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*Search for  $B^0$  meson decays to  $\pi^0 K_S^0 K_S^0$ ,  
 $\eta K_S^0 K_S^0$ , and  $\eta' K_S^0 K_S^0$*

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Search for  $B^0$  meson decays to  $\pi^0 K_S^0 K_S^0$ ,  $\eta K_S^0 K_S^0$ , and  $\eta' K_S^0 K_S^0$ 

B. Aubert,<sup>1</sup> Y. Karyotakis,<sup>1</sup> J. P. Lees,<sup>1</sup> V. Poireau,<sup>1</sup> E. Prencipe,<sup>1</sup> X. Prudent,<sup>1</sup> V. Tisserand,<sup>1</sup> J. Garra Tico,<sup>2</sup> E. Grauges,<sup>2</sup> M. Martinelli,<sup>3a,3b</sup> A. Palano,<sup>3a,3b</sup> M. Pappagallo,<sup>3a,3b</sup> G. Eigen,<sup>4</sup> B. Stugu,<sup>4</sup> L. Sun,<sup>4</sup> M. Battaglia,<sup>5</sup> D. N. Brown,<sup>5</sup> L. T. Kerth,<sup>5</sup> Yu. G. Kolomensky,<sup>5</sup> G. Lynch,<sup>5</sup> I. L. Osipenkov,<sup>5</sup> K. Tackmann,<sup>5</sup> T. Tanabe,<sup>5</sup> C. M. Hawkes,<sup>6</sup> N. Soni,<sup>6</sup> A. T. Watson,<sup>6</sup> H. Koch,<sup>7</sup> T. Schroeder,<sup>7</sup> D. J. Asgeirsson,<sup>8</sup> B. G. Fulsom,<sup>8</sup> C. Hearty,<sup>8</sup> T. S. Mattison,<sup>8</sup> J. A. McKenna,<sup>8</sup> M. Barrett,<sup>9</sup> A. Khan,<sup>9</sup> A. Randle-Conde,<sup>9</sup> V. E. Blinov,<sup>10</sup> A. D. Bukin,<sup>10,\*</sup> A. R. Buzykaev,<sup>10</sup> V. P. Druzhinin,<sup>10</sup> V. B. Golubev,<sup>10</sup> A. P. Onuchin,<sup>10</sup> S. I. Serednyakov,<sup>10</sup> Yu. I. Skovpen,<sup>10</sup> E. P. Solodov,<sup>10</sup> K. Yu. Todyshev,<sup>10</sup> M. Bondioli,<sup>11</sup> S. Curry,<sup>11</sup> I. Eschrich,<sup>11</sup> D. Kirkby,<sup>11</sup> A. J. Lankford,<sup>11</sup> P. Lund,<sup>11</sup> M. Mandelkern,<sup>11</sup> E. C. Martin,<sup>11</sup> D. P. Stoker,<sup>11</sup> H. Atmacan,<sup>12</sup> J. W. Gary,<sup>12</sup> F. Liu,<sup>12</sup> O. Long,<sup>12</sup> G. M. Vitug,<sup>12</sup> Z. Yasin,<sup>12</sup> L. Zhang,<sup>12</sup> V. Sharma,<sup>13</sup> C. Campagnari,<sup>14</sup> T. M. Hong,<sup>14</sup> D. Kovalskiy,<sup>14</sup> M. A. Mazur,<sup>14</sup> J. D. Richman,<sup>14</sup> T. W. Beck,<sup>15</sup> A. M. Eisner,<sup>15</sup> C. A. Heusch,<sup>15</sup> J. Kroseberg,<sup>15</sup> W. S. Lockman,<sup>15</sup> A. J. Martinez,<sup>15</sup> T. Schalk,<sup>15</sup> B. A. Schumm,<sup>15</sup> A. Seiden,<sup>15</sup> L. Wang,<sup>15</sup> L. O. Winstrom,<sup>15</sup> C. H. Cheng,<sup>16</sup> D. A. Doll,<sup>16</sup> B. Echenard,<sup>16</sup> F. Fang,<sup>16</sup> D. G. Hitlin,<sup>16</sup> I. Narsky,<sup>16</sup> T. Piatenko,<sup>16</sup> F. C. Porter,<sup>16</sup> R. Andreassen,<sup>17</sup> G. Mancinelli,<sup>17</sup> B. T. Meadows,<sup>17</sup> K. Mishra,<sup>17</sup> M. D. Sokoloff,<sup>17</sup> P. C. Bloom,<sup>18</sup> W. T. Ford,<sup>18</sup> A. Gaz,<sup>18</sup> J. F. Hirschauer,<sup>18</sup> M. Nagel,<sup>18</sup> U. Nauenberg,<sup>18</sup> J. G. Smith,<sup>18</sup> S. R. Wagner,<sup>18</sup> R. Ayad,<sup>19,†</sup> W. H. Toki,<sup>19</sup> R. J. Wilson,<sup>19</sup> E. Feltresi,<sup>20</sup> A. Hauke,<sup>20</sup> H. Jasper,<sup>20</sup> T. M. Karbach,<sup>20</sup> J. Merkel,<sup>20</sup> A. Petzold,<sup>20</sup> B. Spaan,<sup>20</sup> K. Wacker,<sup>20</sup> M. J. Kobel,<sup>21</sup> R. Nogowski,<sup>21</sup> K. R. Schubert,<sup>21</sup> R. Schwierz,<sup>21</sup> A. Volk,<sup>21</sup> D. Bernard,<sup>22</sup> E. Latour,<sup>22</sup> M. Verderi,<sup>22</sup> P. J. Clark,<sup>23</sup> S. Playfer,<sup>23</sup> J. E. Watson,<sup>23</sup> M. Andreotti,<sup>24a,24b</sup> D. Bettoni,<sup>24a</sup> C. Bozzi,<sup>24a</sup> R. Calabrese,<sup>24a,24b</sup> A. Cecchi,<sup>24a,24b</sup> G. Cibinetto,<sup>24a,24b</sup> E. Fioravanti,<sup>24a,24b</sup> P. Franchini,<sup>24a,24b</sup> E. Luppi,<sup>24a,24b</sup> M. Munerato,<sup>24a,24b</sup> M. Negrini,<sup>24a,24b</sup> A. Petrella,<sup>24a,24b</sup> L. Piemontese,<sup>24a</sup> V. Santoro,<sup>24a,24b</sup> R. Baldini-Ferrolì,<sup>25</sup> A. Calcaterra,<sup>25</sup> R. de Sangro,<sup>25</sup> G. Finocchiaro,<sup>25</sup> S. Pacetti,<sup>25</sup> P. Patteri,<sup>25</sup> I. M. Peruzzi,<sup>25,‡</sup> M. Piccolo,<sup>25</sup> M. Rama,<sup>25</sup> A. Zallo,<sup>25</sup> R. Contri,<sup>26a,26b</sup> E. Guido,<sup>26a,26b</sup> M. Lo Vetere,<sup>26a,26b</sup> M. R. Monge,<sup>26a,26b</sup> S. Passaggio,<sup>26a</sup> C. Patrignani,<sup>26a,26b</sup> E. Robutti,<sup>26a</sup> S. Tosi,<sup>26a,26b</sup> K. S. Chaisanguanthum,<sup>27</sup> M. Morii,<sup>27</sup> A. Adametz,<sup>28</sup> J. Marks,<sup>28</sup> S. Schenk,<sup>28</sup> U. Uwer,<sup>28</sup> F. U. Bernlochner,<sup>29</sup> V. Klose,<sup>29</sup> H. M. Lacker,<sup>29</sup> D. J. Bard,<sup>30</sup> P. D. Dauncey,<sup>30</sup> M. Tibbetts,<sup>30</sup> P. K. Behera,<sup>31</sup> M. J. Charles,<sup>31</sup> U. Mallik,<sup>31</sup> J. Cochran,<sup>32</sup> H. B. Crawley,<sup>32</sup> L. Dong,<sup>32</sup> V. Eyges,<sup>32</sup> W. T. Meyer,<sup>32</sup> S. Prell,<sup>32</sup> E. I. Rosenberg,<sup>32</sup> A. E. Rubin,<sup>32</sup> Y. Y. Gao,<sup>33</sup> A. V. Gritsan,<sup>33</sup> Z. J. Guo,<sup>33</sup> N. Arnaud,<sup>34</sup> J. Béquilleux,<sup>34</sup> A. D'Orazio,<sup>34</sup> M. Davier,<sup>34</sup> D. Derkach,<sup>34</sup> J. Firmino