

## Evidence For $B^0 \rightarrow \rho^0 K_s^0$

The *BABAR* Collaboration

August 16, 2004

### Abstract

We present evidence for the decay  $B^0 \rightarrow \rho^0 K_s^0$ . The results are obtained from a data sample of  $227 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$  decays collected with the *BABAR* detector at the PEP-II asymmetric-energy *B* Factory at SLAC. From a maximum-likelihood fit giving a yield of  $99 \pm 19$  events and efficiency estimated from simulation we make a preliminary measurement of the branching fraction  $\mathcal{B}(B^0 \rightarrow \rho^0 K^0) = (5.1 \pm 1.0 \pm 1.2) \times 10^{-6}$  where the first error is statistical and the second systematic. The hypothesis of zero signal in the  $\rho^0$  mass region,  $600\text{MeV} - 930\text{MeV}$ , is excluded at the  $6.1\sigma$  level. Allowing a  $B^0 \rightarrow f_0(600)K_s^0$  contribution in the fit allows us to exclude the hypothesis of zero  $B^0 \rightarrow \rho^0 K_s^0$  at the  $3.5\sigma$  level.

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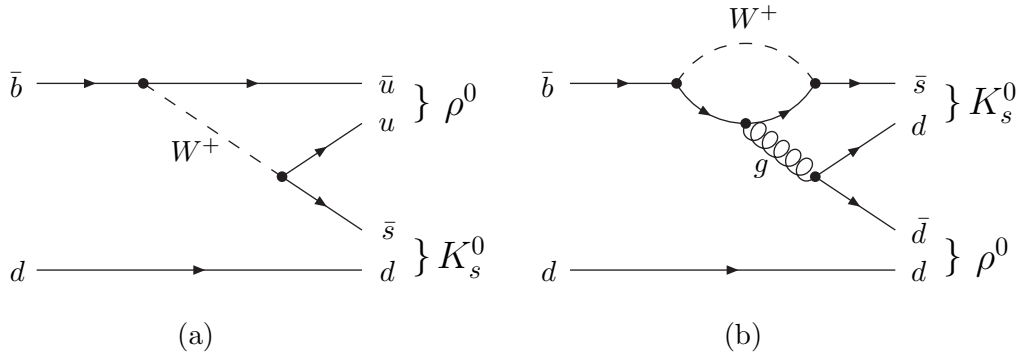


Figure 1: The two main amplitudes expected to contribute to the decay  $B^0 \rightarrow \rho^0 K_s^0$  are shown above. These are a colour suppressed tree diagram (a) and a gluonic penguin (b).

## 1 Introduction

In the Standard Model (SM),  $CP$  violation arises from a single phase in the three-generation Cabibbo-Kobayashi-Maskawa quark-mixing matrix [1]. Any measurement indicating additional sources of  $CP$  violation would be evidence for new physics. A number of penguin-dominated decays [2] (states such as  $\phi K^0$ ,  $\eta' K^0$ ,  $K^+ K^- K^0$ ,  $f_0(980) K^0$  and  $\rho^0 K^0$ ) offer potential for making such an observation: they carry the same weak phase as the decay  $B^0 \rightarrow J/\psi K^0$  [3], neglecting CKM-suppressed amplitudes, and therefore the Standard Model predicts their mixing-induced  $CP$ -violation parameter to be  $-\eta_f \sin 2\beta = -\eta_f \times 0.74 \pm 0.05$  [4]. Heavy non-SM particles may appear in additional penguin diagrams, potentially leading to new  $CP$ -violating phases and  $CP$ -violation parameters measurably different from those predicted by the Standard Model.

The two leading diagrams for the channel  $B^0 \rightarrow \rho^0 K^0$  are shown in Figure 1. The penguin diagram is expected to dominate. We present evidence for the decay  $B^0 \rightarrow \rho^0 K_s^0$ . We take the quasi-two-body (Q2B) approach, restricting ourselves to the region of the  $\pi^+ \pi^- K_s^0$  Dalitz plot dominated by the  $\rho^0$  contribution and taking effects due to the interference between the  $\rho^0$  and the other resonances in the Dalitz plot as systematic uncertainties.

