

## Measurements of branching fractions, polarizations, and direct $CP$ -violation asymmetries in $B \rightarrow \rho K^*$ and $B \rightarrow f_0(980)K^*$ decays

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We report searches for  $B$ -meson decays to the charmless final states  $\rho K^*$  and  $f_0(980)K^*$  with a sample of 232 million  $B\bar{B}$  pairs collected with the BABAR detector at the PEP-II asymmetric-energy  $e^+e^-$  collider at SLAC. We measure the following branching fractions in units of  $10^{-6}$ :  $\mathcal{B}(B^+ \rightarrow \rho^0 K^{*+}) = 3.6 \pm 1.7 \pm 0.8$  ( $< 6.1$ ),  $\mathcal{B}(B^+ \rightarrow \rho^+ K^{*0}) = 9.6 \pm 1.7 \pm 1.5$ ,  $\mathcal{B}(B^0 \rightarrow \rho^- K^{*+}) = 5.4 \pm 3.6 \pm 1.6$  ( $< 12.0$ ),  $\mathcal{B}(B^0 \rightarrow \rho^0 K^{*0}) = 5.6 \pm 0.9 \pm 1.3$ ,  $\mathcal{B}(B^+ \rightarrow f_0(980)K^{*+}) = 5.2 \pm 1.2 \pm 0.5$ , and  $\mathcal{B}(B^0 \rightarrow f_0(980)K^{*0}) = 2.6 \pm 0.6 \pm 0.9$  ( $< 4.3$ ). The first error quoted is statistical, the second systematic, and the upper limits, in parentheses, are given at the 90% confidence level. For the statistically significant modes we also measure the fraction of longitudinal polarization and the charge asymmetry:  $f_L(B^+ \rightarrow \rho^+ K^{*0}) = 0.52 \pm 0.10 \pm 0.04$ ,  $f_L(B^0 \rightarrow \rho^0 K^{*0}) = 0.57 \pm 0.09 \pm 0.08$ ,  $\mathcal{A}_{CP}(B^+ \rightarrow \rho^+ K^{*0}) = -0.01 \pm 0.16 \pm 0.02$ ,  $\mathcal{A}_{CP}(B^0 \rightarrow \rho^0 K^{*0}) = 0.09 \pm 0.19 \pm 0.02$ ,  $\mathcal{A}_{CP}(B^+ \rightarrow f_0(980)K^{*+}) = -0.34 \pm 0.21 \pm 0.03$ , and  $\mathcal{A}_{CP}(B^0 \rightarrow f_0(980)K^{*0}) = -0.17 \pm 0.28 \pm 0.02$ .

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The study of  $B$ -meson decays to charmless hadronic final states plays an important role in understanding  $CP$  violation. The charmless decays  $B \rightarrow \rho K^*$  proceed through dominant penguin loops and Cabibbo-suppressed tree processes ( $B^+ \rightarrow \rho^+ K^{*0}$  is pure penguin) to two vector particles (VV). A large longitudinal polarization fraction  $f_L$  (of order  $(1 - 4m_V^2/m_B^2) \sim 0.9$ ) is predicted for both tree and penguin dominated VV decays [1]. However, recent measurements of the pure penguin VV decays  $B \rightarrow \phi K^*$  indicate  $f_L \sim 0.5$  [2]. Several attempts to understand this small value of  $f_L$  within or beyond the Standard Model (SM) have been made [3]. Further information about  $SU(3)$ -related decays may provide some insight into this polarization puzzle. Characterization of the four  $B \rightarrow \rho K^*$  modes can also be used within the SM framework to help constrain the angles  $\alpha$  and  $\gamma$  of the Unitarity Triangle [4].

We report measurements of branching fractions, longitudinal polarizations, and direct  $CP$ -violating asymmetries for the  $B \rightarrow \rho K^*$  decay modes. We also measure branching fractions and direct  $CP$ -violating asymmetries for the  $B \rightarrow f_0(980)K^*$  modes that share the same final states. We present improved analyses of previously measured modes [5], with larger statistics and explicit consideration of non-resonant backgrounds. We measure  $B^0 \rightarrow \rho^- K^{*+}$ ,  $B^0 \rightarrow \rho^0 K^{*0}$ ,  $B^+ \rightarrow f_0(980)K^{*+}$ , and  $B^0 \rightarrow f_0(980)K^{*0}$  for the first time. Charge-conjugate modes are implied throughout.

