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Measurements of the branching fractions of charged B decays to $K^\pm \pi^\mp \pi^\pm$ final states

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We present results of searches for B -meson decays to $K^+ \pi^- \pi^+$ with the BABAR detector. With a data sample of 61.6×10^6 $B\bar{B}$ pairs, we measure the branching fractions and 90% confidence-level upper

limits averaged over charge-conjugate states (the first error is statistical and the second is systematic): $\mathcal{B}[B^+ \rightarrow K^{*0}(892)\pi^+] = (15.5 \pm 1.8_{-4.0}^{+1.5}) \times 10^{-6}$, $\mathcal{B}[B^+ \rightarrow f_0(980)K^+, f_0 \rightarrow \pi^+\pi^-] = (9.2 \pm 1.2_{-2.6}^{+2.1}) \times 10^{-6}$, $\mathcal{B}[B^+ \rightarrow \bar{D}^0\pi^+, \bar{D}^0 \rightarrow K^+\pi^-] = (184.6 \pm 3.2 \pm 9.7) \times 10^{-6}$, $\mathcal{B}[B^+ \rightarrow \rho^0(770)K^+] < 6.2 \times 10^{-6}$ and $\mathcal{B}[B^+ \rightarrow K^+\pi^-\pi^+ \text{ nonresonant}] < 17 \times 10^{-6}$.

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The study of charmless hadronic B decays can make important contributions to our understanding of hadronic decays and CP violation in the standard model [1]. Branching fraction predictions for B meson decays to Pseudoscalar-Vector final states have recently been calculated using QCD Factorization and SU(3) flavor symmetry models [2–4]. The measurement of B^+ meson [5] decays to the final state $K^+\pi^-\pi^+$ via intermediate resonances can be used to search for weak phases and direct CP violation. The signal can be used to examine the light-meson mass spectrum [6,7]. The charm state χ_{c0} might be sensitive to the angle γ of the Unitarity Triangle through interference with the nonresonant component producing an observable charge asymmetry [8]; the branching fraction also constrains some models for charmonium hybrid production [9].

The data used in this analysis were collected at the PEP-II asymmetric e^+e^- storage ring with the BABAR detector [10]. The BABAR detector consists of a five-layer silicon tracker, a drift chamber, a new type of Cherenkov detector [11], an electromagnetic calorimeter and a magnet with instrumented flux return. The data sample has an integrated luminosity of 56.4 fb^{-1} collected at the $\Upsilon(4S)$ resonance, which corresponds to $(61.6 \pm 0.7) \times 10^6 B\bar{B}$ pairs ($N_{B\bar{B}}$). We assume that the $\Upsilon(4S)$ decays equally to neutral and charged B meson pairs.

The $K^+\pi^-\pi^+$ phase space can be represented in a Dalitz plot, in which the many resonant B decay modes form overlapping bands and interference occurs where the bands overlap [12]. As a consequence, the whole Dalitz plot should be considered before assigning a branching fraction to a specific mode. However, the data sample is not large enough for a full Dalitz plot fit to be effective. In this analysis, the Dalitz plot is divided into eight regions, reflecting as much as possible the known decay modes. We first determine the yields in these regions using a maximum-likelihood fit. We then interpret the yields as branching fractions, assuming a particular collection of quasi-two-body decay modes. We evaluate the systematic uncertainty due to the particular choice of decay modes and the effect of interference between the different contributions.

The regions are defined in $m_{K\pi}$ and $m_{\pi\pi}$, the invariant masses of the neutral $K\pi$ and $\pi\pi$ systems, as given in Table I and illustrated in Fig. 1. Region I is expected to be dominated by $K^{*0}(892)\pi^+$. Region II could have contributions from several higher K^* resonances. Region III is dominated by the production of $\bar{D}^0\pi^+$. The high branch-

ing fraction for this mode allows it to be used to correct for differences between data and simulated events and to evaluate systematic uncertainties. Regions IV and V are expected to be dominated by $\rho^0(770)K^+$ and $f_0(980)K^+$, respectively. The resonance contributions to Region VI are not known *a priori*. The area where these regions intersect the \bar{D}^0 band, $1.8 < m_{K\pi} < 1.9 \text{ GeV}/c^2$, is excluded. Region VII could contain higher mass charmless and charmonium resonances, as well as a nonresonant contribution that extends across the whole Dalitz plot. Region VIII is dominated by $\chi_{c0}K^+$. This channel is vetoed from other regions using $3.355 < m_{\pi\pi} < 3.475 \text{ GeV}/c^2$.