The data we use in this analysis were recorded with the *BABAR* detector at the PEP-II asymmetric-energy  $e^+ e^-$  storage ring at SLAC. The data sample consists of an integrated luminosity of  $205 \text{ fb}^{-1}$ , corresponding to  $(227 \pm 2) \times 10^6 B\bar{B}$  pairs, collected at the  $\Upsilon(4S)$  resonance (“on-resonance”) and  $16 \text{ fb}^{-1}$  collected about 40 MeV below the  $\Upsilon(4S)$  (“off-resonance”). In Ref. [9] we describe the silicon vertex tracker and drift chamber used for track and vertex reconstruction, and the Cerenkov detector (DIRC), the electromagnetic calorimeter (EMC), and the instrumented flux return (IFR) used for particle identification.



## 2 The Candidate Selection

We reconstruct  $B^0 \rightarrow \rho^0 K_S^0$  candidates ( $B_{\text{rec}}^0$  in the following) from combinations of a  $\rho^0$  decaying to  $\pi^+\pi^-$  and a  $K_S^0$  decaying to  $\pi^+\pi^-$ . For the  $\pi^+\pi^-$  pair from the  $\rho^0$  candidate, we use the combined information of the tracking system, EMC, and DIRC to remove tracks positively identified as electrons, kaons, or protons. In addition, we require at least one of the two tracks to have a signature in the IFR that is inconsistent with the muon hypothesis. The mass of the  $\rho^0$  candidate is restricted to the interval  $0.6 < m(\pi^+\pi^-) < 0.93 \text{ GeV}/c^2$ . To reduce combinatorial background from low momentum pions, we require  $|\cos \theta_{\pi^+}| < 0.95$ , where  $\theta_{\pi^+}$  is the angle between the directions of the positive pion and the parent  $B^0$  in the  $\rho^0$  rest frame. The  $K_S^0$  candidate is required to have a mass within  $13 \text{ MeV}/c^2$  of the nominal  $K^0$  mass [10] and a decay vertex separated from the  $\rho^0$  decay vertex by at least three standard deviations. In addition, the cosine of the angle between the  $K_S^0$  flight direction and the vector between the  $\rho^0$  and the  $K_S^0$  decay vertices must be greater than 0.995.

Two kinematic variables are used to discriminate between signal and combinatorial background. The first is the difference  $\Delta E$  between the measured center-of-mass (CM) energy of the  $B$  candidate and  $\sqrt{s}/2$ , where  $\sqrt{s}$  is the CM beam energy. The second variable is the beam-energy-substituted mass  $m_{\text{ES}} \equiv \sqrt{(s/2 + \mathbf{p}_B \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$ , where the  $B$  momentum  $\mathbf{p}_B$  and the four-momentum of the initial  $\Upsilon(4S)$  state ( $E_i, \mathbf{p}_i$ ) are defined in the laboratory frame. We require  $5.23 < m_{\text{ES}} < 5.29 \text{ GeV}/c^2$  and  $|\Delta E| < 0.15 \text{ GeV}$ .

Continuum  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) events are the dominant background. To enhance discrimination between signal and continuum, we use a neural network (NN) to combine five variables: the cosine of the angle between the  $B_{\text{rec}}^0$  direction and the beam axis in the CM, the cosine of the angle between the thrust axis of the  $B_{\text{rec}}^0$  candidate and the beam axis, the sum of momenta transverse to the direction of flight of the  $B_{\text{rec}}^0$ , and the zeroth and second angular moments  $L_{0,2}$  of the energy flow about the  $B_{\text{rec}}^0$  thrust axis. The moments are defined by  $L_j = \sum_i \mathbf{p}_i \times |\cos \theta_i|^j$ , where  $\theta_i$  is the angle with respect to the  $B_{\text{rec}}^0$  thrust axis of the track or neutral cluster  $i$ , and  $p_i$  is its momentum. The sum excludes the tracks that make up the  $B_{\text{rec}}^0$  candidate. The NN is trained with off-resonance data and simulated signal events. The signal efficiency determined from Monte Carlo (MC) simulation is 25%. MC simulation shows that 13.8% of the selected signal events are mis-reconstructed, mainly due to combinatorial background from low-momentum background tracks being used to form the  $\rho^0$  candidate in place of one of the pions it decayed to. In total, 21000 on-resonance events pass all selection criteria.

