koeneke,[46] G. Sciolla,[46] S. J. Sekula,[46] M. Spitznagel,[46] F. Taylor,[46] R. K. Yamamoto,[46] H. Kim,[47] P. M. Patel,[47] C. T. Potter,[47] S. H. Robertson,[47] A. Lazzaro,[48] V. Lombardo,[48] F. Palombo,[48] J. M. Bauer,[49] L. Cremaldi,[49] V. Eschenburg,[49] R. Godang,[49] R. Kroeger,[49] J. Reidy,[49] D. A. Sanders,[49] D. J. Summers,[49] H. W. Zhao,[49] S. Brunet,[50] D. Côté,[50] M. Simard,[50] P. Taras,[50] F. B. Viaud,[50] H. Nicholson,[51] N. Cavallo,[52,‡] G. De Nardo,[52] D. del Re,[52] F. Fabozzi,[52,‡] C. Gatto,[52] L. Lista,[52] D. Monorchio,[52] D. Piccolo,[52] C. Sciacca,[52] M. Baak,[53] H. Bulten,[53] G. Raven,[53] H. L. Snoek,[53] C. P. Jessop,[54] J. M. LoSecco,[54] T. Allmendinger,[55] G. Benelli,[55] K. K. Gan,[55] K. Honscheid,[55] D. Hufnagel,[55] P. D. Jackson,[55] H. Kagan,[55] R. Kass,[55] T. Pulliam,[55] A. M. Rahimi,[55] R. Ter-Antonyan,[55] Q. K. Wong,[55] N. L. Blount,[56] J. Brau,[56] R. Frey,[56] O. Igonkina,[56] M. Lu,[56] R. Rahmat,[56] N. B. Sinev,[56] D. Strom,[56] J. Strube,[56]

