Measurements of Charmless Hadronic $b \to s$ Penguin Decays in the $\pi^+\pi^-K^+\pi^-$ Final State and First Observation of $B^0 \to \rho^0 K^+\pi^-$

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FIG. 1: Feynman diagrams for charmless hadronic $B^0$ decays pertaining to $B^0 \rightarrow \rho^0 K^{*0}$. (a) $b \rightarrow s$ penguin diagram, (b) $b \rightarrow u$ tree diagram.

We report measurements of charmless hadronic $B^0$ decays into the $\pi^+\pi^-K^+\pi^-$ final state. The analysis uses a sample of $657 \times 10^6 \overline{B}B$ pairs collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider at the $\Upsilon(4S)$ resonance. The decay $B^0 \rightarrow \rho^0 K^+\pi^-$ is observed for the first time; the significance is $5.0\sigma$ and the corresponding partial branching fraction for $M_{K\pi} \in (0.75, 1.20) \text{ GeV}/c^2$ is $[2.8 \pm 0.5(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-6}$. We also obtain the first evidence for $B^0 \rightarrow f_0(980)K^+\pi^-$ with $3.5\sigma$ significance and for $B^0 \rightarrow \pi^+\pi^-K^{*0}$ with $4.5\sigma$ significance. For the two-body decays $B^0 \rightarrow \rho^0 K^{*0}$ and $B^0 \rightarrow f_0(980)K^{*0}$, the significances are $2.7\sigma$ and $2.5\sigma$, respectively, and the upper limits on the branching fractions are $3.4 \times 10^{-6}$ and $2.2 \times 10^{-6}$ at 90\% confidence level.

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In the Standard Model (SM), charmless hadronic $B$ meson decays occur mainly via two processes: (i) $b \rightarrow sq\bar{q}$ transitions mediated by penguin diagrams, and (ii) $b \rightarrow uW^*$ transitions mediated by tree diagrams. These diagrams as they pertain to $B^0 \rightarrow \rho^0 K^{*0}$ [4], for example, are shown in Fig. 1. Both of these processes are suppressed relative to the more common $b \rightarrow c\bar{c}$ decays due to either (i) the one-loop structure or (ii) the small ratio of CKM matrix elements $|V_{ub}/V_{cb}|$, respectively. Because of this suppression, these decays are especially sensitive to non-SM contributions [3].

There have been several puzzling results from measurements of charmless hadronic $B$ decays. For example, $B$ decays to $K^+\pi^-$ and $K^-\pi^0$ show different patterns of direct $CP$ violation [4], which are inconsistent with naive SM expectations. It has been suggested [5] that vector-vector ($VV$) final states with the same quark combinations, e.g. $B \rightarrow \rho K^*$ may give insights to this puzzle, as any difference between $K\pi$ and their $VV$ counterparts will be mainly hadronic. In addition, charmless $B$ decays to $VV$ final states show intriguing results in the final-state polarizations. The decays $B \rightarrow \phi K^*$ and $B \rightarrow \rho K^*$, both occurring mostly via the $b \rightarrow s$ penguin process, are found to have large transverse polarizations [4, 7, 8], in contrast to the expectation from factorization. On the other hand, $B^{+(0)} \rightarrow \rho^+\rho^0(-)$, which is mostly a $b \rightarrow uW^*$ tree-diagram process, is almost fully polarized longitudinally [4]. There have been theoretical [5, 10] studies of these modes, in part focusing on the final-state polarizations within and beyond the SM.

One difficulty in measuring charmless $B \rightarrow VV$ decays, however, is that non-resonant decays to the same final state can be a significant background [11]. Such non-resonant decays may have different decay properties, e.g., different polarization of the vector mesons. While there are several experimental studies of $B^0$ decays to the $\pi^+\pi^-K^+\pi^-$ final state [7, 12], there is no experimental information on the non-resonant components of these final states.

In this paper, we analyze charmless hadronic decays of $B^0$ to the $\pi^+\pi^-K^+\pi^-$ final state. We search for two-body final states such as $B^0 \rightarrow \rho^0 K^{*0}$ and $f_0(980)K^{*0}$, and also for three-body states $\rho^0 K^+\pi^-$, $f_0(980)K^+\pi^-$, and $\pi^+\pi^-K^{*0}$, where the $\pi^+\pi^-$ or $K^+\pi^-$ pairs are non-resonant. A comprehensive understanding of these decays with a clear distinction between non-resonant and two-body resonant decays would advance our understanding of strong and weak interaction dynamics.