## 3 Background from other $B$ Decays

We use high statistics MC-simulated events to study the background from other  $B$  decays. The charmless decay modes are grouped into eight classes. The six  $B^0$  decay modes to the  $\pi^+\pi^-K_S^0$  final state are of particular importance since they have signal-like  $\Delta E$  and  $m_{\text{ES}}$  distributions and their decay amplitudes interfere with the  $\rho^0 K_S^0$  decay amplitude. Among these modes are  $f_0(980)K_S^0$ ,  $f_2(1270)K_S^0$ ,  $K^{*+}\pi^-$  (including other kaon resonances decaying to  $K_S^0\pi^+$ ), and non-resonant  $B^0 \rightarrow \pi^+\pi^-K_S^0$  decays. The inclusive charmless  $B^0 \rightarrow \pi^+\pi^-K_S^0$  branching fraction  $(23 \pm 3) \times 10^{-6}$  together with the available exclusive measurements [4], are used to infer upper limits on the contributions of these decays. Selection efficiencies are obtained from MC and used with these branching fractions to estimate the expected background. The charmed decay  $B^0 \rightarrow D^-\pi^+(D^- \rightarrow \pi^-K_S^0)$  contributes significantly to the selected data sample despite the veto requiring the invariant mass of both  $K_S^0\pi$

Background Mode	Efficiency (%)	Branching Fraction ( $10^{-6}$ )	Number of Expected Events
$B^0 \rightarrow K_0^*(1680)^- \pi^+$	$0.04 \pm 0.01$	$14 \pm 14$	$2 \pm 2$
$B^0 \rightarrow f_0(980) K_s^0$	$0.40 \pm 0.02$	$2 \pm 2$	$2 \pm 2$
$B^0 \rightarrow K_2^*(1430)^+ \pi^-$	$0.20 \pm 0.02$	$14 \pm 14$	$6 \pm 6$
$B^0 \rightarrow f_2(1270) K_s^0$	$1.68 \pm 0.04$	$1.7 \pm 1.7$	$6 \pm 6$
$B^0 \rightarrow K_s^0 \pi^+ \pi^-$	$1.11 \pm 0.10$	$2.8 \pm 1.7$	$7 \pm 4$
$B^0 \rightarrow K_0^*(1430)^+ \pi^-$	$0.13 \pm 0.01$	$14 \pm 14$	$2 \pm 2$
$B^0 \rightarrow \eta' K_s^0$	$6.29 \pm 0.10$	$6.6 \pm 0.9$	$94 \pm 13$
$B^0 \rightarrow \rho^0 K^{*0}$	$0.64 \pm 0.03$	$7.1 \pm 7.1$	$10 \pm 10$
$B^0 \rightarrow D^- \pi^+$	$0.34 \pm 0.02$	$42 \pm 6$	$32 \pm 8$
Charmed $B^0$			$171 \pm 86$
Charmed $B^+$			$106 \pm 58$

Table 1: Table of the B background modes included in the Maximum Likelihood fit. The first six modes in this table all decay to the final state  $\pi^+ \pi^- K_s^0$ . The number of expected events refers to the full fit region. The error on the number of expected events (used to calculate the systematic error) is taken from the measured branching fraction or is set to 100% when the value is not obtained from a direct branching fraction measurement.

combinations to be more than 40 Mev/ $c^2$  from the  $D^-$  mass as quoted in [10]. As a result it is dealt with as an individual component in the fit. Two additional classes account for the remaining neutral and charged  $B$  backgrounds, with  $b \rightarrow c$  decays being the dominant component in both cases.

## 4 The Maximum-Likelihood Fit

We use an unbinned extended-maximum-likelihood fit to extract the  $\rho^0 K_s^0$  event yield. In view of a future analysis of time-dependent CP asymmetry, the events in this sample are flavour-tagged as  $B^0$  or  $\bar{B}^0$  with the method described in [11]. Four flavour tagging categories and an ‘‘untagged’’ category are defined each having a different expected purity for the signal. The likelihood function for the  $N_k$  candidates in flavour tagging category  $k$  is

$$\mathcal{L}_k = e^{-N'_k} \prod_{i=1}^{N_k} \left\{ N_S \epsilon_k \left[ (1 - f_{\text{MR}}^k) \mathcal{P}_{i,k}^{S-\text{CR}} + f_{\text{MR}}^k \mathcal{P}_{i,k}^{S-\text{MR}} \right] + N_{C,k} \mathcal{P}_{i,k}^C + \sum_{j=1}^{n_B} N_{B,j} \epsilon_{j,k} \mathcal{P}_{i,j,k}^B \right\} \quad (1)$$

where  $N'_k$  is the sum of the yields of all components, signal and backgrounds, tagged in category  $k$ ,  $N_S$  is the number of  $\rho^0 K_s^0$  signal events in the sample,  $\epsilon_k$  is the fraction of signal events tagged in category  $k$ ,  $f_{\text{MR}}^k$  is the fraction of mis-reconstructed signal events in tagging category  $k$ ,  $N_{C,k}$  is the number of continuum background events that are tagged in category  $k$ , and  $N_{B,j} \epsilon_{j,k}$  is the number of  $B$ -background events of class  $j$  that are tagged in category  $k$ . The  $B$ -background event yields are fixed in the default fit. The total likelihood  $\mathcal{L}$  is the product of the likelihoods for each tagging category.

