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Search for $B^0$ meson decays to $\pi^0 K^0 S^0, \eta K^0 S_0^0$, and $\eta' K^0 S_0^0$.
(BABAR Collaboration)

1Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
2Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain
3aINFN Sezione di Bari, I-70126 Bari, Italy
3bDipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
4University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6University of Birmingham, Birmingham, B15 2TT, United Kingdom
7Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
8University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
9Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
10Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
11University of California at Irvine, Irvine, California 92697, USA
12University of California at Riverside, Riverside, California 92521, USA
13University of California at San Diego, La Jolla, California 92093, USA
14University of California at Santa Barbara, Santa Barbara, California 93106, USA
15University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
16California Institute of Technology, Pasadena, California 91125, USA
17University of Cincinnati, Cincinnati, Ohio 45221, USA
18University of Colorado, Boulder, Colorado 80309, USA
19Colorado State University, Fort Collins, Colorado 80523, USA
20Technische Universität Dortmund, Fakultät Physik, D-44221 Dortmund, Germany
21Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
22Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
23University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
24aINFN Sezione di Ferrara, I-44100 Ferrara, Italy
24bDipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
25aINFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
25bINFN Sezione di Genova, I-16146 Genova, Italy
26aDipartimento di Fisica, Università di Genova, I-16146 Genova, Italy
27aHarvard University, Cambridge, Massachusetts 02138, USA
28Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
29Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
30Imperial College London, London, SW7 2AZ, United Kingdom
31University of Iowa, Iowa City, Iowa 52242, USA
32Iowa State University, Ames, Iowa 50011-3160, USA
33Johns Hopkins University, Baltimore, Maryland 21218, USA
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34 Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B. P. 34, F-91898 Orsay Cedex, France

35 Lawrence Livermore National Laboratory, Livermore, California 94550, USA

36 University of Liverpool, Liverpool L69 7ZE, United Kingdom

37 Queen Mary, University of London, London, E1 4NS, United Kingdom

38 University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom

39 University of Louisville, Louisville, Kentucky 40292, USA

40 Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany

41 University of Manchester, Manchester M13 9PL, United Kingdom

42 University of Maryland, College Park, Maryland 20742, USA

43 University of Massachusetts, Amherst, Massachusetts 01003, USA

44 Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA

45 McGill University, Montréal, Québec, Canada H3A 2T8

46b Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy

46 University of Mississippi, University, Mississippi 38677, USA

47 Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

48 Mount Holyoke College, South Hadley, Massachusetts 01075, USA

49 INFN Sezione di Napoli, I-80126 Napoli, Italy

50b Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy

50 Dipartimento Fisica, Università di Padova, I-35131 Padova, Italy

51 NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

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

55a INFN Sezione di Padova, I-35131 Padova, Italy

55b Dipartimento di Fisica, Università di Padova, I-35131 Padova, Italy

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

57 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

58a INFN Sezione di Perugia, I-06100 Perugia, Italy

58b Dipartimento di Fisica, Università di Perugia, I-06100 Perugia, Italy

59a INFN Sezione di Pisa, I-56127 Pisa, Italy

59b Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy

59c Scuola Normale Superiore di Pisa, I-56127 Pisa, Italy

60 Princeton University, Princeton, New Jersey 08544, USA

61a INFN Sezione di Roma, I-00185 Roma, Italy

61b Dipartimento di Fisica, Università di Roma La Sapienza, I-00185 Roma, Italy

62 Universität Rostock, D-18051 Rostock, Germany

63 Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom

64 CEA, Ifca, SPF, Centre de Saclay, F-91191 Gif-sur-Yvette, France

65 SLAC National Accelerator Laboratory, Stanford, California 94309 USA

66 University of South Carolina, Columbia, South Carolina 29208, USA

67 Stanford University, Stanford, California 94305-4060, USA

68 State University of New York, Albany, New York 12222, USA

69 Tel Aviv University, School of Physics and Astronomy, Tel Aviv, 69978, Israel

70 University of Tennessee, Knoxville, Tennessee 37996, USA

71 University of Texas at Austin, Austin, Texas 78712, USA

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

73 INFN Sezione di Torino, I-10125 Torino, Italy

74 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.
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 $467 \times 10^6 \ U \ BB$ pairs produced in $e^+ e^-$ annihilation and collected with the BABAR detector at the SLAC National Accelerator Laboratory. We find no significant signals and to determine the 90% confidence level upper limits on the branching fractions, in units of $10^{-7}$, $\mathcal{B}(B^0 \to \pi^0 K_S^0 K_S^0) < 9$, $\mathcal{B}(B^0 \to \eta K_S^0 K_S^0) < 10$, and $\mathcal{B}(B^0 \to \eta' K_S^0 K_S^0) < 20$.