We use a data sample containing $657 \times 10^6 \overline{B}B$ pair events collected with the Belle detector [14] at the KEKB [15] asymmetric-energy $e^+e^-$ collider (3.5 on 8 GeV), operating at the $\Upsilon(4S)$ resonance. To reconstruct $B^0 \rightarrow \pi^+\pi^-K^+\pi^-$ decays including the in-
termediate states $\rho^0 \rightarrow \pi^+\pi^-$, $f_0(980) \rightarrow \pi^+\pi^-$, and $K^{*0} \rightarrow K^+\pi^-$, we select four charged tracks of which two are positively charged and two are negatively charged. Each track is required to originate within 5.0 cm of the interaction point (IP) along the beam direction, and within 0.2 cm of the IP in the transverse plane [8]. We also require that the transverse momentum of each track be larger than 0.1 $\text{GeV}/c$ [8]. Tracks identified as electrons are rejected. We identify charged kaons and pions by combining particle identification (PID) information obtained from the central drift chamber, the time-of-flight system, and the aerogel Cherenkov counters [16].

Signal candidates are selected for further analysis based on four kinematic variables: the $\pi^+\pi^-$ and $K^+\pi^-$ invariant masses ($M_{\pi\pi}$ and $M_{K\pi}$), the energy difference $\Delta E \equiv E_B - E_{\text{beam}}$, and the beam-energy-constrained mass $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$, where $E_{\text{beam}}$ is the beam energy and $E_B$ and $p_B$ are the energy and momentum, respectively, of the candidate $B$-meson. These variables are all evaluated in the $Y(4S)$-center-of-mass (CM) frame. We retain events satisfying $|\Delta E| < 0.1 \text{ GeV}$, $5.24 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$, $0.55 \text{ GeV}/c^2 < M_{\pi\pi} < 1.20 \text{ GeV}/c^2$ and $0.75 \text{ GeV}/c^2 < M_{K\pi} < 1.20 \text{ GeV}/c^2$. To optimize the background suppression criteria, tighter “signal regions” are defined for $M_{bc}$ and $\Delta E$: $5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $|\Delta E| < 0.045 \text{ GeV}$. The fraction of events having multiple candidates is approximately 20%. For multiple-candidate events, we select the candidate decay having the smallest $\chi^2$ from the $B$ vertex fit. Given a set of four particles, $\pi^+\pi^-K^+\pi^-$, two combinations of $(\pi^+\pi^-)$ and $(K^+\pi^-)$ may lie inside the selected mass ranges. In this case, which occurs in less than 1% of signal decays, we pair the higher-momentum $\pi^-$ with the $\pi^+$. The dominant source of background is from continuum $e^+e^- \rightarrow q\bar{q}$ events ($q = u, d, s, c$). These events are distinguished from the signal by their event shape. Since $B$ mesons are spinless and produced nearly at rest in the CM frame, their daughter particles are distributed almost isotropically. On the other hand, continuum events usually produce two back-to-back jets in the CM frame. We use Monte Carlo (MC) simulated [17] signal events and sideband data ($5.20 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$) for optimizing the continuum suppression requirements. First we form a Fisher discriminant $\mathcal{F}$ based on a set of modified Fox-Wolfram moments [18]. These moments are uncorrelated with the four kinematical variables mentioned above. Two more variables are used for continuum suppression: $\cos \theta_B$, the cosine of the polar angle of the $B$ flight direction in the CM frame; and $\Delta z$, the displacement along the beam direction between the vertex of the signal $B$ and that of the other $B$ in the event. Likelihood functions for signal ($\mathcal{L}_s$) and continuum background ($\mathcal{L}_{q\bar{q}}$) are formed from products of the probability density functions (PDFs) for $\mathcal{F}$, $\cos \theta_B$, and $\Delta z$. These are combined into a likelihood ratio $\mathcal{R}_{q\bar{q}} = \mathcal{L}_s / (\mathcal{L}_s + \mathcal{L}_{q\bar{q}})$. To obtain improved continuum suppression, we optimize the requirement on $\mathcal{R}_{q\bar{q}}$ as a function of flavor-tagging information from the accompanying $B$ meson. The Belle flavor-tagging algorithm [19] yields the $b$-flavor variable $q$ ($= \pm 1$), and the quality variable $r$. The latter ranges from zero for no flavor discrimination to one for unambiguous flavor assignment. We optimize the $\mathcal{R}_{q\bar{q}}$ requirement independently in six bins of $qr$. For $B^0 \rightarrow \rho^0 K^{*0}$, for example, the optimized $\mathcal{R}_{q\bar{q}}$ requirements remove 99% of the $q\bar{q}$ background while retaining 42% of the signal.