da Costa,<sup>34</sup> G. Grosdidier,<sup>34</sup> F. Le Diberder,<sup>34</sup> V. Lepeltier,<sup>34</sup> A. M. Lutz,<sup>34</sup> B. Malaescu,<sup>34</sup> S. Pruvot,<sup>34</sup> P. Roudeau,<sup>34</sup> M. H. Schune,<sup>34</sup> J. Serrano,<sup>34</sup> V. Sordini,<sup>34,§</sup> A. Stocchi,<sup>34</sup> G. Wormser,<sup>34</sup> D. J. Lange,<sup>35</sup> D. M. Wright,<sup>35</sup> I. Bingham,<sup>36</sup> J. P. Burke,<sup>36</sup> C. A. Chavez,<sup>36</sup> J. R. Fry,<sup>36</sup> E. Gabathuler,<sup>36</sup> R. Gamet,<sup>36</sup> D. E. Hutchcroft,<sup>36</sup> D. J. Payne,<sup>36</sup> C. Touramanis,<sup>36</sup> A. J. Bevan,<sup>37</sup> C. K. Clarke,<sup>37</sup> F. Di Lodovico,<sup>37</sup> R. Sacco,<sup>37</sup> M. Sigamani,<sup>37</sup> G. Cowan,<sup>38</sup> S. Paramesvaran,<sup>38</sup> A. C. Wren,<sup>38</sup> D. N. Brown,<sup>39</sup> C. L. Davis,<sup>39</sup> A. G. Denig,<sup>40</sup> M. Fritsch,<sup>40</sup> W. Gradl,<sup>40</sup> A. Hafner,<sup>40</sup> K. E. Alwyn,<sup>41</sup> D. Bailey,<sup>41</sup> R. J. Barlow,<sup>41</sup> G. Jackson,<sup>41</sup> G. D. Lafferty,<sup>41</sup> T. J. West,<sup>41</sup> J. I. Yi,<sup>41</sup> J. Anderson,<sup>42</sup> C. Chen,<sup>42</sup> A. Jawahery,<sup>42</sup> D. A. Roberts,<sup>42</sup> G. Simi,<sup>42</sup> J. M. Tuggle,<sup>42</sup> C. Dallapiccola,<sup>43</sup> E. Salvati,<sup>43</sup> S. Saremi,<sup>43</sup> R. Cowan,<sup>44</sup> D. Dujmic,<sup>44</sup> P. H. Fisher,<sup>44</sup> S. W. Henderson,<sup>44</sup> G. Sciolla,<sup>44</sup> M. Spitznagel,<sup>44</sup> R. K. Yamamoto,<sup>44</sup> M. Zhao,<sup>44</sup> P. M. Patel,<sup>45</sup> S. H. Robertson,<sup>45</sup> M. Schram,<sup>45</sup> P. Biassoni,<sup>46a,46b</sup> F. Cerutti,<sup>46a,46b</sup> A. Lazzaro,<sup>46a,46b</sup> V. Lombardo,<sup>46a</sup> F. Palombo,<sup>46a,46b</sup> S. Stracka,<sup>46a,46b</sup> J. M. Bauer,<sup>47</sup> L. Cremaldi,<sup>47</sup> R. Godang,<sup>47,||</sup> R. Kroeger,<sup>47</sup> P. Sonnek,<sup>47</sup> D. J. Summers,<sup>47</sup> H. W. Zhao,<sup>47</sup> M. Simard,<sup>48</sup> P. Taras,<sup>48</sup> H. Nicholson,<sup>49</sup> G. De Nardo,<sup>50a,50b</sup> L. Lista,<sup>50a</sup> D. Monorchio,<sup>50a,50b</sup> G. Onorato,<sup>50a,50b</sup> C. Sciacca,<sup>50a,50b</sup> G. Raven,<sup>51</sup> H. L. Snoek,<sup>51</sup> C. P. Jessop,<sup>52</sup> K. J. Knoepfel,<sup>52</sup> J. M. LoSecco,<sup>52</sup> W. F. Wang,<sup>52</sup> L. A. Corwin,<sup>53</sup> K. Honscheid,<sup>53</sup> H. Kagan,<sup>53</sup> R. Kass,<sup>53</sup> J. P. Morris,<sup>53</sup> A. M. Rahimi,<sup>53</sup> J. J. Regensburger,<sup>53</sup> S. J. Sekula,<sup>53</sup> Q. K. Wong,<sup>53</sup> N. L. Blount,<sup>54</sup> J. Brau,<sup>54</sup> R. Frey,<sup>54</sup> O. Igonkina,<sup>54</sup> J. A. Kolb,<sup>54</sup> M. Lu,<sup>54</sup> R. Rahmat,<sup>54</sup> N. B. Sinev,<sup>54</sup> D. Strom,<sup>54</sup> J. Strube,<sup>54</sup> E. Torrence,<sup>54</sup> G. Castelli,<sup>55a,55b</sup> N. Gagliardi,<sup>55a,55b</sup> M. Margoni,<sup>55a,55b</sup> M. Morandin,<sup>55a</sup> M. Posocco,<sup>55a</sup> M. Rotondo,<sup>55a</sup> F. Simonetto,<sup>55a,55b</sup> R. Stroili,<sup>55a,55b</sup> C. Voci,<sup>55a,55b</sup> P. del Amo Sanchez,<sup>56</sup> E. Ben-Haim,<sup>56</sup> G. R. Bonneaud,<sup>56</sup> H. Briand,<sup>56</sup> J. Chauveau,<sup>56</sup> O. Hamon,<sup>56</sup> Ph. Leruste,<sup>56</sup> G. Marchiori,<sup>56</sup> J. Ocariz,<sup>56</sup> A. Perez,<sup>56</sup> J. Prendki,<sup>56</sup> S. Sitt,<sup>56</sup> L. Gladney,<sup>57</sup> M. Biasini,<sup>58a,58b</sup> E. Manoni,<sup>58a,58b</sup> C. Angelini,<sup>59a,59b</sup> G. Batignani,<sup>59a,59b</sup> S. Bettarini,<sup>59a,59b</sup> G. Calderini,<sup>59a,59b,¶</sup> M. Carpinelli,<sup>59a,59b,\*\*</sup> A. Cervelli,<sup>59a,59b</sup> F. Forti,<sup>59a,59b</sup> M. A. Giorgi,<sup>59a,59b</sup> A. Lusiani,<sup>59a,59c</sup> M. Morganti,<sup>59a,59b</sup> N. Neri,<sup>59a,59b</sup> E. Paoloni,<sup>59a,59b</sup> G. Rizzo,<sup>59a,59b</sup> J. J. Walsh,<sup>59a</sup> D. Lopes Pegna,<sup>60</sup> C. Lu,<sup>60</sup> J. Olsen,<sup>60</sup> A. J. S. Smith,<sup>60</sup> A. V. Telnov,<sup>60</sup> F. Anulli,<sup>61a</sup> E. Baracchini,<sup>61a,61b</sup> G. Cavoto,<sup>61a</sup> R. Faccini,<sup>61a,61b</sup> F. Ferrarotto,<sup>61a</sup> F. Ferroni,<sup>61a,61b</sup> M. Gaspero,<sup>61a,61b</sup> P. D. Jackson,<sup>61a</sup> L. Li Gioi,<sup>61a</sup> M. A. Mazzoni,<sup>61a</sup> S. Morganti,<sup>61a</sup> G. Piredda,<sup>61a</sup> F. Renga,<sup>61a,61b</sup> C. Voena,<sup>61a</sup> M. Ebert,<sup>62</sup> T. Hartmann,<sup>62</sup> H. Schröder,<sup>62</sup> R. Waldi,<sup>62</sup> T. Adye,<sup>63</sup> B. Franek,<sup>63</sup> E. O. Olaiya,<sup>63</sup> F. F. Wilson,<sup>63</sup> S. Emery,<sup>64</sup> L. Esteve,<sup>64</sup> G. Hamel de Monchenault,<sup>64</sup> W. Kozanecki,<sup>64</sup> G. Vasseur,<sup>64</sup> Ch. Yèche,<sup>64</sup> M. Zito,<sup>64</sup> M. T. Allen,<sup>65</sup> D. Aston,<sup>65</sup> R. Bartoldus,<sup>65</sup> J. F. Benitez,<sup>65</sup>