The observation of mixing-induced CP violation in $B^0 \to J/\psi K_S^0$ decays [1], as well as in the charmless penguin-diagram dominated $B^0 \to \eta' K^0$ decays [2], and of direct CP violation both in the neutral kaon system [3] and in $B^0 \to K^- \pi^+$ 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 $K^0_d K^0_S K^0_S$ [7] and to $\pi^0 \pi^0 K^0_S$ [8], and a search has been performed in $B \to \eta' \eta' K$ [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 $B^+ \to K^+ K^- \pi^+$ 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 to 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 fb$^{-1}$, corresponding to $467 \times 10^6 \ U \ BB$ pairs, recorded at the $Y(4S)$ resonance (center-of-mass energy $\sqrt{s} = 10.58$ GeV) and, for the study of the background, 44 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: $\eta \to \gamma \gamma$ ($\eta_{\gamma\gamma}$), $\eta \to \pi^+ \pi^- \pi^0$ ($\eta_{\pi\pi\pi}$) where $\pi^0 \to \gamma \gamma$, $\eta \to \pi^+ \pi^- \pi^0$ ($\eta_{\pi\pi\pi}$) where $\eta \to \gamma \gamma$, and $\eta \to \rho^0 \gamma$ ($\eta_{\rho\gamma}$) where $\rho^0 \to \pi^+ \pi^-$. We require the laboratory energy of the photons to be greater than 30 MeV for $\eta_{\gamma\gamma}$ in $\eta_{\pi\pi\pi}$, $50$ MeV for $\eta_{\gamma\gamma}$ in $\eta_{\pi\pi\pi}$, and 100 MeV for $\eta_{\rho\gamma}$, and for $\rho^0$ 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 $\eta_{\pi\pi\pi}$, $538 < m(\pi^+ \pi^- \pi^0) < 558$ for $\eta_{\gamma\gamma}$ in $\eta_{\pi\pi\pi}$, $945 < m(\pi^+ \pi^- \eta) < 970$ for $\eta_{\pi\pi\pi}$, $930 < m(\pi^+ \pi^- \gamma) < 980$ for $\eta_{\rho\gamma}$, and $470 < m(\pi^+ \pi^-) < 980$ for $\rho^0$. Tracks from $\eta$ and $\eta'\gamma$ 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 $486 < m(\pi^+ \pi^-) < 510$ 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 $Y(4S)$ decays we determine the energy-substituted mass $m_{ES} = \sqrt{s} - p_T^2$ and the energy difference $\Delta E = E_B - \frac{1}{2} \sqrt{s}$, where $(E_B, p_B)$ is the $B$ meson 4-
momentum vector, and all values are expressed in the Y(4S) rest frame. The resolution is 3.0 MeV/c$^2$ for $m_{ES}$ and in the range (12–32) MeV for $\Delta E$, depending on the decay mode. We require $5.25 < m_{ES} < 5.29$ GeV/c$^2$ and $|\Delta E| < 0.2$ 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 ($B_{tag}$) from the Y(4S) decay. This requirement improves the precision of the determination of $B_{tag}$ thrust axis. The $B^0 \rightarrow \pi^0 K_S^0 K_S^0$ decay has background from $B^0 \rightarrow D^0 K_S^0$, with $D^0 \rightarrow \pi^0 K_S^0$, 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 1.815–1.899 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 $\Delta E$, $m_{ES}$, and a Fisher discriminant $F$. The Fisher discriminant $F$ [15] is a linear combination of four event shape variables and $|T|$, the absolute value of the continuous output of a flavor tagging algorithm [16]. The event shape variables used for $F$ 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 $L_j = \sum_j p_j \times |\cos\theta_j|^j$, where $\theta_j$ 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 $B_{tag}$.