E. Torrence,[56] F. Galeazzi,[57] A. Gaz,[57] M. Margoni,[57] M. Morandin,[57] A. Pompili,[57] M. Posocco,[57] M. Rotondo,[57] F. Simonetto,[57] R. Stroili,[57] C. Voci,[57] M. Benayoun,[58] J. Chauveau,[58] P. David,[58] L. Del Buono,[58] Ch. de la Vaissière,[58] O. Hamon,[58] B. L. Hartfiel,[58] M. J. J. John,[58] Ph. Leruste,[58] J. Malclès,[58] J. Ocariz,[58] L. Roos,[58] G. Therin,[58] P. K. Behera,[59] L. Gladney,[59] J. Panetta,[59] M. Biasini,[60] R. Covarelli,[60] M. Pioppi,[60] C. Angelini,[61] G. Batignani,[61] S. Bettarini,[61] F. Bucci,[61] G. Calderini,[61] M. Carpinelli,[61] R. Cenci,[61] F. Forti,[61] M. A. Giorgi,[61] A. Lusiani,[61] G. Marchiori,[61] M. A. Mazur,[61] M. Morganti,[61] N. Neri,[61] E. Paoloni,[61] G. Rizzo,[61] J. Walsh,[61] M. Haire,[62] D. Judd,[62] D. E. Wagoner,[62] J. Biesiada,[63] N. Danielson,[63] P. Elmer,[63] Y. P. Lau,[63] C. Lu,[63] J. Olsen,[63] A. J. S. Smith,[63] A. V. Telnov,[63] F. Bellini,[64] G. Cavoto,[64] A. D'Orazio,[64] E. Di Marco,[64] R. Faccini,[64] F. Ferrarotto,[64] F. Ferroni,[64] M. Gaspero,[64] L. Li Gioi,[64] M. A. Mazzoni,[64] S. Morganti,[64] G. Piredda,[64] F. Polci,[64] F. Safai Tehrani,[64] C. Voena,[64] M. Ebert,[65] H. Schröder,[65] R. Waldi,[65] T. Adye,[66] N. De Groot,[66] B. Franek,[66] E. O. Olaiya,[66] F. F. Wilson,[66] S. Emery,[67] A. Gaidot,[67] S. F. Ganzhur,[67] G. Hamel de Monchenault,[67] W. Kozanecki,[67] M. Legendre,[67] B. Mayer,[67] G. Vasseur,[67] Ch. Yèche,[67] M. Zito,[67] W. Park,[68] M. V. Purohit,[68] A. W. Weidemann,[68] J. R. Wilson,[68] M. T. Allen,[69] D. Aston,[69] R. Bartoldus,[69] P. Bechtle,[69] N. Berger,[69] A. M. Boyarski,[69] R. Claus,[69] J. P. Coleman,[69] M. R. Convery,[69] M. Cristinziani,[69] J. C. Dingfelder,[69] D. Dong,[69] J. Dorfan,[69] G. P. Dubois-Felsmann,[69] D. Dujmic,[69] W. Dunwoodie,[69] R. C. Field,[69] T. Glanzman,[69] S. J. Gowdy,[69] M. T. Graham,[69] V. Halyo,[69] C. Hast,[69] T. Hryn'ova,[69] W. R. Innes,[69] M. H. Kelsey,[69] P. Kim,[69] M. L. Kocian,[69] D. W. G. S. Leith,[69] S. Li,[69] J. Libby,[69] S. Luitz,[69] V. Luth,[69] H. L. Lynch,[69] D. B. MacFarlane,[69] H. Marsiske,[69] R. Messner,[69] D. R. Muller,[69] C. P. O'Grady,[69] V. E. Ozcan,[69] A. Perazzo,[69] M. Perl,[69] B. N. Ratcliff,[69] A. Roodman,[69] A. A. Salnikov,[69] R. H. Schindler,[69] J. Schwiening,[69] A. Snyder,[69] J. Stelzer,[69] D. Su,[69] M. K. Sullivan,[69] K. Suzuki,[69] S. K. Swain,[69] J. M. Thompson,[69] J. Va'vra,[69] N. van Bakel,[69] M. Weaver,[69] A. J. R. Weinstein,[69] W. J. Wisniewski,[69] M. Wittgen,[69] D. H. Wright,[69] A. K. Yarritu,[69] K. Yi,[69] C. C. Young,[69] P. R. Burchat,[70] A. J. Edwards,[70] S. A. Majewski,[70] B. A. Petersen,[70] C. Roat,[70] L. Wilden,[70] S. Ahmed,[71] M. S. Alam,[71] R. Bula,[71] J. A. Ernst,[71] V. Jain,[71] B. Pan,[71] M. A. Saeed,[71] F. R. Wappler,[71] S. B. Zain,[71] W. Bugg,[72] M. Krishnamurthy,[72] S. M. Spanier,[72] R. Eckmann,[73] J. L. Ritchie,[73] A. Satpathy,[73] C. J. Schilling,[73] R. F. Schwitters,[73] J. M. Izen,[74] I. Kitayama,[74] X. C. Lou,[74] S. Ye,[74] F. Bianchi,[75] F. Gallo,[75] D. Gamba,[75] M. Bomben,[76] L. Bosisio,[76] C. Cartaro,[76] F. Cossutti,[76] G. Della Ricca,[76] S. Dittongo,[76] S. Grancagnolo,[76] L. Lanceri,[76] L. Vitale,[76] V. Azzolini,[77] F. Martinez-Vidal,[77] Sw. Banerjee,[78] B. Bhuyan,[78] C. M. Brown,[78] D. Fortin,[78] K. Hamano,[78] R. Kowalewski,[78] I. M. Nugent,[78] J. M. Roney,[78] R. J. Sobie,[78] J. J. Back,[79] P. F. Harrison,[79] T. E. Latham,[79] G. B. Mohanty,[79] H. R. Band,[80] X. Chen,[80] B. Cheng,[80] S. Dasu,[80] M. Datta,[80] A. M. Eichenbaum,[80] K. T. Flood,[80] J. J. Hollar,[80] J. R. Johnson,[80] P. E. Kutter,[80] H. Li,[80] R. Liu,[80] B. Mellado,[80] A. Mihalyi,[80] A. K. Mohapatra,[80] Y. Pan,[80] M. Pierini,[80] R. Prepost,[80] P. Tan,[80] S. L. Wu,[80] Z. Yu,[80] and H. Neal[81]

(*BaBar* Collaboration)