R. Cenci,<sup>65</sup> J. P. Coleman,<sup>65</sup> M. R. Convery,<sup>65</sup> J. C. Dingfelder,<sup>65</sup> J. Dorfan,<sup>65</sup> G. P. Dubois-Felsmann,<sup>65</sup> W. Dunwoodie,<sup>65</sup> R. C. Field,<sup>65</sup> M. Franco Sevilla,<sup>65</sup> A. M. Gabareen,<sup>65</sup> M. T. Graham,<sup>65</sup> P. Grenier,<sup>65</sup> C. Hast,<sup>65</sup> W. R. Innes,<sup>65</sup> J. Kaminski,<sup>65</sup> M. H. Kelsey,<sup>65</sup> H. Kim,<sup>65</sup> P. Kim,<sup>65</sup> M. L. Kocian,<sup>65</sup> D. W. G. S. Leith,<sup>65</sup> S. Li,<sup>65</sup> B. Lindquist,<sup>65</sup> S. Luitz,<sup>65</sup> V. Luth,<sup>65</sup> H. L. Lynch,<sup>65</sup> D. B. MacFarlane,<sup>65</sup> H. Marsiske,<sup>65</sup> R. Messner,<sup>65,\*</sup> D. R. Muller,<sup>65</sup> H. Neal,<sup>65</sup> S. Nelson,<sup>65</sup> C. P. O'Grady,<sup>65</sup> I. Ofte,<sup>65</sup> M. Perl,<sup>65</sup> B. N. Ratcliff,<sup>65</sup> A. Roodman,<sup>65</sup> A. A. Salnikov,<sup>65</sup> R. H. Schindler,<sup>65</sup> J. Schwiening,<sup>65</sup> A. Snyder,<sup>65</sup> D. Su,<sup>65</sup> M. K. Sullivan,<sup>65</sup> K. Suzuki,<sup>65</sup> S. K. Swain,<sup>65</sup> J. M. Thompson,<sup>65</sup> J. Va'vra,<sup>65</sup> A. P. Wagner,<sup>65</sup> M. Weaver,<sup>65</sup> C. A. West,<sup>65</sup> W. J. Wisniewski,<sup>65</sup> M. Wittgen,<sup>65</sup> D. H. Wright,<sup>65</sup> H. W. Wulsin,<sup>65</sup> A. K. Yarritu,<sup>65</sup> C. C. Young,<sup>65</sup> V. Ziegler,<sup>65</sup> X. R. Chen,<sup>66</sup> H. Liu,<sup>66</sup> W. Park,<sup>66</sup> M. V. Purohit,<sup>66</sup> R. M. White,<sup>66</sup> J. R. Wilson,<sup>66</sup> P. R. Burchat,<sup>67</sup> A. J. Edwards,<sup>67</sup> T. S. Miyashita,<sup>67</sup> S. Ahmed,<sup>68</sup> M. S. Alam,<sup>68</sup> J. A. Ernst,<sup>68</sup> B. Pan,<sup>68</sup> M. A. Saeed,<sup>68</sup> S. B. Zain,<sup>68</sup> A. Soffer,<sup>69</sup> S. M. Spanier,<sup>70</sup> B. J. Wogslund,<sup>70</sup> R. Eckmann,<sup>71</sup> J. L. Ritchie,<sup>71</sup> A. M. Ruland,<sup>71</sup> C. J. Schilling,<sup>71</sup> R. F. Schwitters,<sup>71</sup> B. C. Wray,<sup>71</sup> B. W. Drummond,<sup>72</sup> J. M. Izen,<sup>72</sup> X. C. Lou,<sup>72</sup> F. Bianchi,<sup>73a,73b</sup> D. Gamba,<sup>73a,73b</sup> M. Pelliccioni,<sup>73a,73b</sup> M. Bomben,<sup>74a,74b</sup> L. Bosisio,<sup>74a,74b</sup> C. Cartaro,<sup>74a,74b</sup> G. Della Ricca,<sup>74a,74b</sup> L. Lanceri,<sup>74a,74b</sup> L. Vitale,<sup>74a,74b</sup> V. Azzolini,<sup>75</sup> N. Lopez-March,<sup>75</sup> F. Martinez-Vidal,<sup>75</sup> D. A. Milanes,<sup>75</sup> A. Oyanguren,<sup>75</sup> J. Albert,<sup>76</sup> Sw. Banerjee,<sup>76</sup> B. Bhuyan,<sup>76</sup> H. H. F. Choi,<sup>76</sup> K. Hamano,<sup>76</sup> G. J. King,<sup>76</sup> R. Kowalewski,<sup>76</sup> M. J. Lewczuk,<sup>76</sup> I. M. Nugent,<sup>76</sup> J. M. Roney,<sup>76</sup> R. J. Sobie,<sup>76</sup> T. J. Gershon,<sup>77</sup> P. F. Harrison,<sup>77</sup> J. Ilic,<sup>77</sup> T. E. Latham,<sup>77</sup> G. B. Mohanty,<sup>77</sup> E. M. T. Puccio,<sup>77</sup> H. R. Band,<sup>78</sup> X. Chen,<sup>78</sup> S. Dasu,<sup>78</sup> K. T. Flood,<sup>78</sup> Y. Pan,<sup>78</sup> R. Prepost,<sup>78</sup> C. O. Vuosalo,<sup>78</sup> and S. L. Wu<sup>78</sup>