Candidate B mesons are formed by combining three charged tracks, where each track is required to have at least 12 hits in the drift chamber, to have transverse momentum of at least 100 MeV/ c and to be consistent with originating from the beam-spot. Charged pions and kaons are identified using energy loss (dE/dx) measured in the tracking system and the Cherenkov angle and number of photons measured by the Cherenkov detector. Pions are required to fail the kaon selection. The efficiency of selecting kaons is approximately 80%, while the probability of misidentifying pions as kaons is below 5%, up to a laboratory momentum of 4.0 GeV/ c . Pions are also required to fail an electron selector which uses dE/dx , the energy to momentum ratio and the shape of the calorimeter signal. Over 99% of pions from the signal decay pass this requirement.

Signal decays are identified using two kinematic variables: ΔE , the difference between the center-of-mass

TABLE I. Regions of the $K^+\pi^-\pi^+$ Dalitz plot and signal yields obtained (the first error is statistical and the second is systematic). The \bar{D}^0 band, $1.8 < m_{K\pi} < 1.9 \text{ GeV}/c^2$, is excluded from all regions except Region III, and the χ_{c0} band, $3.355 < m_{\pi\pi} < 3.475 \text{ GeV}/c^2$, is excluded from all regions except Region VIII.

Region	Selection Criteria (GeV/c^2)	Signal Yield
I	$0.816 < m_{K\pi} < 0.976, m_{\pi\pi} > 1.5$	$161 \pm 18 \pm 4$
II	$0.976 < m_{K\pi} < 1.8, m_{\pi\pi} > 1.5$	$405 \pm 28 \pm 13$
III	$1.835 < m_{K\pi} < 1.895$	$3755 \pm 66 \pm 11$
IV	$0.6 < m_{\pi\pi} < 0.9$	$66 \pm 15_{-7}^{+3}$
V	$0.9 < m_{\pi\pi} < 1.1$	$179 \pm 19 \pm 5$
VI	$1.1 < m_{\pi\pi} < 1.5$	$126 \pm 19 \pm 5$
VII	$m_{K\pi} > 1.9, m_{\pi\pi} > 1.5$	$133 \pm 23_{-22}^{+9}$
VIII	$m_{K\pi} > 1.9, 3.37 < m_{\pi\pi} < 3.46$	$26 \pm 6 \pm 1$

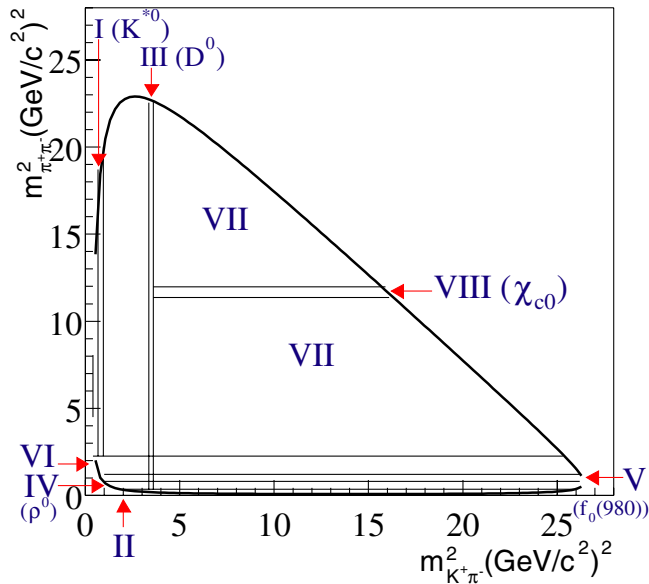


FIG. 1 (color online). A Dalitz plot showing the defined regions.

(CM) energy of the B candidate and $\sqrt{s}/2$, where \sqrt{s} is the total CM energy; and the beam-energy-substituted mass $m_{ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, where \mathbf{p}_B is the momentum of the reconstructed B candidate and (E_i, \mathbf{p}_i) is the four-momentum of the initial e^+e^- system. The ΔE and m_{ES} distributions for signal events have widths of 20 MeV and 2.7 MeV/ c^2 , respectively. We require $5.22 < m_{ES} < 5.29$ GeV/ c^2 and $|\Delta E| < 0.1$ GeV for events entering the fit. Events with $0.1 < |\Delta E| < 0.3$ GeV are used for continuum background characterization as described below.

A very small proportion of events, fewer than 4%, have two or more candidates that pass the above requirements. For these events a single candidate is selected at random, so as not to bias the fit distributions. This random selection has a minimal impact on the efficiency, and any systematic uncertainty due to this effect is negligible. A single candidate per event is similarly selected for the data with $0.1 < |\Delta E| < 0.3$ GeV used in continuum background characterization.