[1]*Laboratoire de Physique des Particules, F-74941 Annecy-le-Vieux, France*
[2]*Faculte Fisica. Department ECM, Universitat de Barcelona, Avda Diagonal 647, 6a planta E-08028 Barcelona, Spain*
[3]*Dipartimento di Fisica, Università di Bari, and INFN, I-70126 Bari, Italy*
[4]*Institute of High Energy Physics, Beijing 100039, China*
[5]*Institute of Physics, University of Bergen, N-5007 Bergen, Norway*
[6]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[7]*University of Birmingham, Birmingham, B15 2TT, United Kingdom*
[8]*Institut für Experimentalphysik 1, Ruhr Universität Bochum, D-44780 Bochum, Germany*
[9]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[10]*University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[11]*Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom*
[12]*Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[13]*University of California at Irvine, Irvine, California 92697, USA*
[14]*University of California at Los Angeles, Los Angeles, California 90024, USA*
[15]*University of California at Riverside, Riverside, California 92521, USA*
[16]*University of California at San Diego, La Jolla, California 92093, USA*
[17]*University of California at Santa Barbara, Santa Barbara, California 93106, USA*
[18]*Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, California 95064, USA*
[19]*California Institute of Technology, Pasadena, California 91125, USA*
[20]*University of Cincinnati, Cincinnati, Ohio 45221, USA*
[21]*University of Colorado, Boulder, Colorado 80309, USA*
[22]*Colorado State University, Fort Collins, Colorado 80523, USA*
[23]*Institut für Physik, Universität Dortmund, D-44221 Dortmund, Germany*

[24] Institut für Kern- und Teilchenphysik, Technische Universität Dresden,D-01062 Dresden, Germany
[25]LLR, Ecole Polytechnique, F-91128 Palaiseau, France
[26]University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
[27]Dipartimento di Fisica, Università di Ferrara, and INFN, I-44100 Ferrara, Italy
[28]Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
[29]Dipartimento di Fisica, Università di Genova, and INFN, I-16146 Genova, Italy
[30]Harvard University, Cambridge, Massachusetts 02138, USA
[31]Physikalisches Institut, Universität Heidelberg, Philosophenweg 12, D-69120 Heidelberg, Germany
[32]Imperial College London, London, SW7 2AZ, United Kingdom
[33]University of Iowa, Iowa City, Iowa 52242, USA
[34]Iowa State University, Ames, Iowa 50011-3160, USA
[35]Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street Baltimore, Maryland 21218, USA
[36]Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany
[37]Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, Boîte Postale 34, F-91898 ORSAY Cedex, France
[38]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[39]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[40]Queen Mary, University of London, E1 4NS, United Kingdom
[41]Royal Holloway and Bedford New College, University of London, Egham, Surrey TW20 0EX, United Kingdom
[42]University of Louisville, Louisville, Kentucky 40292, USA
[43]University of Manchester, Manchester M13 9PL, United Kingdom
[44]University of Maryland, College Park, Maryland 20742, USA
[45]University of Massachusetts, Amherst, Massachusetts 01003, USA
[46]Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[47]McGill University, Montréal, Québec, Canada H3A 2T8
[48]Dipartimento di Fisica, Università di Milano, and INFN, I-20133 Milano, Italy
[49]University of Mississippi, University, Mississippi 38677, USA
[50]Physique des Particules, Université de Montréal, Montréal, Québec H3C 3J7, Canada
[51]Mount Holyoke College, South Hadley, Massachusetts 01075, USA
[52]Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
[53]NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
[54]University of Notre Dame, Notre Dame, Indiana 46556, USA
[55]Ohio State University, Columbus, Ohio 43210, USA
[56]University of Oregon, Eugene, Oregon 97403, USA
[57]Dipartimento di Fisica, Università di Padova, and INFN, I-35131 Padova, Italy
[58]Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris VI et VII, F-75252 Paris, France
[59]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[60]Dipartimento di Fisica, Università di Perugia, and INFN, I-06100 Perugia, Italy
[61]Dipartimento di Fisica, Scuola Normale Superiore, Università di Pisa, and INFN, I-56127 Pisa, Italy
[62]Prairie View A&M University, Prairie View, Texas 77446, USA
[63]Princeton University, Princeton, New Jersey 08544, USA
[64]Dipartimento di Fisica, Università di Roma La Sapienza, and INFN, I-00185 Roma, Italy
[65]Universität Rostock, D-18051 Rostock, Germany
[66]Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
[67]DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
[68]University of South Carolina, Columbia, South Carolina 29208, USA
[69]Stanford Linear Accelerator Center, Stanford, California 94309, USA
[70]Stanford University, Stanford, California 94305-4060, USA
[71]State University of New York, Albany, New York 12222, USA
[72]University of Tennessee, Knoxville, Tennessee 37996, USA
[73]University of Texas at Austin, Austin, Texas 78712, USA
[74]University of Texas at Dallas, Richardson, Texas 75083, USA
[75]Dipartimento di Fisica Sperimentale, Università di Torino, and INFN, I-10125 Torino, Italy
[76]Dipartimento di Fisica, Università di Trieste, and INFN, I-34127 Trieste, Italy
[77]IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
[78]University of Victoria, Victoria, British Columbia V8W 3P6, Canada
[79]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[80]University of Wisconsin, Madison, Wisconsin 53706, USA
[81]Yale University, New Haven, Connecticut 06511, USA
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We present a measurement of the branching fraction of the decay $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ with $a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$. The data sample corresponds to 218×10^6 $B\bar{B}$ pairs produced in e^+e^- annihilation through the $\Upsilon(4S)$ resonance. We measure the branching fraction $\mathcal{B}(B^0 \to a_1^{\pm}(1260)\pi^{\mp})\mathcal{B}(a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm}) = (16.6 \pm 1.9 \pm 1.5) \times 10^{-6}$, where the first error quoted is statistical and the second is systematic.