(BABAR Collaboration)

<sup>1</sup>Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France

<sup>2</sup>Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain

<sup>3a</sup>INFN Sezione di Bari, I-70126 Bari, Italy

<sup>3b</sup>Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy

<sup>4</sup>University of Bergen, Institute of Physics, N-5007 Bergen, Norway

<sup>5</sup>Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

<sup>6</sup>University of Birmingham, Birmingham, B15 2TT, United Kingdom

<sup>7</sup>Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

<sup>8</sup>University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

<sup>9</sup>Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom

<sup>10</sup>Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

<sup>11</sup>University of California at Irvine, Irvine, California 92697, USA

<sup>12</sup>University of California at Riverside, Riverside, California 92521, USA

<sup>13</sup>University of California at San Diego, La Jolla, California 92093, USA

<sup>14</sup>University of California at Santa Barbara, Santa Barbara, California 93106, USA

<sup>15</sup>University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

<sup>16</sup>California Institute of Technology, Pasadena, California 91125, USA

<sup>17</sup>University of Cincinnati, Cincinnati, Ohio 45221, USA

<sup>18</sup>University of Colorado, Boulder, Colorado 80309, USA

<sup>19</sup>Colorado State University, Fort Collins, Colorado 80523, USA

<sup>20</sup>Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany

<sup>21</sup>Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany

<sup>22</sup>Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France

<sup>23</sup>University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom

<sup>24a</sup>INFN Sezione di Ferrara, I-44100 Ferrara, Italy

<sup>24b</sup>Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy

<sup>25</sup>INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy

<sup>26a</sup>INFN Sezione di Genova, I-16146 Genova, Italy

<sup>26b</sup>Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy

<sup>27</sup>Harvard University, Cambridge, Massachusetts 02138, USA

<sup>28</sup>Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

<sup>29</sup>Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany

<sup>30</sup>Imperial College London, London, SW7 2AZ, United Kingdom

<sup>31</sup>University of Iowa, Iowa City, Iowa 52242, USA

<sup>32</sup>Iowa State University, Ames, Iowa 50011-3160, USA

<sup>33</sup>Johns Hopkins University, Baltimore, Maryland 21218, USA

- <sup>34</sup>Laboratoire de l'Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d'Orsay, B. P. 34, F-91898 Orsay Cedex, France
- <sup>35</sup>Lawrence Livermore National Laboratory, Livermore, California 94550, USA
- <sup>36</sup>University of Liverpool, Liverpool L69 7ZE, United Kingdom
- <sup>37</sup>Queen Mary, University of London, London, E1 4NS, United Kingdom
- <sup>38</sup>University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
- <sup>39</sup>University of Louisville, Louisville, Kentucky 40292, USA
- <sup>40</sup>Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
- <sup>41</sup>University of Manchester, Manchester M13 9PL, United Kingdom
- <sup>42</sup>University of Maryland, College Park, Maryland 20742, USA
- <sup>43</sup>University of Massachusetts, Amherst, Massachusetts 01003, USA
- <sup>44</sup>Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
- <sup>45</sup>McGill University, Montréal, Québec, Canada H3A 2T8
- <sup>46a</sup>INFN Sezione di Milano, I-20133 Milano, Italy
- <sup>46b</sup>Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
- <sup>47</sup>University of Mississippi, University, Mississippi 38677, USA
- <sup>48</sup>Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
- <sup>49</sup>Mount Holyoke College, South Hadley, Massachusetts 01075, USA
- <sup>50a</sup>INFN Sezione di Napoli, I-80126 Napoli, Italy
- <sup>50b</sup>Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy
- <sup>51</sup>NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
- <sup>52</sup>University of Notre Dame, Notre Dame, Indiana 46556, USA
- <sup>53</sup>Ohio State University, Columbus, Ohio 43210, USA
- <sup>54</sup>University of Oregon, Eugene, Oregon 97403, USA
- <sup>55a</sup>INFN Sezione di Padova, I-35131 Padova, Italy
- <sup>55b</sup>Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy
- <sup>56</sup>Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
- <sup>57</sup>University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
- <sup>58a</sup>INFN Sezione di Perugia, I-06100 Perugia, Italy
- <sup>58b</sup>Dipartimento di Fisica, Università di Perugia, I-06100 Perugia, Italy
- <sup>59a</sup>INFN Sezione di Pisa, I-56127 Pisa, Italy
- <sup>59b</sup>Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy
- <sup>59c</sup>Scuola Normale Superiore di Pisa, I-56127 Pisa, Italy
- <sup>60</sup>Princeton University, Princeton, New Jersey 08544, USA
- <sup>61a</sup>INFN Sezione di Roma, I-00185 Roma, Italy
- <sup>61b</sup>Dipartimento di Fisica, Università di Roma La Sapienza, I-00185 Roma, Italy
- <sup>62</sup>Universität Rostock, D-18051 Rostock, Germany
- <sup>63</sup>Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
- <sup>64</sup>CEA, Irfu, SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, France