This analysis is based on a data sample of 232 million  $B\bar{B}$  pairs, corresponding to an integrated luminosity of  $210 \text{ fb}^{-1}$ , collected with the BABAR detector [6] at the SLAC PEP-II asymmetric-energy  $e^+e^-$  collider operating at a center-of-mass (c.m.) energy  $\sqrt{s} = 10.58 \text{ GeV}$ , corresponding to the  $\mathcal{T}(4S)$  resonance mass.

The angular distribution of the  $\rho K^*$  decay products, after integrating over the angle between the decay planes of the vector mesons, for which the acceptance is uniform,

is proportional to

$$\frac{1}{4}(1 - f_L) \sin^2 \theta_{K^*} \sin^2 \theta_\rho + f_L \cos^2 \theta_{K^*} \cos^2 \theta_\rho, \quad (1)$$

where  $\theta_{K^*}$  and  $\theta_\rho$  are the helicity angles of the  $K^*$  and  $\rho$ , defined between the  $K(\pi^+)$  momentum and the direction opposite to the  $B$  in the  $K^*(\rho)$  rest frame [7]. We also measure the time-integrated direct  $CP$ -violating asymmetry  $\mathcal{A}_{CP} = (\Gamma^- - \Gamma^+)/(\Gamma^- + \Gamma^+)$ , where the superscript on the total width  $\Gamma$  indicates the sign of the  $b$ -quark charge in the  $B$  meson.

We fully reconstruct charged and neutral decay products including the intermediate states  $\rho^0$  or  $f_0(980) \rightarrow \pi^+\pi^-$ ,  $\rho^+ \rightarrow \pi^+\pi^0$ ,  $K^{*0} \rightarrow K^+\pi^-$ ,  $K^{*+} \rightarrow K^+\pi^0$ ,  $K^{*+} \rightarrow K_S^0\pi^+$  (only in  $\rho^0 K^{*+}$ ),  $\pi^0 \rightarrow \gamma\gamma$ , and  $K_S^0 \rightarrow \pi^+\pi^-$ . We assume the  $f_0(980)$  measured lineshape [8] and a branching ratio of 100% for  $f_0(980) \rightarrow \pi^+\pi^-$ . Table I lists the selection requirements on the invariant mass and helicity angle of  $B$ -daughter resonances.

TABLE I: Selection requirements on the invariant mass (in GeV) and helicity angle of  $B$ -daughter resonances.

Mode	$m_{\pi\pi}$	$m_{K\pi}$	$\cos \theta_\rho$	$\cos \theta_{K^*}$
$\rho^0 K^{*+}_{K^+\pi^0}$	(0.52,1.10)	(0.75,1.05)	(-0.95,0.95)	(-0.5,1.0)
$\rho^0 K^{*+}_{K_S^0\pi^+}$	(0.52,1.10)	(0.75,1.05)	(-0.95,0.95)	(-0.9,1.0)
$\rho^+ K^{*0}$	(0.40,1.15)	(0.77,1.02)	(-0.66,0.95)	(-0.95,1.0)
$\rho^- K^{*+}_{K^+\pi^0}$	(0.40,1.15)	(0.77,1.02)	(-0.80,0.98)	(-0.80,0.98)
$\rho^0 K^{*0}$	(0.52,1.15)	(0.77,1.02)	(-0.95,0.95)	(-0.95,1.0)

Charged tracks from the  $B$ -meson candidate are required to originate from the interaction point. Looser criteria are applied to tracks forming  $K_S^0$  candidates, for which we require  $|m_{\pi^+\pi^-} - m_{K_S^0}| < 12 \text{ MeV}$ , a measured proper decay time greater than five times its uncertainty, and the cosine of the angle between the reconstructed flight and momentum directions to exceed

0.995. Charged particle identification provides discrimination between kaons and pions, and is also used to reject electrons and protons. We reconstruct  $\pi^0$  mesons from pairs of photons, each with a minimum energy of 30 MeV ( $\rho^0 K^{*+}$ ) or 50 MeV ( $\rho^+ K^{*0}$  and  $\rho^- K^{*+}$ ). The invariant mass of  $\pi^0$  candidates is required to be within 15 MeV ( $\rho^0 K^{*+}$ ) or 25 MeV ( $\rho^+ K^{*0}$  and  $\rho^- K^{*+}$ ) of the nominal mass [9].