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The rare decay $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ is expected to be dominated by $b \to u\bar{u}d$ contributions. For the branching fraction of this decay mode an upper limit of 49×10^{-5} at the 90% C.L. has been set by CLEO [1]. Bauer *et al.* have predicted a branching fraction 38×10^{-6} for the decay $\bar{B}^0$ to $a_1^-(1260)\pi^+$ within the framework of the factorization model and assuming $|V_{ub}/V_{cb}| = 0.08$ [2]. The study of this decay mode is complicated by the large discrepancies between the parameters of the $a_1(1260)$ meson obtained from analyses involving hadronic interactions [3] and τ decays [4]. The decay $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$, in addition to the decays $B^0 \to \pi^+\pi^-$, $B^0 \to \rho^{\pm}\pi^{\mp}$, and $B^0 \to \rho^+\rho^-$, can be used to give a new measurement of the Cabibbo-Kobayashi-Maskawa angle α of the unitarity triangle [5].

We present a measurement of the branching fraction of the decay $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ with $a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$. The $a_1(1260) \to 3\pi$ decay proceeds mainly through the intermediate states $(\pi\pi)_\rho\pi$ and $(\pi\pi)_\sigma\pi$ [6]. No attempt is made to separate the contributions of the dominant P wave $(\pi\pi)_\rho$ and the S wave $(\pi\pi)_\sigma$ in the channel $\pi^+\pi^-$; a systematic uncertainty is estimated due to the difference in the selection efficiencies. Possible background from the decay $B^0 \to a_2^{\pm}(1320)\pi^{\mp}$ is investigated. We have also studied the decay $B^0 \to \pi^{\pm}(1300)\pi^{\mp}$ as a potential background. We find the contribution from this decay to be negligible.

The data were collected with the *BABAR* detector [7] at the PEP-II asymmetric e^+e^- collider [8]. An integrated luminosity of 198 fb^{-1}, corresponding to 218×10^6 $B\bar{B}$ pairs, was recorded at the $\Upsilon(4S)$ resonance ("on-resonance", center-of-mass energy $\sqrt{s} = 10.58$ GeV). An additional 15 fb^{-1} were taken about 40 MeV below this energy ("off-resonance") for the study of continuum background in which a light or charm quark pair is produced instead of an $\Upsilon(4S)$.

Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker, consisting of five layers of double-sided silicon detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. The tracking system covers 92% of the solid angle in the center-of-mass frame.