$B$ decays to a charm meson ($D^0$ or $D^{(*)+}$) and multiple pions constitute a significant background that exhibits peaking behavior in $M_{bc}$ and $\Delta E$ similar to that of the signal. To eliminate this background, we veto candidates that have a $K\pi\pi$, $\pi\pi$, or $\pi\pi$ invariant mass consistent with a $D^{(*)+} \rightarrow K^-\pi^+\pi^+$, $D^0 \rightarrow K^-\pi^+$, and $D^0 \rightarrow \pi^-\pi^+$ decay, respectively.

The signal yields are obtained from a four-dimensional extended unbinned maximum-likelihood [20] fit (4D fit) to $M_{bc}$, $\Delta E$, $M_{\pi\pi}$ and $M_{K\pi}$. The likelihood function is

$$\mathcal{L} = \frac{\exp(-\sum Y_j)}{N!} \prod_{i=1}^{N} Y_j \mathcal{P}^j_i,$$

where $Y_j$ is the yield of the $j$-th component, $\mathcal{P}^j_i$ is the PDF value for the $j$-th component of the $i$-th event, and $i$ runs over all events in the fit region ($N$). We include 13 components in Eq. (1): $B^0$ decays to $\rho^0 K^{*0}$, $f_0(980)K^{*0}$, and $f_2(1270)K^{*0}$; the non-resonant components $\rho^0 K^+\pi^-$, $f_0(980)K^+\pi^-$, $\pi^+\pi^- K^{*0}$, and $\pi^+\pi^- K^+\pi^-$; the feed-down components $a_1(1260)K^+$, $K^+_1(1270)\pi^-$, and $K^0_s(1400)\pi^-$; and background components from $q\bar{q}$ continuum ($q\bar{q}$), charm $B$-decays ($b \rightarrow c$), and charmless $B$-decays ($b \rightarrow s, u, d$).

The PDFs for the signal are separated into two categories: correctly reconstructed events and self-cross-feed (SCF) events. The SCF events include at least one track that is taken from the accompanying $B$ meson decay. For correctly reconstructed events, a sum of two Gaussians with a common mean is used for the $M_{bc}$ and $\Delta E$ shapes. The $M_{\pi\pi}$ and $M_{K\pi}$ distributions are modeled by relativistic Breit-Wigner functions. The $\rho^0$, $f_2(1270)$ and $K^{*0}$ resonance parameters are fixed to their PDG values [21]. Parameters of the $f_0(980)$ resonance shape are fixed to the results of Ref. [22]; these values have higher precision than the corresponding PDG values. PDFs for the SCF components are modeled using Kernel Estimation (KDE) of SCF MC distributions. For the $M_{\pi\pi}$ and $M_{K\pi}$ PDFs of non-resonant components, a threshold function and/or Chebyshev polynomials are used. The $M_{bc}$ and $\Delta E$ shapes for the signal PDFs are calibrated using a large $B^0 \rightarrow D^-\pi^+$, $D^- \rightarrow K^-\pi^-\pi^-$ control sample, to take into account small differences observed between MC-simulated events and data.

The PDF shape of the $q\bar{q}$ background are modeled with an ARGUS [24] function for $M_{bc}$, linear functions...
for $\Delta E$, and combinatorial shapes for $M_{\pi\pi}$ and $M_{K\pi}$. For $b \rightarrow c$ background, the PDFs are obtained separately for correctly reconstructed $K^{*0}$ and for random $K$ combinations. The fraction of each component is fixed from the MC simulation. The PDF shapes for $b \rightarrow s,u,d$ background are modeled with non-parametric PDFs using Kernel Estimation [23].