Continuum light-quark and charm production is the dominant source of background. This is suppressed using two event-shape variables. The first is the cosine of the angle θ_T between the thrust axis of the selected B candidate and the thrust axis of the rest of the event. For continuum background, the distribution of $|\cos\theta_T|$ is strongly peaked towards unity whereas the distribution is uniform for signal events. We require $|\cos\theta_T| < 0.9$. The second event-shape variable is a Fisher discriminant (\mathcal{F}) [13]. For \mathcal{F} we use a linear combination of the cosine of the angle between the B -candidate momentum and the beam axis, the cosine of the angle between the B -candidate thrust axis and the beam axis, and the energy

flow of the rest of the event into each of nine contiguous, concentric, 10° cones around the thrust axis of the reconstructed B [14].

There are also B -decay backgrounds, mainly four-body decays, and three-body decays with one or more particles misidentified. These backgrounds are studied using Monte Carlo simulations (MC). They are reduced by the particle identification selections and by excluding events containing J/ψ or $\psi(2S)$ decays to l^+l^- with vetoes $2.97 < m_{\pi\pi} < 3.17$ GeV/ c^2 and $3.56 < m_{\pi\pi} < 3.76$ GeV/ c^2 , however some B -decay backgrounds remain and must be accounted for. For backgrounds contributing only a few events to the maximum-likelihood (ML) fit, the estimated contribution is subtracted from the final signal yield with a systematic uncertainty to account for the unknown probability of the background to be selected as signal in the fit. Larger backgrounds are parameterized in the ML fit as described below. These were $B^+ \rightarrow \bar{D}^0 \pi^+$, $\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$ in Regions II and VII, $B^+ \rightarrow \bar{D}^0 \rho^+(770)$ with $\bar{D}^0 \rightarrow K^+ \pi^-$ and $\rho^+ \rightarrow \pi^+ \pi^0$ in Region VII and $B^+ \rightarrow \eta' K^+$ with $\eta' \rightarrow \rho^0(770)\gamma$, $\rho^0 \rightarrow \pi^+ \pi^-$ in Regions IV and V.

We form probability density functions (PDFs) with parameters $\vec{\alpha}$ for the three variables (\vec{x}) m_{ES} , ΔE , and \mathcal{F} in each region. We find the correlations among these variables to be negligible; accordingly, for each hypothesis l (signal, continuum background, and B background), we form a product $P_l = P_{l,m_{ES}} P_{l,\Delta E} P_{l,\mathcal{F}}$ that models that hypothesis. The likelihood for an event j is the sum over the M hypotheses of the products P_l , with each product weighted by the number of events (to be determined), n_l , for that hypothesis. A product over the N events in the data sample of the event likelihoods along with a Poisson factor forms the likelihood function:

$$\mathcal{L} = \exp\left(-\sum_{i=1}^M n_i\right) \prod_{j=1}^N \left[\sum_{l=1}^M n_l P_l(\vec{\alpha}, \vec{x}_j)\right]. \quad (1)$$

This likelihood is maximized to obtain n_l for the signal and continuum background components; n_l for the B -background component is fixed to an estimate of the contribution from MC. The parameters of the signal and B -background PDFs are determined from MC and held fixed in the final fit. The continuum background parameters for \mathcal{F} are fixed from the data with $0.1 < |\Delta E| < 0.3$ GeV. The continuum background parameters for ΔE and m_{ES} are left free in the final fit. Each m_{ES} PDF is a Gaussian distribution for signal, and an ARGUS threshold function [15] for continuum background. Each ΔE PDF is a sum of two Gaussian distributions with equal means for the signal and a first-degree polynomial for the continuum background. The signal and background \mathcal{F} PDFs are Gaussian distributions with different widths above and below the mean. For the B -background parametrizations, signal or continuum shapes are used depending on the nature of the background. The projections

of the Region I data in m_{ES} , ΔE and \mathcal{F} and the results of the fit are shown in Fig. 2, demonstrating a clear signal. The data in the plots pass a selection on the per event signal-to-background likelihood ratio formed from the other two fit variables, which has been optimized to give the greatest significance to the signal.

The signal yields for the regions of the Dalitz plot are shown in Table I. The systematic uncertainty arises from the PDF parameters and from B -background subtraction. We find that all yields have a significance greater than 5 standard deviations, where $\sqrt{2 \ln(\mathcal{L}_{\max}/\mathcal{L}_{\max}(n_{\text{signal}}=0))}$ is used as an estimator of the significance.