Charged-particle identification (PID) is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. A K/π separation of better than 4 standard deviations (σ) is achieved for momenta below 3 GeV/c, decreasing to 2.5σ at the highest momenta in the B decay final states.

Monte Carlo (MC) simulations of the signal decay modes, continuum, $B\bar{B}$ backgrounds and detector response [9] are used to establish the event selection criteria. The MC signal events are simulated as B^0 decays to $a_1(1260)\pi$ with $a_1 \to \rho\pi$. For the $a_1(1260)$ meson parameters we take the mass $m_0 = 1230$ MeV/c^2 and $\Gamma_0 = 400$ MeV/c^2 [6,10].

We reconstruct the decay $a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$ with the following requirement on the invariant mass: $0.83 < m_{a_1(1260)} < 1.8$ GeV/c^2. The intermediate dipion state is reconstructed with an invariant mass between 0.51 and 1.1 GeV/c^2. We impose several PID requirements to ensure the identity of the signal pions. For the bachelor charged track we require an associated DIRC Cherenkov angle between -2σ and $+5\sigma$ from the expected value for a pion. With this requirement all but 1.4% of any background from $a_1(1260)K$ is removed.

A B meson candidate is characterized kinematically by the energy-substituted mass $m_{ES} = \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate in the lab frame, respectively, and the asterisk denotes the $\Upsilon(4S)$ frame. The resolutions in m_{ES} and in ΔE are about 3.0 MeV/c^2 and 20 MeV, respectively. We require $|\Delta E| \leq 0.2$ GeV and $5.25 \leq m_{ES} \leq 5.29$ GeV/c^2. To reduce fake B meson candidates we require a B vertex χ^2 probability >0.01. The cosine of the angle between the direction of the π meson from $a_1(1260) \to \rho\pi$ with respect to the flight direction of the B in the $a_1(1260)$ meson rest frame is required to be between -0.85 and 0.85 to suppress combinatorial background. The distribution of this variable is flat for signal and peaks near ± 1 for this background.

To reject continuum background, we use the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for combinations drawn from jetlike $q\bar{q}$ pairs and is nearly uniform for the isotropic B meson decays; we require $|\cos\theta_T| < 0.65$. The remaining continuum background is modeled from off-resonance data. We use MC simulations of $B^0\bar{B}^0$ and B^+B^- decays to look for $B\bar{B}$ backgrounds, which can come from both charmless and charm decays. We find that the decay mode $B^0 \to D^- \pi^+$, with $D^- \to K^+ \pi^- \pi^-$ or $D^- \to K_S^0 \pi^-$, gives the dominant $B\bar{B}$ background in final states different than the signal. The decay mode $B^0 \to a_2^{\pm}(1320)\pi^{\mp}$ has the same final daughters as the signal. We suppress this background with the angular variable $\mathcal{A}$, defined as the cosine of the angle between the normal to the plane of the 3π resonance and the flight direction of the bachelor pion evaluated in the 3π resonance rest frame. Since the $a_1(1260)$ and $a_2(1320)$ have spins of 1 and 2, respectively, the distributions of the variable $\mathcal{A}$ for these two resonances differ. We require $|\mathcal{A}| < 0.62$.

We use an unbinned, multivariate maximum-likelihood fit to extract the yields of $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ and $B^0 \to a_2^{\pm}(1320)\pi^{\mp}$. The likelihood function incorporates five variables. As mentioned above, we describe the B decay kinematics with two variables: ΔE and $m_{\rm ES}$. We also include the invariant mass of the 3π system, a Fisher discriminant $\mathcal{F}$, and the variable $\mathcal{A}$ (though the later provides little discrimination after the requirement mentioned above). The Fisher discriminant combines four variables: the angles with respect to the beam axis, in the $\Upsilon(4S)$ frame, of the B momentum and B thrust axis, and the zeroth and second angular moments $L_{0,2}$ of the energy flow around the B thrust axis. The moments are defined by

$$L_j = \sum_i p_i |\cos\theta_i|^j, \tag{1}$$

where θ_i is the angle with respect to the B thrust axis of track or neutral cluster i, p_i is its momentum, and the sum excludes tracks and clusters used to build the B candidate.