The following parameters are floated in the 4D fit: the yields of the signal modes (given in Table I) and background yields of $b \rightarrow c$ and $q\bar{q}$; the parameters of the $q\bar{q}$ PDF describing the $M_{bc}$, $\Delta E$ and combinatorial shapes of $M_{\pi\pi}$ and $M_{K\pi}$. The branching fractions of the feed-down components are fixed to the results of Ref. [23]. The yield of $f_2(1270)K^{*0}$ is fixed to 43.0 events as obtained from two-dimensional $M_{bc}-\Delta E$ fitting in bins of $M_{\pi\pi}$ as discussed later. The remaining parameters are fixed to values obtained from MC simulations.

The fit projections are shown in Fig. 2 and the results are summarized in Table I. There are moderate correlations between some modes, which we check by fitting an ensemble of GEANT-simulated MC samples. We find a negligible effect on the measured signal yields. The branching fraction of each mode is determined by

$$B = Y/(\varepsilon_{MC}\varepsilon_{PID}N_{B\bar{B}}),$$

where $Y$ is the fitted signal yield, $\varepsilon_{MC}$ is the event selection efficiency including daughter branching fractions as obtained from MC simulation and $\varepsilon_{PID}$ is an efficiency correction ($\varepsilon_{PID}=0.96$) for PID that accounts for small differences between MC and data. The production rates of $B^0\bar{B}^0$ and $B^+\bar{B}^-$ pairs are assumed to be equal.

The fit yields the first observation for $B^0 \rightarrow \rho^0 K^{+}\pi^-$ with a significance of $5.0\sigma$. The significance is defined as

$$\sqrt{-2\ln(L_0/L_{max})},$$

where $L_0$ ($L_{max}$) is the value of the likelihood function when the yield is fixed to zero (allowed to vary). We include systematic uncertainties by smear- ing the likelihood function with a Gaussian whose width is equal to the systematic uncertainty (discussed below). We also find evidence for $B^0 \rightarrow f_0(980)K^{+}\pi^-$ with a significance of $3.5\sigma$, and evidence for $B^0 \rightarrow \pi^{+}\pi^{-}K^{*0}$ with a significance of $4.5\sigma$. For $B^0 \rightarrow \rho^0 K^{*0}$ and $B^0 \rightarrow f_0(980)K^{*0}$, we observe excesses of events with significances of $2.7\sigma$ and $2.5\sigma$, respectively. For the non-resonant decay components, the $B$ and $\varepsilon_{MC}$ values correspond to the ranges $M_{K\pi} \in (0.75, 1.20)$ GeV/c$^2$, $M_{\pi\pi} \in (0.55, 1.20)$ GeV/c$^2$, and assume three-body phase space distributions. For modes with less than $3\sigma$ significance, we also list a $90\%$ confidence level (C.L.) upper limit. This limit is determined via

$$\int_0^{B_{UL}} L(B)dB / \int_0^{\infty} L(B)dB = 90\%.$$  (2)

The sources and sizes of systematic uncertainties in

### Table I: The signal yield $Y$ and its statistical uncertainty, corrected MC efficiency $\varepsilon$ (assuming $f_L = 0.5$ for $B^0 \rightarrow \rho^0 K^{*0}$), significance $S$ including the systematic uncertainties, measured branching fraction $B$ and the upper limit (UL) at the $90\%$ confidence level $B_{UL}$. For non-resonant decay components, $\varepsilon$, $B$ and $B_{UL}$ are obtained for $M_{K\pi} \in (0.75, 1.20)$ GeV/c$^2$ and $M_{\pi\pi} \in (0.55, 1.20)$ GeV/c$^2$ assuming phase space distributions. For the branching fraction, the first (second) uncertainty is statistical (systematic).