The probability density functions (PDFs)  $\mathcal{P}_k^{S-\text{CR}}$ ,  $\mathcal{P}_k^{S-\text{MR}}$ ,  $\mathcal{P}_k^C$  and  $\mathcal{P}_{j,k}^B$ , for correctly reconstructed signal, mis-reconstructed signal, continuum background and  $B$ -background class  $j$  (see

Table 1), respectively, are each the product of the PDFs of four discriminating variables. Each signal and background PDF is thus given by:  $\mathcal{P}_k = \mathcal{P}(m_{ES}) \cdot \mathcal{P}(\Delta E) \cdot \mathcal{P}_k(\text{NN}) \cdot \mathcal{P}(|\cos(\theta_{\pi^+})|)$  where  $m_{ES}$ ,  $\Delta E$ , NN and  $|\cos(\theta_{\pi^+})|$  are the variables described in section 2.

The  $m_{ES}$ ,  $\Delta E$ , NN,  $|\cos(\theta_{\pi^+})|$  PDFs for signal and  $B$  background are taken from the simulation

There are 15 free parameters in the default fit, including the yields of continuum events in each of the tag categories and the signal yield. Nine of the free parameters are used to describe the shape of the continuum background - third order polynomials to describe the NN shape and  $|\cos(\theta_{\pi^+})|$ , a second order polynomial to describe the  $\Delta E$  distribution and for  $m_{ES}$  a function describing phase space with a single free parameter for its slope.

## 5 Fit Results

The maximum likelihood fit results in a signal yield of  $99 \pm 19$ , where the signal is the combination of  $B^0 \rightarrow \rho^0 K_S^0$  and  $B^0 \rightarrow f_0(600)K_S^0$  events. When selection efficiency (25%), fraction of  $K^0$  decaying to  $K_S^0$  (50%), the fraction of  $K^0$  decaying to  $\pi^+\pi^-$  (69%) and the initial number of  $B^0$   $\bar{B}^0$  pairs are taken into consideration this leads to:

$$\mathcal{B}(B^0 \rightarrow \rho^0 K^0) = (5.1 \pm 1.0 \pm 1.2) \times 10^{-6}$$

where the first error is statistical and the second systematic. The hypothesis of zero signal in the  $\rho^0$  mass region,  $600\text{MeV} - 930\text{MeV}$ , is excluded at the  $6.1\sigma$  level. Allowing as a free parameter the yield of a  $B^0 \rightarrow f_0(600)K_S^0$  contribution in the fit, discussed in Section 6, allows us to exclude the hypothesis of zero  $B^0 \rightarrow \rho^0 K_S^0$  at the  $3.5\sigma$  level.

Figure 2 shows distributions of  $\Delta E$ ,  $m_{ES}$ ,  $|\cos\theta_{\pi^+}|$  and  $m_{\pi^+\pi^-}$ , that are enhanced in signal content by cuts on the signal-to-continuum likelihood ratios of the other discriminating variables.

We performed a number of validation fits with different fit configurations to test the stability of the nominal fit; the results are consistent within errors. We made use of simulated experiments where events are generated from the PDFs for signal, continuum and  $B$  Backgrounds (toy Monte Carlo). The likelihood of our sample was found to be in good agreement with that obtained from toy Monte Carlo.

Among the additional tests we have performed are:

1. Adding  $B^0 \rightarrow \rho^0 K^0$  simulated events to data to check that the fitted yield increases with the number of added events.
2. Fitting for  $B^0 \rightarrow f_0(980)K_S^0$  and observing a yield consistent with our previous analysis [5].
3. Fits where background yields are allowed to vary: this is attempted with  $B^0 \rightarrow \eta' K_S^0$ , charged and neutral charmed  $B$  contributions and  $f_2(1270)K_S^0$ . Background yields are consistent with the estimated values used in the default fit, and signal yield does not change by a significant amount.