$B$ -meson candidates are characterized kinematically by the energy difference  $\Delta E = E_B^* - \sqrt{s}/2$  and the energy-substituted mass  $m_{\text{ES}} = [(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2 / E_i^2 - \mathbf{p}_B^2]^{1/2}$ , where  $(E_i, \mathbf{p}_i)$  and  $(E_B, \mathbf{p}_B)$  are the four-momenta of the  $\Upsilon(4S)$  and  $B$  candidate respectively, and the asterisk denotes the  $\Upsilon(4S)$  frame. Our signal lies in the region  $|\Delta E| \leq 0.1$  GeV and  $5.27 \leq m_{\text{ES}} \leq 5.29$  GeV. Sidebands in  $m_{\text{ES}}$  and  $\Delta E$  are used to characterize the continuum background. The average number of signal  $B$  candidates per selected data event ranges from 1.05 to 1.27, depending on the final state. A single candidate per event is chosen as the one with the smallest  $B$  vertex-fit  $\chi^2$  ( $\rho^+ K^{*0}$  and  $\rho^0 K^{*0}$ ), the smallest value of  $\chi^2$  constructed from deviations of reconstructed  $\pi^0$  masses from the expected value ( $\rho^- K^{*+}$ ), or randomly ( $\rho^0 K^{*+}$ ). Monte Carlo (MC) simulation shows that up to 38% (23%) of longitudinally (transversely) polarized signal events are misreconstructed with one or more tracks originating from the other  $B$  in the event.

To reject the dominant  $q\bar{q}$  continuum background we require  $|\cos\theta_T| < 0.8$ , where  $\theta_T$  is the c.m. frame angle between the thrust axes of the  $B$ -candidate and that formed from the other tracks and neutral clusters in the event. We also use as discriminant variables the polar angles of the  $B$ -momentum vector and the  $B$ -candidate thrust axis with respect to the beam axis, and the two Legendre moments  $L_0$  and  $L_2$  of the energy flow around the  $B$ -candidate thrust axis in the c.m. frame [10]. These variables are combined in a Fisher discriminant  $\mathcal{F}$  ( $\rho^0 K^{*+}$ ) or a neural network (NN) (other modes). Finally, we suppress background from  $B$  decays to charmed states by removing signal candidates that have decay products consistent with  $D^0 \rightarrow K^- \pi^+ (\pi^0)$  and  $D^- \rightarrow K^+ \pi^- \pi^-$  decays.

We use an extended (not extended in the  $\rho^+ K^{*0}$  mode) unbinned maximum-likelihood (ML) fit to extract signal yields, asymmetries, and angular polarizations simultaneously. We define the likelihood  $\mathcal{L}_i$  for each event candidate  $i$  as the sum of  $n_j \mathcal{P}_j(\vec{x}_i; \vec{\alpha})$  over hypotheses  $j$  (signal,  $q\bar{q}$  background, and several  $B\bar{B}$  backgrounds discussed below), where the  $\mathcal{P}_j(\vec{x}_i; \vec{\alpha})$  are the probability density functions (PDFs) for the measured variables  $\vec{x}_i$ , and  $n_j$  are the yields for the different hypotheses. The quantities  $\vec{\alpha}$  represent parameters in the expected distributions of the measured variables for each hypothesis. They are extracted from MC simulation and  $(m_{\text{ES}}, \Delta E)$  sideband data. They are fixed in the fit except for some shape

parameters of the continuum  $\Delta E$  and  $m_{\text{ES}}$  distributions. The extended likelihood function for a sample of  $N$  candidates is  $\mathcal{L} = \exp(-\sum n_j) \prod_{i=1}^N \mathcal{L}_i$ .

The fit input variables  $\vec{x}_i$  are  $m_{\text{ES}}$ ,  $\Delta E$ , NN or  $\mathcal{F}$ , invariant masses of the candidates  $\rho$  ( $f_0(980)$ ) and  $K^*$ , and helicity angles  $\theta_\rho$  and  $\theta_{K^*}$ . We study large control samples of  $B \rightarrow D\pi$  decays of similar topology to verify the simulated resolutions in  $\Delta E$  and  $m_{\text{ES}}$ , adjusting the PDFs to account for any difference found.