- <sup>65</sup>SLAC National Accelerator Laboratory, Stanford, California 94309 USA
- <sup>66</sup>University of South Carolina, Columbia, South Carolina 29208, USA
- <sup>67</sup>Stanford University, Stanford, California 94305-4060, USA
- <sup>68</sup>State University of New York, Albany, New York 12222, USA
- <sup>69</sup>Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel
- <sup>70</sup>University of Tennessee, Knoxville, Tennessee 37996, USA
- <sup>71</sup>University of Texas at Austin, Austin, Texas 78712, USA
- <sup>72</sup>University of Texas at Dallas, Richardson, Texas 75083, USA
- <sup>73a</sup>INFN Sezione di Torino, I-10125 Torino, Italy
- <sup>73b</sup>Dipartimento di Fisica Sperimentale, Università di Torino, I-10125 Torino, Italy
- <sup>74a</sup>INFN Sezione di Trieste, I-34127 Trieste, Italy

\*Deceased.

†Now at Temple University, Philadelphia, PA 19122, USA.

‡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, AL 36688, USA.

¶Also with Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France.

\*\*Also with Università di Sassari, Sassari, Italy.

<sup>74b</sup>*Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*<sup>75</sup>*IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain*<sup>76</sup>*University of Victoria, Victoria, British Columbia, Canada V8W 3P6*<sup>77</sup>*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*<sup>78</sup>*University of Wisconsin, Madison, Wisconsin 53706, USA*

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We describe searches for  $B^0$  meson decays to the charmless final states  $\pi^0 K_S^0 K_S^0$ ,  $\eta K_S^0 K_S^0$ , and  $\eta' K_S^0 K_S^0$ . The data sample corresponds to  $467 \times 10^6 B\bar{B}$  pairs produced in  $e^+e^-$  annihilation and collected with the BABAR detector at the SLAC National Accelerator Laboratory. We find no significant signals and determine the 90% confidence level upper limits on the branching fractions, in units of  $10^{-7}$ ,  $\mathcal{B}(B^0 \rightarrow \pi^0 K_S^0 K_S^0) < 9$ ,  $\mathcal{B}(B^0 \rightarrow \eta K_S^0 K_S^0) < 10$ , and  $\mathcal{B}(B^0 \rightarrow \eta' K_S^0 K_S^0) < 20$ .

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The observation of mixing-induced  $CP$  violation in  $B^0 \rightarrow J/\psi K_S^0$  decays [1], as well as in the charmless penguin-diagram dominated  $B^0 \rightarrow \eta' K^0$  decays [2], and of direct  $CP$  violation both in the neutral kaon system [3] and in  $B^0 \rightarrow K^+ \pi^-$  decays [4], are in agreement with predictions of the standard model (SM) of electroweak interactions [5]. Further information about  $CP$  violation and hadronic  $B$  decays can be provided by the measurement of branching fractions and time-dependent  $CP$  asymmetries in  $B$  decays to three-body final states containing two identical neutral spin zero particles and another  $CP$  eigenstate spin zero particle [6].  $CP$  violating asymmetries have already been measured in  $B^0$  decays to  $K_S^0 K_S^0 K_S^0$  [7] and to  $\pi^0 \pi^0 K_S^0$  [8], and a search has been performed in  $B \rightarrow \eta' \eta' K$  [9]. Other examples, in which study of time-dependent  $CP$  violation asymmetry might be particularly interesting, are the  $B^0$  decays to  $\pi^0 K_S^0 K_S^0$ ,  $\eta K_S^0 K_S^0$ , and  $\eta' K_S^0 K_S^0$ . There are no theoretical estimations for the branching fractions of these SM-suppressed decay modes. Contributions from physics beyond the SM may appear in these decays.

Among  $B$  meson decays to final states containing two kaons and an additional light meson, only  $B^+ \rightarrow K^+ K^- \pi^+$  has been observed, with a branching fraction of  $(5.0 \pm 0.5 \pm 0.5) \times 10^{-6}$  [10]. In this analysis an unexpected peak was observed around 1.5 GeV/ $c^2$  in the  $K^+ K^-$  invariant-mass spectrum. Studies of decays with two neutral or charged kaons in the final state, such as those presented herein, may help to elucidate the nature of this structure [11].

We present the results of searches for neutral  $B$  decays to charmless final states  $\pi^0 K_S^0 K_S^0$ ,  $\eta K_S^0 K_S^0$ , and  $\eta' K_S^0 K_S^0$ , which are studied for the first time. The results are based on data collected with the BABAR detector [12] at the PEP-II asymmetric-energy  $e^+e^-$  collider located at the SLAC National Accelerator Laboratory. We use an integrated luminosity of  $426 \text{ fb}^{-1}$ , corresponding to  $467 \times 10^6 B\bar{B}$  pairs, recorded at the  $\Upsilon(4S)$  resonance (center-of-mass energy  $\sqrt{s} = 10.58 \text{ GeV}$ ) and, for the study of the background,  $44 \text{ fb}^{-1}$  collected 40 MeV below the resonance (off-peak).

Charged particles from the  $e^+e^-$  interactions are detected, and their momenta measured, by a combination of five layers of double-sided silicon microstrip detectors and a 40-layer drift chamber. Both systems operate in the 1.5 T magnetic field of a superconducting solenoid. Photons and electrons are identified with a CsI(Tl) crystal electromagnetic calorimeter. Charged particle identification is provided by the average energy loss ( $dE/dx$ ) in the tracking devices and by an internally reflecting, ring-imaging Cherenkov detector covering the central region (DIRC). A  $K/\pi$  separation of better than 4 standard deviations ( $\sigma$ ) is achieved for momenta below 3 GeV/ $c$ . Detector details may be found elsewhere [12].