## 6 Systematic Uncertainty

The contributions to the systematic error on the signal yield are summarized in Table 2. To estimate the errors due to the fit procedure, we perform fits on 1000 toy Monte Carlo samples with the proportions of signal, continuum and  $B$ -background events measured from data. A bias

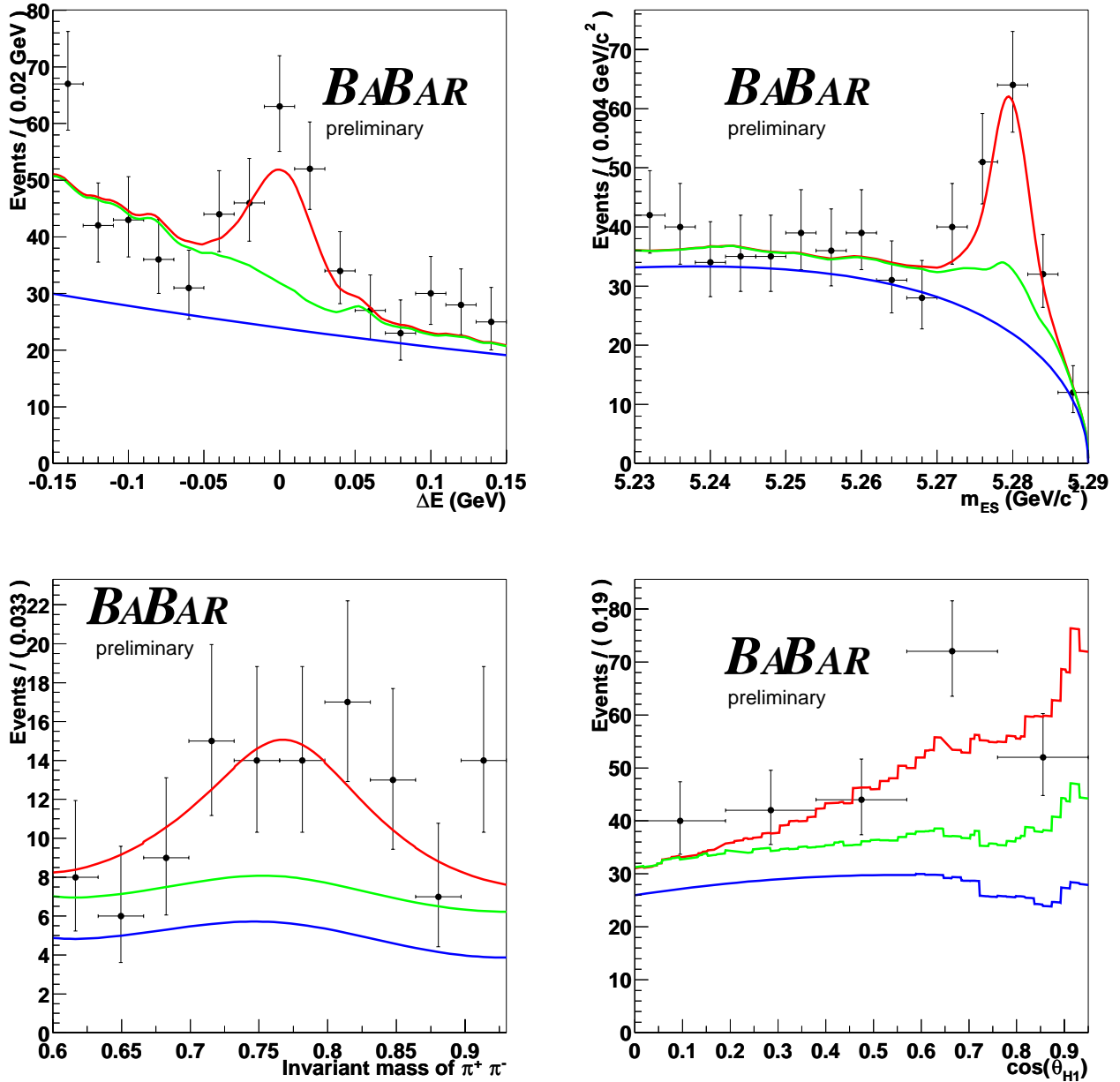


Figure 2: Projections of (clockwise from top left)  $\Delta E$ ,  $m_{ES}$ ,  $|\cos \theta(\pi^+)|$ ,  $m_{\pi^+\pi^-}$  enhanced in  $\rho^0 K_S^0$  signal through a cut on the ratio of signal to background likelihood using all discriminating variables except the one plotted. The red (upper) curve represents a projection of the maximum-likelihood fit result. The blue (lower) curve represents the contribution from continuum events, and the green line (middle) indicates the combined contributions from continuum events and  $B$  backgrounds.