| Mode          | $Y$ (events) | $Y$ (%) | $\varepsilon$ (%) | $S$ (\(\sigma\)) | $B$ (10$^{-6}$) | $B_{UL}$ (10$^{-6}$) |
|---------------|--------------|---------|-------------------|-------------------|----------------|---------------------|
| $\rho^0 K^{*0}$ | 77.6$^{+28.8}_{-27.9}$ | 5.73 | 2.7 | 2.1$^{+0.9+0.9}_{-0.7-0.5}$ | $<3.4$ | - |
| $f_0(980)K^{*0}$ | 51.2$^{+20.4}_{-19.3}$ | 5.56 | 2.5 | 1.4$^{+0.6+0.6}_{-0.5-0.4}$ | $<2.2$ | - |
| $\rho^0 K^{+}\pi^-$ | 207.8$^{+39.8}_{-39.2}$ | 11.15 | 5.0 | 2.8$^{+0.5+0.5}_{-0.5-0.5}$ | - | - |
| $f_0(980)K^{+}\pi^-$ | 106.9$^{+31.6}_{-29.9}$ | 11.43 | 3.5 | 1.4$^{+0.4+0.4}_{-0.5-0.4}$ | $<2.1$ | - |
| $\pi^{+}\pi^{-}K^{*0}$ | 200.7$^{+46.7}_{-44.9}$ | 6.74 | 4.5 | 4.5$^{+1.1+1.1}_{-1.0-1.0}$ | - | - |
| $\pi^{+}\pi^{-}K^{+}\pi^-$ | $-5.4^{+54.9}_{-44.9}$ | 6.84 | 0.0 | $-0.1^{+1.2+1.2}_{-1.1-1.1}$ | $<2.1$ | - |

### Table II: Summary of systematic uncertainties (%) in the efficiency ($\varepsilon$) determination.

| Source | $\rho K^*$ | $f K^*$ | $\rho K\pi$ | $f K\pi$ | $\pi\pi K^*$ | $\pi\pi K\pi$ |
|--------|------------|---------|-------------|---------|-------------|-------------|
| MC statistics | $\pm 0.5$ | $\pm 0.7$ | $\pm 1.3$ | $\pm 1.7$ | $\pm 1.3$ | $\pm 2.1$ |
| Tracking | $\pm 4.2$ | $\pm 4.2$ | $\pm 4.2$ | $\pm 4.2$ | $\pm 4.2$ | $\pm 4.2$ |
| PID | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.7$ | $\pm 3.8$ | $\pm 3.8$ | $\pm 3.7$ |
| $R_{q\bar{q}}$ cut | $\pm 3.4$ | $\pm 3.4$ | $\pm 3.4$ | $\pm 3.4$ | $\pm 3.4$ | $\pm 3.4$ |
| $N_{q\bar{q}}|_{B\bar{B}}$ | $\pm 1.4$ | $\pm 1.4$ | $\pm 1.4$ | $\pm 1.4$ | $\pm 1.4$ | $\pm 1.4$ |
| $f_L$ | $\pm 1.6$ | $\pm 1.6$ | $\pm 1.6$ | $\pm 1.6$ | $\pm 1.6$ | $\pm 1.6$ |
| Sum | $\pm 20.1$ | $\pm 6.7$ | $\pm 6.8$ | $\pm 7.0$ | $\pm 6.9$ | $\pm 7.0$ |
TABLE III: Summary of systematic uncertainties (events) in the signal yield ($Y$) extraction.

| Source                          | $pK^*$ | $fK^*$ | $\rho K\pi$ | $fK\pi$ | $\pi\pi K^*$ | $\pi\pi K\pi$ |
|--------------------------------|--------|--------|-------------|--------|--------------|---------------|
| Fitting PDFs                   | $+6.4$ | $+12.7$| $+5.5$      | $+24.1$| $+35.1$      | $+32.4$       |
| $f_{f(1270)K^{*0}}$            | $+11.0$| $+5.9$ | $+0.3$      | $+3.3$ | $+3.9$      | $+3.0$       |
| $f_{\text{feed-down}}$         | $-11.3$| $-6.4$ | $-0.3$      | $-13.7$| $-35.4$      | $-35.4$       |
| $f_{s,u,d}$                    | $-1.4$ | $-0.1$ | $-1.5$      | $-3.8$ | $-1.9$      | $-1.9$       |
| $f_{\text{CF}}$               | $+2.1$ | $+1.2$ | $+19.9$     | $+7.4$ | $+8.2$      | $+11.8$      |
| $f_{K_0^0(1430)}^0$            | $+12.4$| $+7.3$ | $+8.3$      | $+11.4$| $+11.4$      | $+11.4$      |
| Fitting bias                   | $-1.9$ | $-0.1$ | $+7.0$      | $+0.0$ | $+3.7$      | $+3.7$       |
| Interference                   | $-1.9$ | $-0.1$ | $+7.0$      | $+0.0$ | $+3.7$      | $+3.7$       |
| Sum                            | $+31.5$| $+20.5$| $+34.8$     | $+25.6$| $+35.5$      | $+76.2$      |