The  $B$  daughter candidates are reconstructed through their dominant decays:  $\eta \rightarrow \gamma\gamma$  ( $\eta_{\gamma\gamma}$ ),  $\eta \rightarrow \pi^+ \pi^- \pi^0$  ( $\eta_{3\pi}$ ) where  $\pi^0 \rightarrow \gamma\gamma$ ,  $\eta' \rightarrow \eta \pi^+ \pi^-$  ( $\eta'_{\eta\pi\pi}$ ) where  $\eta \rightarrow \gamma\gamma$ , and  $\eta' \rightarrow \rho^0 \gamma$  ( $\eta'_{\rho\gamma}$ ) where  $\rho^0 \rightarrow \pi^+ \pi^-$ . We require the laboratory energy of the photons to be greater than 30 MeV for  $\pi^0$  in  $\eta_{3\pi}$ , 50 MeV for  $\eta_{\gamma\gamma}$  in  $\eta'_{\eta\pi\pi}$ , and 100 MeV for  $\eta'_{\rho\gamma}$ , and for  $\pi^0$  and  $\eta_{\gamma\gamma}$  produced directly from the  $B$  decay. We impose the following requirements on the invariant mass (in MeV/ $c^2$ ) of the candidate final states:  $120 < m(\gamma\gamma) < 150$  for  $\pi^0$ ,  $510 < m(\gamma\gamma) < 585$  for  $\eta_{\gamma\gamma}$  produced directly from the  $B$  decay,  $490 < m(\gamma\gamma) < 600$  for  $\eta_{\gamma\gamma}$  in  $\eta'_{\eta\pi\pi}$ ,  $538 < m(\pi^+ \pi^- \pi^0) < 558$  for  $\eta_{3\pi}$ ,  $945 < m(\pi^+ \pi^- \eta) < 970$  for  $\eta'_{\eta\pi\pi}$ ,  $930 < m(\pi^+ \pi^- \gamma) < 980$  for  $\eta'_{\rho\gamma}$ , and  $470 < m(\pi^+ \pi^-) < 980$  for  $\rho^0$ . Tracks from  $\eta$  and  $\eta'$  candidate decays are rejected if their particle identification signatures from the DIRC and  $dE/dx$  are consistent with those of protons, kaons, or electrons. Candidate  $K_S^0$  decays are formed from pairs of oppositely charged tracks with  $486 < m(\pi^+ \pi^-) < 510 \text{ MeV}/c^2$ , a decay vertex  $\chi^2$  probability larger than 0.001, and a reconstructed decay length greater than 3 times its uncertainty.

We reconstruct the  $B$  meson candidate by combining two  $K_S^0$  candidates and a  $\pi^0$ ,  $\eta$ , or  $\eta'$  candidate. From the kinematics of the  $\Upsilon(4S)$  decays we determine the energy-substituted mass  $m_{\text{ES}} = \sqrt{\frac{1}{4}s - \mathbf{p}_B^2}$  and the energy difference  $\Delta E = E_B - \frac{1}{2}\sqrt{s}$ , where  $(E_B, \mathbf{p}_B)$  is the  $B$  meson 4-

momentum vector, and all values are expressed in the  $Y(4S)$  rest frame. The resolution is  $3.0 \text{ MeV}/c^2$  for  $m_{\text{ES}}$  and in the range  $(12\text{--}32) \text{ MeV}$  for  $\Delta E$ , depending on the decay mode. We require  $5.25 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$  and  $|\Delta E| < 0.2 \text{ GeV}$ .

Backgrounds arise primarily from continuum  $e^+e^- \rightarrow q\bar{q}$  events ( $q = u, d, s, c$ ). We reduce these with a requirement on the angle  $\theta_T$  between the thrust axis of the  $B$  candidate in the  $Y(4S)$  rest frame and that of the rest of the charged tracks and neutral calorimeter clusters in the event [13]. The distribution is sharply peaked near  $|\cos\theta_T| = 1$  for  $q\bar{q}$  jet pairs and is nearly uniform for  $B$  meson decays. The requirement is  $|\cos\theta_T| < 0.9$ . For the  $\rho^0$  decays we also use  $|\cos\theta_\rho|$  where the helicity angle  $\theta_\rho$  is defined as the angle between the momenta of a daughter pion and the  $\eta'$ , measured in the  $\rho^0$  meson rest frame. For  $\eta\gamma\gamma$  decays we use  $|\cos\theta_\eta|$  where the decay angle  $\theta_\eta$  is defined as the angle between the momenta of the most energetic daughter photon and the  $B^0$  meson, measured in the  $\eta$  meson rest frame. We require  $|\cos\theta_{\rho(\eta)}| < 0.9$ . Events are retained only if they contain at least one charged track in the decay products of the other  $B$  meson ( $B_{\text{tag}}$ ) from the  $Y(4S)$  decay. This requirement improves the precision of the determination of  $B_{\text{tag}}$  thrust axis. The  $B^0 \rightarrow \pi^0 K_S^0 K_S^0$  decay has background from  $B^0 \rightarrow \bar{D}^0 K_S^0$ , with  $\bar{D}^0 \rightarrow \pi^0 K_S^0$ , which has the same final state as the signal mode. In order to suppress this background, we define  $m(\pi^0 K_S^0)$  as the closer of the two invariant-mass combinations to the nominal  $D^0$  mass [14]. By requiring  $m(\pi^0 K_S^0)$  to be outside the range  $1.815\text{--}1.899 \text{ GeV}/c^2$ , we veto 80% of this background.

We obtain the signal event yields from unbinned extended maximum likelihood (ML) fits. The observables used in the fit are  $\Delta E$ ,  $m_{\text{ES}}$ , and a Fisher discriminant  $\mathcal{F}$ . The Fisher discriminant  $\mathcal{F}$  [15] is a linear combination of four event shape variables and  $|\mathcal{T}|$ , the absolute value of the continuous output of a flavor tagging algorithm [16]. The event shape variables used for  $\mathcal{F}$  are the angles, with respect to the beam axis, of the  $B$  momentum and the  $B$  thrust axis in the  $Y(4S)$  frame, and the zeroth and second angular moments,  $L_{0,2}$ , of the energy flow about the  $B$  thrust axis [17]. The moments are defined by  $L_j = \sum_i p_i \times |\cos\theta_i|^j$ , where  $\theta_i$  is the angle, with respect to the  $B$  thrust axis, of track or neutral cluster  $i$ , and  $p_i$  is its momentum. The sum excludes the  $B$  candidate daughters. We use a neural network based technique [16] to determine the flavor at decay of the  $B_{\text{tag}}$ .