We have on average 1.4 candidates per event and we select the B candidate with the smallest value of a χ^2 constructed from the deviations from the expected value of ρ resonance mass. From the simulation we find that this algorithm selects the correct-combination candidate in 94% of events containing multiple candidates, and that it induces negligible bias.

Since the correlation between the observables in the selected data and in MC signal events is small, we take the probability density function (PDF) for each event to be a product of the PDFs for the separate observables. The product PDF for event i and hypothesis j, where j can be signal $a_1^{\pm}(1260)\pi^{\mp}$ or $a_2^{\pm}(1320)\pi^{\mp}$ background, continuum background, or $B\bar{B}$ background (2 types), is given by

$$\mathcal{P}_j^i = \mathcal{P}_j(m_{\rm ES}) \cdot \mathcal{P}_j(\Delta E) \cdot \mathcal{P}_j(\mathcal{F}) \cdot \mathcal{P}_j(m_{a_1}) \cdot \mathcal{P}_j(\mathcal{A}). \tag{2}$$

The probability that inside the signal event the primary pion from the B candidate is confused with a pion from the $a_1(1260)$ is negligible because of the high momentum of the primary pion in $\Upsilon(4S)$ frame. There is the possibility that a track from a $a_1^{\pm}(1260)\pi^{\mp}$ event is exchanged with a track from the rest of the event. These so-called self-cross-feed (SCF) events are considered as background events. The likelihood function for the event i is defined as

$$\mathcal{L}^i = n_1\mathcal{P}_1 + n_1^{\rm SCF}\mathcal{P}_1^{\rm SCF} + n_2\mathcal{P}_2 + n_{q\bar{q}}\mathcal{P}_{q\bar{q}} + n_{B\bar{B}1}\mathcal{P}_{B\bar{B}1} + n_{B\bar{B}2}\mathcal{P}_{B\bar{B}2}, \tag{3}$$

where n_1 and $n_1^{\rm SCF}$ are the signal and SCF yields for $a_1^{\pm}(1260)\pi^{\mp}$, n_2 is the yield for the $a_2^{\pm}(1320)\pi^{\mp}$, $n_{q\bar{q}}$ is the number of continuum background events, $n_{B\bar{B}1}$ is the number of $B\bar{B}$ background events $D^-\pi^+$ with $D^- \to K^+\pi^-\pi^-$ and $n_{B\bar{B}2}$ is the number of $B\bar{B}$ background events $D^-\pi^+$ with $D^- \to K_S^0\pi^-$. $\mathcal{P}_k$ is the PDF for correctly reconstructed MC signal events; $\mathcal{P}_k^{\rm SCF}$ is the PDF for SCF events, $\mathcal{P}_{q\bar{q}}$ is the PDF for continuum background events, and $\mathcal{P}_{B\bar{B}1}$ and $\mathcal{P}_{B\bar{B}2}$ are the PDFs for the two types of $B\bar{B}$ backgrounds, all evaluated with the observables of the ith event.

We write the extended likelihood function for all events as

$$\mathcal{L} = \exp\Big(-\sum_j n_j\Big)\prod_i^N \mathcal{L}^i, \tag{4}$$

where n_j is the number of events of hypothesis j found by the fitter, and N is the number of events in the sample. The first factor takes into account the Poisson fluctuations in the total number of events.

We determine the PDFs for signal and $B\bar{B}$ backgrounds from MC distributions in each observable. For the continuum background we establish the functional forms and initial parameter values of the PDFs with off-resonance data.

The PDF of the invariant mass of the $a_1(1260)$ meson in signal events is parametrized as a relativistic Breit-Wigner line shape with a mass-dependent width which takes into account the effect of the mass-dependent ρ width [11]. The PDFs of the invariant mass of the $a_2(1320)$ meson is parametrized by a triple Gaussian function. The $m_{\rm ES}$ and ΔE distributions for signal are parametrized as double Gaussian functions. The ΔE distribution for continuum background is parametrized by a linear function. The combinatorial background in $m_{\rm ES}$ is described by a phase-space-motivated empirical function [12]. We model the Fisher distribution $\mathcal{F}$ using a Gaussian function with different widths above and below the mean. The $\mathcal{A}$ distributions are modeled using polynomials.