The coefficients of $F$ 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 (92–98)% 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 $\eta_{\gamma\gamma}$ 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 $m_{ES}$ 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 (10–21)%, 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)

$$P_j = P_j(m_{ES})P_j(\Delta E)|P_j(F)|$$

and the likelihood function

$$L = e^{-\sum_{m,j} N} \prod_{i=1}^N \left[ \sum_j {\eta_j |P_j|^2} \right].$$

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 $m_{ES}$ and $\Delta E$ sideband data (5.25 < $m_{ES}$ < 5.27 GeV/c$^2$, 0.1 < |$\Delta E$| < 0.2 GeV) to model the PDFs of continuum background.

We parameterize $P(m_{ES})$ as a Chrystal 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 $P(\Delta E)$ 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 $F$ 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 $\prod B_i$, significance $S$, and measured branching fraction $B$ with statistical error for each decay mode. For the combined measurements (in bold) we give $S$ (with systematic uncertainties included) and the branching fraction with statistical and systematic uncertainties with the 90% CL upper limit in parentheses.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield (ev)</th>
<th>Fit bias (ev)</th>
<th>$\epsilon$ (%)</th>
<th>$\prod B_i$ (%)</th>
<th>$S(\sigma)$</th>
<th>$B(10^{-7})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 K_S^0 K_S^0$</td>
<td>$11.7^{+16.2}_{-14.5}$</td>
<td>$+1.0 \pm 0.7$</td>
<td>17.5</td>
<td>47.9</td>
<td>0.7</td>
<td>$2.7^{+0.2}_{-0.3} \pm 0.6$</td>
</tr>
<tr>
<td>$\eta\gamma K_S^0 K_S^0$</td>
<td>$3.2^{+9.0}_{-7.2}$</td>
<td>$+1.1 \pm 0.7$</td>
<td>17.5</td>
<td>18.8</td>
<td>0.3</td>
<td>$1.4^{+5.9}_{-4.7}$</td>
</tr>
<tr>
<td>$\eta\pi K_S^0 K_S^0$</td>
<td>$2.2^{+5.5}_{-3.6}$</td>
<td>$+0.2 \pm 0.6$</td>
<td>12.0</td>
<td>10.9</td>
<td>0.5</td>
<td>$3.3^{+3.0}_{-5.9}$</td>
</tr>
<tr>
<td>$\eta K_S^0 K_S^0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>$\eta'\pi K_S^0 K_S^0$</td>
<td>$2.4^{+4.7}_{-3.4}$</td>
<td>$+0.1 \pm 0.4$</td>
<td>12.6</td>
<td>8.4</td>
<td>0.6</td>
<td>$4.6^{+9.5}_{-6.9}$</td>
</tr>
<tr>
<td>$\eta'\gamma K_S^0 K_S^0$</td>
<td>$13.4^{+16.1}_{-14.1}$</td>
<td>$+4.7 \pm 1.1$</td>
<td>15.9</td>
<td>14.1</td>
<td>0.6</td>
<td>$8.3^{+15.4}_{-13.5}$</td>
</tr>
<tr>
<td>$\eta K_S^0 K_S^0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.8</td>
</tr>
</tbody>
</table>

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 $BB$ background subcomponents.

We allow the continuum background PDF parameters to float in the fit. Large control samples of $B^- \rightarrow D^{0}(K_S^0 \pi^+ \pi^- \pi^0)\pi^- \pi^0$ 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 $BB$ background are drawn from the PDFs, and we embed the expected number of peaking $BB$ 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 $S$, 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 $-2\ln L$ increases by one unit from its minimum value. The significance is the square root of the difference between the value of $-2\ln L$ (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 $-2\ln L$. In order to account properly for systematic uncertainties when combining results from different subdecays, we convolve the $L$ 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...
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% × \( N_i \) where \( N_i \) 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 \( K_S \). 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 \( \pi^0 K^0_S K^0_S \), \( \eta K^0_S K^0_S \), and \( \eta' K^0_S K^0_S \) 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: \( B(B^0 \to \pi^0 K^0_S K^0_S) < 9 \times 10^{-7} \), \( B(B^0 \to \eta K^0_S K^0_S) < 10 \times 10^{-7} \), and \( B(B^0 \to \eta' K^0_S K^0_S) < 20 \times 10^{-7} \).

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