The coefficients of  $\mathcal{F}$  are chosen to maximize the separation between the signal and the continuum background. They are determined from studies of Monte Carlo (MC) [18] simulated signal data and off-peak data. Signal MC events are distributed uniformly across the Dalitz plot. Correlations among the ML input observables are below 10%. The average number of candidates found per selected event is between 1.13 and 1.22, depending on the final state. We choose the candidate with the highest  $B$  vertex  $\chi^2$

probability, determined from a vertex fit that includes both charged and neutral particles [19]. From simulated events we find that this algorithm selects the correct candidate in  $(92\text{--}98)\%$  of the events containing multiple candidates, depending on the final state, and introduces negligible bias.

We use a MC simulation to estimate backgrounds from other  $B$  decays, including final states with and without charm. These contributions are negligible for the  $\eta'\pi\pi$  mode. In all the other modes we introduce a non-peaking  $B\bar{B}$  component in the fit. In the  $\pi^0 K_S^0 K_S^0$  analysis we also introduce a  $B\bar{B}$  background component that peaks in  $m_{\text{ES}}$  and  $\Delta E$ , to take into account the main contribution to background from  $B^0 \rightarrow K_S^0 K_S^0 K_S^0$  decay mode. We consider three components in the likelihood fit: signal, continuum, and  $B\bar{B}$  background. We have studied the possibility of misreconstruction of our  $B$  candidates. We divide signal events into two subcomponents: correctly reconstructed (COR) signal and self cross feed (SCF) signal, where at least one  $B$  candidate daughter has been exchanged with a particle from the rest of the event. The signal component is split according to this classification. The fractions of SCF events are fixed in the fit to the values found in MC simulated events, which are in the range  $(10\text{--}21)\%$ , depending on the final state. For the  $\pi^0 K_S^0 K_S^0$  decay mode, which has the lowest SCF fraction (6.6%), we use one signal component, comprising COR and SCF events.

For each event  $i$  and component  $j$ , we define the probability density function (PDF)

$$\mathcal{P}_j^i = \mathcal{P}_j(m_{\text{ES}}^i) \mathcal{P}_j(\Delta E^i) \mathcal{P}_j(\mathcal{F}^i) \quad (1)$$

and the likelihood function

$$\mathcal{L} = e^{-\sum n_j} \prod_{i=1}^N \left[ \sum_j n_j \mathcal{P}_j^i \right], \quad (2)$$

where  $N$  is the number of reconstructed events and  $n_j$  is the number of events in component  $j$  which is returned by the fit. We determine the PDF parameters from MC simulation of the signal and  $B\bar{B}$  backgrounds, while we use  $m_{\text{ES}}$  and  $\Delta E$  sideband data ( $5.25 < m_{\text{ES}} < 5.27 \text{ GeV}/c^2$ ,  $0.1 < |\Delta E| < 0.2 \text{ GeV}$ ) to model the PDFs of continuum background.

We parameterize  $\mathcal{P}(m_{\text{ES}})$  as a Crystal Ball function [20] for the COR and SCF signal subcomponents, an ARGUS function [21] for continuum and non-peaking  $B\bar{B}$  background components, and by an ARGUS function plus an asymmetric Gaussian distribution for peaking  $B\bar{B}$  background. The  $\mathcal{P}(\Delta E)$  distribution is described by an asymmetric Gaussian distribution plus an exponential tail (AGT) [22] for the COR signal subcomponent, an asymmetric Gaussian distribution plus a linear Chebyshev polynomial or an AGT for the SCF, and Chebyshev polynomials for continuum and  $B\bar{B}$  background components. The distribution of  $\mathcal{F}$  is described with an asymmetric Gaussian distribution plus a Gaussian distribution

TABLE I. Fitted signal yield in events and fit bias in events (ev), detection efficiency  $\epsilon$  (%), daughter branching-fraction product  $\prod \mathcal{B}_i$ , significance  $\mathcal{S}$ , and measured branching fraction  $\mathcal{B}$  with statistical error for each decay mode. For the combined measurements (in bold) we give  $\mathcal{S}$  (with systematic uncertainties included) and the branching fraction with statistical and systematic uncertainties with the 90% CL upper limit in parentheses.

Mode	Yield (ev)	Fit bias (ev)	$\epsilon$ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{S}(\sigma)$	$\mathcal{B}(10^{-7})$
$\pi^0 K_S^0 K_S^0$	$11.7^{+16.2}_{-14.5}$	$+1.0 \pm 0.7$	17.5	47.9	<b>0.7</b>	$2.7^{+4.2}_{-3.7} \pm 0.6$ ( $< 9$ )
$\eta_{\gamma\gamma} K_S^0 K_S^0$	$3.2^{+9.0}_{-7.2}$	$+1.1 \pm 0.7$	17.5	18.8	0.3	$1.4^{+5.9}_{-4.7}$
$\eta_{3\pi} K_S^0 K_S^0$	$2.2^{+5.5}_{-3.6}$	$+0.2 \pm 0.6$	12.0	10.9	0.5	$3.3^{+9.0}_{-5.9}$
<b><math>\eta K_S^0 K_S^0</math></b>					<b>0.5</b>	<b><math>2.1^{+4.7}_{-3.8} \pm 1.2</math></b> ( $< 10$ )
$\eta'_{\eta\pi\pi} K_S^0 K_S^0$	$2.4^{+4.7}_{-3.4}$	$+0.1 \pm 0.4$	12.6	8.4	0.6	$4.6^{+9.5}_{-6.9}$
$\eta'_{\rho\gamma} K_S^0 K_S^0$	$13.4^{+16.1}_{-14.1}$	$+4.7 \pm 1.1$	15.9	14.1	0.6	$8.3^{+15.4}_{-13.5}$
<b><math>\eta' K_S^0 K_S^0</math></b>					<b>0.8</b>	<b><math>5.7^{+8.0}_{-6.5} \pm 3.4</math></b> ( $< 20$ )

for the COR signal subcomponent, an AGT function for SCF signal events, an asymmetric Gaussian distribution plus a linear Chebyshev polynomial for continuum, and an asymmetric Gaussian distribution for  $B\bar{B}$  background subcomponents.