The efficiency determination and the yield extraction are summarized in Tables I and III respectively. The main sources of efficiency uncertainties are tracking (4.2%), PID (3.7%–3.8%), MC sample statistics (0.5%–2.1%) and the $R_{\bar{q}q}$ requirement (3.4%). Table I also includes the uncertainty from $N_{BB}$ (1.4%). While this does not affect the efficiency determination, it leads to a multiplicative uncertainty in $B$. An additional uncertainty in the efficiency for $B^0 \to \rho^0 K^{*0}$ arises from the unknown fraction of longitudinal polarization ($f_L$). For our central value, we take $f_L = 0.5$ and estimate the uncertainty by considering the two extreme cases $f_L = 0$ and $f_L = 1$. The systematic uncertainties in the yield extraction are obtained by varying all fixed parameters of the PDFs by $\pm 1\sigma$, feed-down yields by $\pm 3\sigma$, and the fractions of SCF and $b \to s, u, d$ backgrounds by $\pm 50\%$, respectively. We consider the effects of higher $K^{*0}$ resonances by including a PDF for $B^0 \to \rho^0 K_0^0(1430)$ and repeating the 4D fit with its yield floated by extending the fitting region in $M_{K\pi}$ to 1.5 GeV/$c^2$; the resulting changes are included as a systematic uncertainty.

We study the effects of possible interference among $\rho^0$, $f_0(980)$, $f_2(1270)$, and non-resonant $\pi^+\pi^-\pi^0$ modes by including interference terms with variable phases in the $M_{\pi\pi}$ relativistic Breit-Wigner function. The effect is estimated by refitting with this modified PDF; the resulting shifts in the yields are included in the systematic uncertainties. We obtain the systematic uncertainty due to possible interference between $K^{*0}$, $K_0^0(1430)$, and non-resonant $K^+\pi^-$ in the $M_{K\pi}$ mass spectrum in a similar manner. Uncertainties due to possible fitting bias are determined using a large sample of MC-simulated events. We assign the small biases found in the MC simulation as systematic uncertainties.

To verify the large contribution from non-resonant components (see Table I), we study background-subtracted $M_{\pi\pi}$ and $M_{K\pi}$ spectra. These spectra are obtained by binning the data in $M_{\pi\pi}$ or $M_{K\pi}$ and, for each bin, fitting the two-dimensional $M_{bc}$-$\Delta E$ distribution to determine the sum of resonant and non-resonant yields. Figure 2 shows these yields as a function of $M_{\pi\pi}$ and $M_{K\pi}$. Relativistic Breit-Wigner functions are used as PDF’s for the resonances with their parameters fixed to their PDG values [21]. The PDFs for the non-resonant contributions are modeled by threshold functions using MC-simulated events.

In summary, we have made the first observation of the three-body decay $B^0 \to \rho^0 K^{*0} \pi^0$ with $5.0\sigma$ significance and obtained the first evidence for non-resonant $B^0 \to f_0(980)K^{*0} \pi^-$ and $B^0 \to \pi^+\pi^-K^{*0}$ decays. The corresponding partial branching fractions are measured. For the $B^0 \to \rho^0 K^{*0}$ and $B^0 \to f_0(980)K^{*0}$ modes, we find approximately $2.6\sigma$ signal excesses and obtain the results listed in Table I. Our result for these two-body decays are $2\sigma$ and $1\sigma$ lower, respectively, than in the previous measurement [9]. We have also searched for the fully non-resonant four-body decay $B^0 \to \pi^+\pi^-K^{*0}\pi^-$ and calculated a 90% C.L. upper limit on its partial branching fraction. Our results for the non-resonant modes are the first such results and may help us understand the polarization puzzle in $pK^*$ decays. With additional $B \to VV$ data, these measurements can be used to constrain models of new physics [20].

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FIG. 3: Signal yields obtained from the two-dimensional fits to $M_{\rho\pi}$ and $\Delta E$ in bins of $M_{\pi\pi}$ (left) and $M_{K\pi}$ (right) up to the higher-mass regions. Solid curves show the results of the two-dimensional binned fit, and dashed curves show the contributions of non-resonant $\pi^+\pi^-$ (left) and the sum of non-resonant $K^+\pi^-$ and $K_0^0(1430)^0$ (right). The vertical lines show the nominal 4D fit regions.
Throughout this paper, charge-conjugate processes are implied unless explicitly stated otherwise.

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