In the fit there are 14 free parameters: six yields, the signal $a_1(1260)$ mass and width, and six parameters affecting the shape of the combinatorial background. Table I lists the results of the final fits. Fitted values of $a_1(1260)$ mass and width have statistical errors only. The yield of the decay $B^0 \to a_2^{\pm}(1320)\pi^{\mp}$ is 8.3 ± 23.6 events.

We find a signal yield bias of +3.8% by generating and fitting MC simulated samples containing signal and background populations expected for data. We compute the branching fraction from the fitted signal yield, reconstruction efficiency, daughter branching fractions, and the number of produced B mesons, assuming equal production

TABLE I. Signal yield, detection efficiency (ϵ), statistical significance (with systematic uncertainties), branching fraction, and the mass and width of the $a_1(1260)$ meson.

Fit quantity	$a_1^{\pm}(1260)\pi^{\mp}$
Signal yield	421 ± 48
ϵ (%)	11.7
Stat. sign. (σ)	9.2
$\mathcal{B}(\times 10^{-6})$	$16.6 \pm 1.9 \pm 1.5$
$m(a_1(1260))$	1229 ± 21 MeV$/c^2$
$\Gamma(a_1(1260))$	393 ± 62 MeV$/c^2$

rates of $B^0\bar{B}^0$ and B^+B^- pairs. The signal reconstruction efficiency is obtained from the fraction of signal MC events passing the selection criteria, adjusted for the bias in the likelihood fit. The statistical significance is taken as the square root of the difference between the value of $-2\ln L$ for zero signal and the value at its minimum.

In Fig. 1 we show the ΔE, $m_{\rm ES}$, m_{a_1}, and $\mathcal{F}$ projections made by selecting events with a signal likelihood (computed without the variable shown in the figure) exceeding a threshold that optimizes the expected sensitivity. The enhancement at 1.7 GeV$/c^2$ in Fig. 1(c) comes from $D^-\pi^+$ background.

In Fig. 2 we show the distribution of the ratio of the likelihood for signal events L(Sg) and the sum of likelihoods for signal and all types of background [L(Sg) + L(Bg)] for on-resonance data and for Monte Carlo events generated from PDFs. We see good agreement between the model and the data. By construction the background is concentrated near zero, while the signal appears as an excess of events near one.

The main systematic uncertainties are summarized in Table II. Most of the systematic errors on the signal yield that arise from uncertainties in the values of the PDF parameters have already been incorporated into the overall

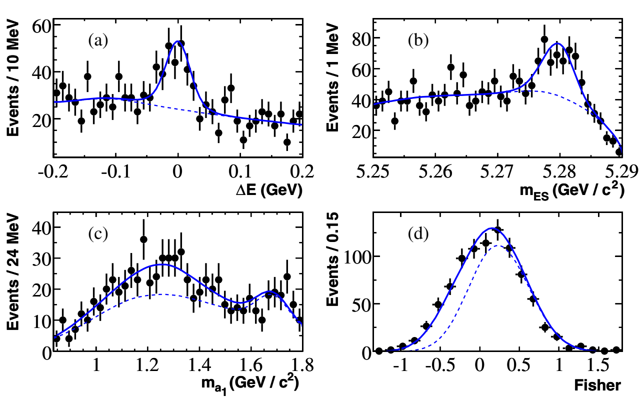

FIG. 1 (color online). Projections of (a) ΔE, (b) $m_{\rm ES}$, (c) m_{a_1}, and (d) $\mathcal{F}$. Points represent on-resonance data, dotted lines the continuum and $B\bar{B}$ backgrounds, and solid lines the full fit function. These plots are made with a cut on the signal likelihood which includes about 40% of the signal.