We allow the continuum background PDF parameters to float in the fit. Large control samples of  $B^- \rightarrow D^0(K_S^0 \pi^+ \pi^- \pi^0) \pi^-$  decays are used to verify the simulated  $\Delta E$  and  $m_{ES}$  resolution. Any bias in the fit, which mainly arises from neglecting the correlations among the discriminating variables used in the likelihood function definition, is determined from a large set of simulated experiments. For each experiment, the  $q\bar{q}$  background and non-peaking  $B\bar{B}$  background are drawn from the PDFs, and we embed the expected number of peaking  $B\bar{B}$  background and signal events taken randomly from fully simulated MC samples.

In Table I we show, for each decay mode, the fitted signal yields and their fit biases in numbers of events, the detection efficiencies, the product of daughter branching fractions, the significance  $\mathcal{S}$ , and the measured branching fractions. The detection efficiency is determined as the ratio of selected events in simulation to the number generated. The significance is given in units of  $\sigma$ . We determine the corrected signal yields from the fitted signal yields and their fit biases, estimated using simulations. We use these values, detection efficiencies, daughter branching fractions, and number of produced  $B$  mesons, assuming equal production rates of charged and neutral  $B$  meson pairs, to compute the branching fractions. The statistical error on the signal yield is the change in the central value when the quantity  $-2 \ln \mathcal{L}$  increases by one unit from its minimum value. The significance is the square root of the difference between the value of  $-2 \ln \mathcal{L}$  (with systematic uncertainties included) for zero corrected signal yield and the value at its minimum. We combine results from different subdecay modes by adding the values of  $-2 \ln \mathcal{L}$ . In order to account properly for systematic uncertainties when combining results from different subdecays, we convolve the  $\mathcal{L}$  of each subdecay mode with a

Gaussian distribution with mean equal to zero and width equal to the uncorrelated systematic uncertainty of that decay mode. For the combined measurements we report the branching fractions, the statistical significances and the 90% confidence level (CL) upper limits. The 90% CL upper limit is taken to be the branching fraction below which lies 90% of the total likelihood integral in the positive branching-fraction region.

Figure 1 shows projections of  $\pi^0 K_S^0 K_S^0$ ,  $\eta K_S^0 K_S^0$ , and  $\eta' K_S^0 K_S^0$  candidates onto  $m_{ES}$  and  $\Delta E$  for the subset of candidates for which the signal likelihood (computed without the variable plotted) exceeds a mode-dependent threshold.

The main sources of systematic error include uncertainties in the detection efficiencies, the PDF parameters, and

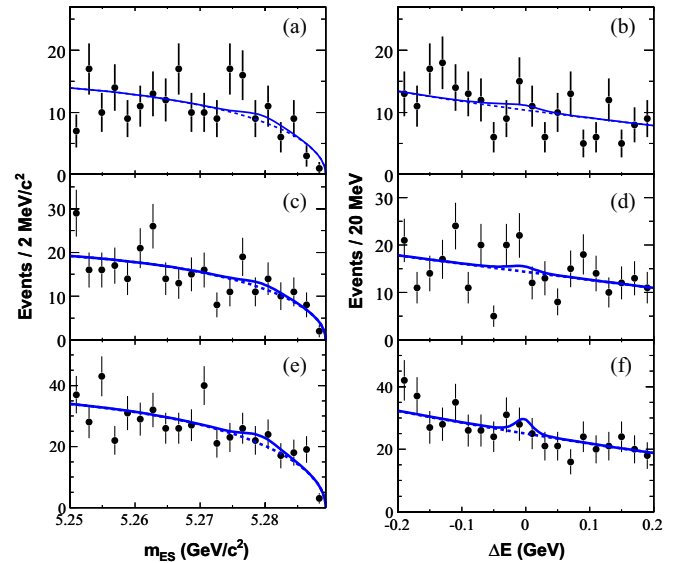


FIG. 1 (color online).  $B^0$  candidate  $m_{ES}$  and  $\Delta E$  projections for  $\pi^0 K_S^0 K_S^0$  [(a), (b)],  $\eta K_S^0 K_S^0$  [(c), (d)], and for  $\eta' K_S^0 K_S^0$  [(e), (f)] with the subdecay modes combined. Points with errors represent the data, solid curves the full fit functions, and dashed curves the background functions. These plots are made with a requirement on the likelihood in order to enhance signal to background ratio.

the maximum likelihood fit bias. We assign systematic uncertainties (13–20%) on the detection efficiencies due to nonuniformity of the efficiencies over the Dalitz plot. This contribution is taken to be the ratio between the standard deviation of the efficiency distribution over the Dalitz plot to its mean value. For the signal, the uncertainties in the PDF parameters are estimated by comparing MC and data control samples. Varying the signal PDF parameters within these uncertainties, we estimate the yield uncertainties of 0–2 events, depending on the mode. The uncertainty from the fit bias is taken as the sum in quadrature of one-half the correction (1–3 events) plus the statistical uncertainty on the correction itself. We assign a systematic error of 0.1–0.4 events, depending on the mode, due to nonuniformity of the SCF fraction over the Dalitz plot. Uncertainties of the efficiency found from auxiliary studies include  $0.8\% \times N_t$  where  $N_t$  is the number of tracks in the  $B$  candidate. A systematic uncertainty of 1.8% and 3.0% is assigned to the single photon and  $\pi^0/\eta_{\gamma\gamma}$  meson reconstruction efficiencies, respectively. There is a systematic error of 0.9% for the reconstruction efficiency of each  $K_S^0$ . The uncertainty on the total number

of  $B\bar{B}$  pairs in the data sample is 1.1%. Uncertainties on the  $B$  daughter branching-fraction products (3.5–4.9)% are taken from Ref. [14].

In conclusion we have searched for the  $B^0$  decay modes to  $\pi^0 K_S^0 K_S^0$ ,  $\eta K_S^0 K_S^0$ , and  $\eta' K_S^0 K_S^0$  with a sample of  $467 \times 10^6$   $B\bar{B}$  pairs. We find no significant signals and set 90% CL upper limits for the branching fractions:  $\mathcal{B}(B^0 \rightarrow \pi^0 K_S^0 K_S^0) < 9 \times 10^{-7}$ ,  $\mathcal{B}(B^0 \rightarrow \eta K_S^0 K_S^0) < 10 \times 10^{-7}$ , and  $\mathcal{B}(B^0 \rightarrow \eta' K_S^0 K_S^0) < 20 \times 10^{-7}$ .

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