Since almost all correlations among the fit input variables are found to be small, we take each  $\mathcal{P}_j$  to be the product of the PDFs for the separate variables with the following exceptions where we explicitly account for correlations: the correlation between the two helicity angles in signal, the correlation due to misreconstructed events in signal, and the correlation between mass and helicity in backgrounds. The effect of neglecting other correlations is evaluated by fitting ensembles of simulated experiments in which we embed the expected numbers of signal and charmless  $B$ -background events, randomly extracted from fully-simulated MC samples.

We use MC-simulated events to study backgrounds from other  $B$  decays. Charmless  $B$ -backgrounds are grouped into up to 11 classes with similar topologies depending on the mode. Yields for decays with poorly known branching fractions are varied in the fit with those remaining kept fixed to their measured values. One to four additional classes account for neutral and charged  $B$  decays to final states with charm. Up to 6 classes account for misreconstructed events in signal. We also introduce components for non-resonant backgrounds such as  $\pi\pi K^*$ ,  $\rho K\pi$ ,  $f_0(980)K\pi$ , and  $f_0(1370)K\pi$ , which differ from signal only in resonance mass and helicity distributions. The magnitudes of these components are determined by extrapolating from fits performed on a wider mass range reaching to higher mass values and are fixed in the fit. Fig. 1 shows the sPlots [11] for the invariant mass of  $K\pi$  and  $\pi\pi$  in the  $\rho^+ K^{*0}$  and  $\rho^0 K^{*0}$  modes, respectively. The data events are weighted by their probability to be signal, calculated from the signal and backgrounds PDFs of the  $\Delta E$ ,  $m_{\text{ES}}$ , and NN variables.

The results of the ML fits are summarized in Table II. For the branching fractions, we assume equal production rates of  $B^+ B^-$  and  $B^0 \bar{B}^0$ . The significance  $S$  of a signal is defined by  $\Delta \ln \mathcal{L} = S^2/2$ , where  $\Delta \ln \mathcal{L}$  represents the change in likelihood from the maximal value when the number of signal events is set to zero, corrected for the systematic error defined below. We find significant signals for  $\rho^+ K^{*0}$ ,  $\rho^0 K^{*0}$ , and  $f_0(980)K^{*+}$ , and some evidence for  $f_0(980)K^{*0}$ . For the modes with significance smaller than five standard deviations we also measure the 90% confidence level (C.L.) upper limit, taking into account the systematic uncertainty. Fig. 2 shows projections of the fits onto  $m_{\text{ES}}$ .

A source of systematic error is related to the determination of the PDFs and is due to the limited statistics

TABLE II: Summary of results for the measured  $B$ -decay modes: signal yield  $n_{sig}$  and its statistical uncertainty, reconstruction efficiency  $\varepsilon$ , daughter branching fraction product  $\prod \mathcal{B}_i$ , significance  $S$  (systematic uncertainties included), measured branching fraction  $\mathcal{B}$ , (90% C.L. upper limit in parentheses), measured longitudinal polarization  $f_L$  (for the modes with non-significant signals the numbers, in brackets, are not quoted as measurements) and charge asymmetry  $\mathcal{A}_{CP}$ .