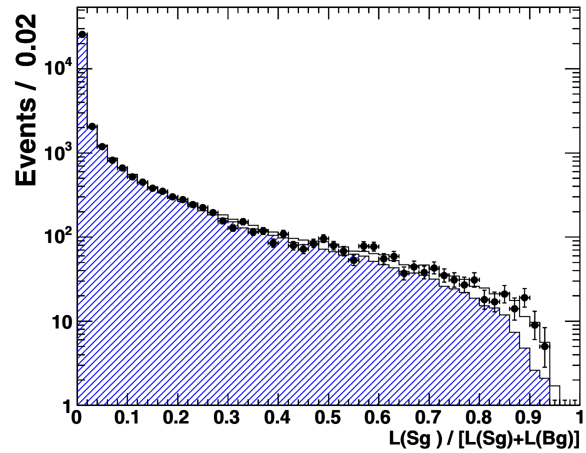

FIG. 2 (color online). Likelihood ratio L(Sg)/[L(Sg) + L(Bg)]. Points represent the data, the solid histogram is from Monte Carlo samples of background plus signal, with the background component shaded.

statistical error, since they are floated in the fit. We determine the sensitivity to the other parameters of the signal and background PDF components by varying these within their uncertainties.

The systematic error on the fit yield is 6.2%, which is obtained by varying the PDF parameters within their uncertainties. The uncertainty in the fit bias correction is 1.9%, taken as half of the fit bias correction. The uncertainty in our knowledge of the efficiency is found to be 3.2%. We estimate the uncertainty in the number of $B\bar{B}$ pairs to be 1.1%. Published world averages [6] provide the B daughter branching fraction uncertainties. The systematic errors on $a_1(1260)K$ cross-feed background and on SCF fraction are both estimated to be 1.4%. The potential background contribution from B^0 decays to $\rho^0\rho^0$, $\rho^0\pi^+\pi^-$ and 4π is estimated assuming the branching fractions of 1, 2, and 2 in 10^{-6} respectively [13]. The associated systematic uncertainty is 3.9%. The systematic effect due to differences between data and MC for the $\cos\theta_T$ selection is 1.8%. A systematic uncertainty of

TABLE II. Summary of systematic uncertainties (in percent) contributing to the total error for the upper limit on the branching fraction.

Fit Yield	6.2
Fit bias	1.9
Tracking Efficiency	3.2
$B\bar{B}$ Pair Counting	1.1
SCF Fraction	1.4
a_1K cross-feed	1.4
$\rho^0\rho^0$, $\rho^0\pi\pi$, 4π cross-feed	3.9
$\cos\theta_T$	1.8
P-wave and S-wave reconstruction	2.5
Total	9.1

2.5% is estimated for the difference in reconstruction efficiency in the decay modes through the dominant P wave $(\pi\pi)_\rho$ and the S wave $(\pi\pi)_\sigma$. The contribution of interference between $a_2(1320)$ and $a_1(1260)$ is negligible. In fact, varying the $a_2(1320)\pi$ background with different selection criteria on the angular variable $\mathcal{A}$ gives no significant change to the efficiency-corrected signal yield of $a_1(1260)\pi$. We find also that the systematic effect due to different form factors in MC signal simulation is negligible. The total systematic error is 9.1%. More details on the determination of systematic uncertainties can be found in Ref. [14].

In conclusion, we have measured the branching fraction $\mathcal{B}(B^0 \to a_1^{\pm}(1260)\pi^{\mp})\mathcal{B}(a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm}) = (16.6 \pm 1.9 \pm 1.5) \times 10^{-6}$. Assuming $\mathcal{B}(a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm})$ is equal to $\mathcal{B}(a_1^{\pm}(1260) \to \pi^{\pm}\pi^0\pi^0)$, and that $\mathcal{B}(a_1^{\pm}(1260) \to (3\pi)^{\pm})$ is equal to 100% [6], we obtain $\mathcal{B}(B^0 \to a_1^{\pm}(1260)\pi^{\mp}) = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$ The decay mode, observed for the first time, is seen with a significance of 9.2σ, which includes systematic uncertainties. A CP time-dependent analysis for the measurement of the angle α is possible with the currently available data sample.

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*Also at Laboratoire de Physique Corpusculaire, Clermont-Ferrand, France
†Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡Also with Università della Basilicata, Potenza, Italy
§Also with Università della Basilicata, Potenza, Italy

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