Table 2: Summary of systematic uncertainties.

Error Source	Error on $BF$
Fitting Procedure	3%
$B$ -background	9%
Signal Model	4%
Q2B Approximation	4%
$f_0(600)K_S^0$	20%
Total	23%

of  $(3 \pm 1)\%$  is observed in these fits and the sum in quadrature of the bias and its error is assigned as a systematic uncertainty. We also perform similar fit tests using fully simulated signal and  $B$ -background events added in the correct proportions to toy Monte Carlo continuum events. We use this technique to pick up any biases that may escape the conventional toy test: we observe no additional statistically significant bias and hence do not add an additional systematic uncertainty.

For each class of  $B$  Background, the expected event yields are varied according to the uncertainties in the measured or estimated branching fractions, and the change in signal yield taken as a systematic.

The uncertainties due to the extraction of the signal PDFs from simulation are obtained from a control sample of fully reconstructed  $B^0 \rightarrow D^-(\rightarrow K_S^0\pi^-)\pi^+$  decays. We assume that differences in PDFs between data and Monte Carlo for this mode imply an equivalent data/Monte Carlo discrepancy in  $B^0 \rightarrow \rho^0 K_S^0$  and use them to estimate a 4% systematic error.

The systematic error introduced through the use of the quasi-two-body approximation, neglecting the interference effects between the  $\rho^0$  and the other resonances in the Dalitz plot, is estimated from simulation. We use a toy Monte Carlo technique, allowing all relative strong phases to take random values in each experiment. We take the RMS change in the signal yield as the systematic uncertainty. All  $B^0$  decays to  $\pi^+\pi^-K_S^0$  expected to provide events that pass selection cuts are included in the study, including  $f_0(980)$ ,  $f_2(1270)$ , and the  $K^{*+}\pi^-$  and higher kaon states. In addition, a non-resonant  $B^0 \rightarrow \pi^+\pi^-K_S^0$  component is included in the study. The proportion of each contribution is estimated using known exclusive measurements and the inclusive  $B^0 \rightarrow \pi^+\pi^-K_S^0$  rate.

An important systematic effect is the possible presence of  $B^0 \rightarrow f_0(600)K_S^0$ , where  $f_0(600)$  is used to denote a broad scalar contribution of ill defined width that may lie beneath the  $\rho^0$ . To determine an upper limit on the size of such an effect we perform a fit with a  $B^0 \rightarrow f_0(600)K_S^0$  contributing a yield allowed to float freely (since we do not include  $\pi\pi$  mass in this fit we make no assumption about mass distribution). We fit a yield of  $31 \pm 27$   $B^0 \rightarrow f_0(600)K_S^0$  events. We back this up by performing fits where helicity is not used as a discriminating variable in the full helicity range and in the  $|\cos(\theta_{\pi^+})| < 0.5$  regions. From the fit to the full range and the efficiency in the low helicity range (estimated from simulation) we expect 22 events in our data sample and observe  $36 \pm 12$ .

We take the difference between the default fit and a fit assuming a  $f_0(600)K_S^0$  contribution estimated from this second study as an estimate of this systematic effect. This leads to a 20% systematic uncertainty in the signal yield.

## 7 Summary

In summary, we have presented evidence for  $B^0 \rightarrow \rho^0 K_S$ . From a maximum-likelihood fit of the signal yield and efficiency estimated from Monte Carlo we measure the branching fraction  $\mathcal{B}(B^0 \rightarrow \rho^0 K^0) = (5.1 \pm 1.0 \pm 1.2) \times 10^{-6}$  where the first error is statistical and the second systematic. The hypothesis of zero signal in the  $\rho^0$  mass region, 600MeV-930MeV, is excluded at the  $6.1\sigma$  level. Floating the yield of a  $B^0 \rightarrow f_0(600)K_S^0$  contribution in the fit, discussed in Section 6, allows us to exclude the hypothesis of zero  $B^0 \rightarrow \rho K_S^0$  at the  $3.5\sigma$  level.

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