Mode	$n_{sig}$	$\varepsilon(\%)$	$\prod \mathcal{B}_i(\%)$	$S(\sigma)$	$\mathcal{B}(10^{-6})$	$f_L$	$\mathcal{A}_{CP}$
$\rho^0 K^{*+}$				2.5	$3.6_{-1.6}^{+1.7} \pm 0.8$ (6.1)	$[0.9 \pm 0.2]$	–
$\rightarrow \rho^0 K^{*+}_{K+\pi^0}$	$19_{-15}^{+16}$	7.9	32.9	1.3	$3.2_{-2.4}^{+2.7} \pm 0.9$	$[0.8_{-0.5}^{+0.3}]$	–
$\rightarrow \rho^0 K^{*+}_{K_S^0 \pi^+}$	$32_{-17}^{+19}$	15.8	22.9	2.1	$3.8_{-2.1}^{+2.2} \pm 0.9$	$[1.0 \pm 0.3]$	–
$\rho^+ K^{*0}$	$194 \pm 29$	13.5	66.7	7.1	$9.6 \pm 1.7 \pm 1.5$	$0.52 \pm 0.10 \pm 0.04$	$-0.01 \pm 0.16 \pm 0.02$
$\rho^- K^{*+}_{K+\pi^0}$	$60_{-22}^{+25}$	15.2	32.5	1.6	$5.4_{-3.4}^{+3.8} \pm 1.6$ (12.0)	$[-0.18_{-1.74}^{+0.52}]$	–
$\rho^0 K^{*0}$	$185 \pm 30$	22.9	66.7	5.3	$5.6 \pm 0.9 \pm 1.3$	$0.57 \pm 0.09 \pm 0.08$	$0.09 \pm 0.19 \pm 0.02$
$f_0(980)K^{*+}$				5.0	$5.2 \pm 1.2 \pm 0.5$	–	$-0.34 \pm 0.21 \pm 0.03$
$\rightarrow f_0(980)K^{*+}_{K+\pi^0}$	$40_{-12}^{+13}$	8.5	32.9	3.8	$6.2_{-1.9}^{+2.1} \pm 0.7$	–	$-0.50 \pm 0.29 \pm 0.03$
$\rightarrow f_0(980)K^{*+}_{K_S^0 \pi^+}$	$37_{-12}^{+14}$	16.6	22.9	3.2	$4.2_{-1.4}^{+1.5} \pm 0.5$	–	$-0.13 \pm 0.30 \pm 0.01$
$f_0(980)K^{*0}$	$83 \pm 19$	21.7	66.7	3.5	$2.6 \pm 0.6 \pm 0.9$ (4.3)	–	$-0.17 \pm 0.28 \pm 0.02$

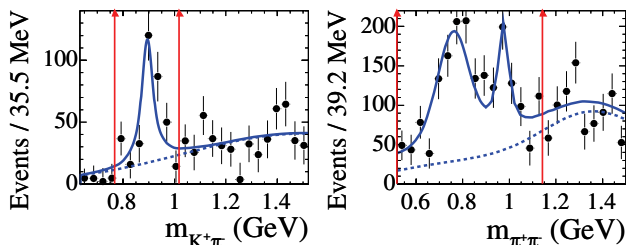


FIG. 1: sPlots for the invariant mass of  $K\pi$  in  $\rho^+ K^{*0}$  (left) and  $\pi\pi$  in  $\rho^0 K^{*0}$  and  $f_0(980)K^{*0}$  (right) up to the higher-mass regions. The points with error bars show the data, and the solid (dashed) lines show the projected PDFs of the signal and non-resonant background (non-resonant background only:  $\rho K\pi$  in  $\rho^+ K^{*0}$ ; the sum of  $f_0(1370)K^*$ ,  $\pi\pi K^*$ , and  $\pi\pi K\pi$  in  $\rho^0 K^{*0}$ ). The arrows show the nominal fit regions.

of the Monte-Carlo and to the uncertainty on the PDF shapes. We obtain variations in the yields ranging from 1 to 18%, depending on the mode. The systematic error due to the non-resonant background extrapolation and interference with signal is in the range 6–21%. Event yields for  $B$ -background modes fixed in the fit are varied by their respective uncertainties. This results in a systematic uncertainty of 2–12%. We evaluate and correct for possible fit biases with MC experiments. We assign a systematic uncertainty of 1–7% for this.

The reconstruction efficiency depends on the decay polarization. For the  $\rho^0 K^{*+}$  mode we calculate the efficiency using the measured polarization (combined for the two  $\rho^0 K^{*+}$  modes) and assign a systematic uncertainty corresponding to the total polarization measurement error (9 and 20% for each mode respectively). For the other modes we exploit the correlation between  $\mathcal{B}$  and  $f_L$  and obtain the values of  $\mathcal{B}$  from fits where  $\mathcal{B}$  and  $f_L$  are free parameters. Fig. 3 shows the behavior of  $-2 \ln \mathcal{L}(f_L, \mathcal{B})$  for the modes with significant signal.

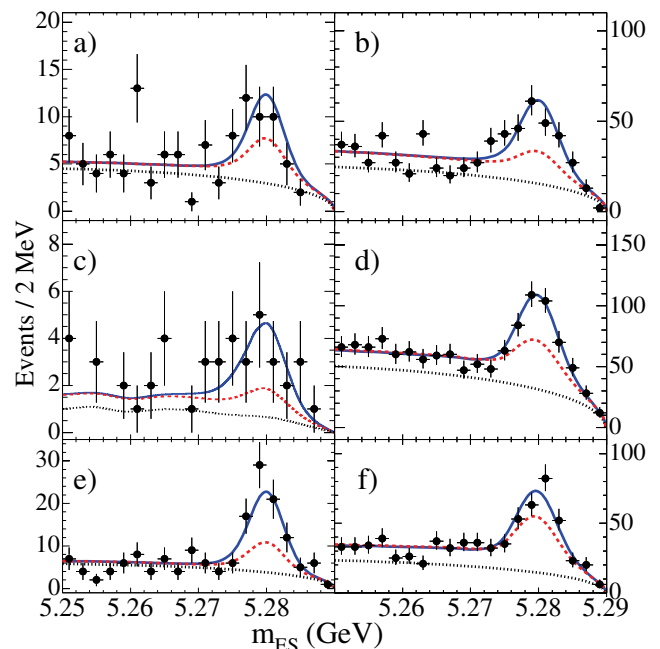


FIG. 2: Projections of the multidimensional fit onto  $m_{ES}$  for events passing a signal-to-total likelihood probability ratio cut with the plotted variable excluded for (a)  $\rho^0 K^{*+}$ , (b)  $\rho^+ K^{*0}$ , (c)  $\rho^- K^{*+}$ , (d)  $\rho^0 K^{*0}$ , (e)  $f_0(980)K^{*+}$ , and (f)  $f_0(980)K^{*0}$ . The points with error bars show the data; the solid, dashed and dotted lines show the total, background, and continuum PDF projections respectively.

Additional reconstruction efficiency uncertainties arise from tracking (3–5%), particle identification (1–2%), vertex probability (2%), track multiplicity (1%) and thrust angle (1%).  $K_S^0$  and  $\pi^0$  reconstruction contribute 2.3% and 3% uncertainty, respectively. Other minor systematic effects are from uncertainty in daughter branching fractions, MC samples statistics, and number of  $B$

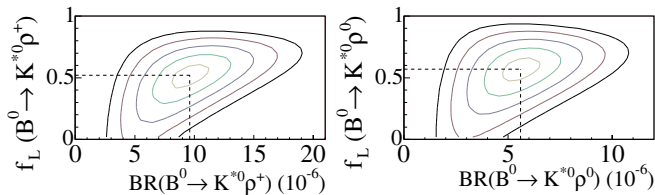


FIG. 3: Distribution of  $-2 \ln \mathcal{L}(\mathcal{B}, f_L)$  for  $B^+ \rightarrow \rho^+ K^{*0}$  (left) and  $B^0 \rightarrow \rho^0 K^{*0}$  (right) decays. The solid dots correspond to the central values and the curves give contours in  $\Delta \sqrt{-2 \ln \mathcal{L}(\mathcal{B}, f_L)} = 1$  steps.

mesons. The absolute systematic uncertainty in  $f_L$  takes into account PDF shape variations (5–10%),  $B$  and non-resonant backgrounds (4–8%), and efficiency dependence on the polarization (1–2%). The absolute uncertainty in the charge asymmetry due to track charge bias is less than 1%. PDF variations and fixed  $B$ -background effects contribute up to 2%.

In summary, we have searched for  $B \rightarrow \rho K^*$  and  $B \rightarrow f_0(980)K^*$  decays. We observe  $B^+ \rightarrow \rho^+ K^{*0}$ ,  $B^0 \rightarrow \rho^0 K^{*0}$ ,  $B^+ \rightarrow f_0(980)K^{*+}$ , and  $B^0 \rightarrow f_0(980)K^{*0}$  with 7.1, 5.3, 5.0, and 3.5  $\sigma$  significance respectively. We measure the branching fractions or 90% C.L. upper limits, the fractions of longitudinal polarization, and the charge asymmetries, summarized in Table II. The measured polarization in the  $\rho^+ K^{*0}$  and  $\rho^0 K^{*0}$  modes agrees with values measured in  $\phi K^*$  decays.

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