We calculate the branching fractions from the measured yields, taking into account the overlapping nature of the resonances, using $\mathcal{B} = M^{-1}Y/N_{B\bar{B}}$ where Y is a vector of the yields in each Dalitz region and \mathcal{B} is a vector of branching fractions. M is the efficiency matrix where M_{ij} is the probability that an event arising from the contribution dominating region i will be found in region j . The elements of M are estimated using MC including small corrections for differences in tracking and in particle identification efficiencies between MC and data, and differences between MC and our resonance model.

In our resonance model we assume one dominant contribution per region. The contributions for the chosen model are given in Table II. For Regions II and VI where the main contributions are not known *a priori*, we take the dominant contributions to be $K_0^{*0}(1430)\pi^+$ and $f_2(1270)K^+$ respectively. However, we quote branching fractions for $B^+ \rightarrow$ “higher K^{*0} ” π^+ where “higher K^{*0} ” means any combination of $K_0^{*0}(1430)$, $K_2^{*0}(1430)$ and $K_1^{*0}(1680)$ and $B^+ \rightarrow$ “higher f ” K^+ , where “higher f ”

TABLE II. A summary of the model used to calculate branching fractions. Alternative lineshapes are given in parentheses. The masses and widths are taken from the Review of Particle Physics [6].

Resonance	Lineshape	Mass (MeV/ c^2)	Width (MeV/ c^2)
$K^{*0}(892)$	BW	896.10 ± 0.27	50.7 ± 0.6
$K_0^{*0}(1430)$	BW (LASS[16])	1412 ± 6	294 ± 23
D^0	BW	1864.5 ± 0.5	0
$\rho^0(770)$	Blatt-Weisskopf[17]	769.0 ± 0.9	150.9 ± 1.7
$f_0(980)$	BW (Flatté[18])	980 ± 10	70 ± 30
$f_2(1270)$	BW	1275 ± 12	185 ± 30
χ_{c0}	BW	3415.1 ± 0.8	16.2 ± 3.2
nonresonant	flat	all masses	...

means any combination of $f_2(1270)$, $f_0(1370)$, and $f_2(1430)$. Nonrelativistic Breit-Wigner line shapes are used for all channels except for the broad $\rho(770)$ resonance, where we use a relativistic Breit-Wigner line shape with Blatt-Weisskopf damping [17].

We evaluate systematic uncertainties on the branching fractions, taking into consideration uncertainties on resonance parameters and alternative line shapes given in Table II. We also include the effect on all branching fractions that in Regions II and VI, the dominant contribution could be any combination of a number of resonances. Also included in the systematic uncertainties is the possibility that the yield measured in Region VII is from a resonant component and does not extend into the other regions. Uncertainties on the branching fractions due to the interference between the resonances are evaluated by generating many simulated $B^+ \rightarrow K^+ \pi^- \pi^+$

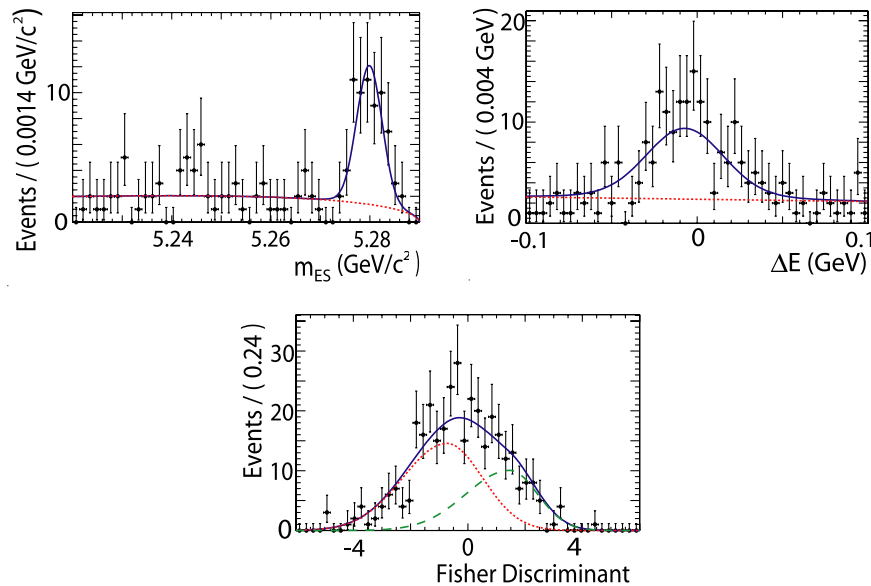


FIG. 2 (color online). Projection plots in m_{ES} , ΔE and \mathcal{F} , for the data in Region I. The superimposed curve is a projection of the full fit with the background component shown as a dotted line and, for \mathcal{F} , the signal component shown as a dashed line.

TABLE III. The measured branching fractions and uncertainties. The first uncertainty is statistical, the second includes the systematic uncertainties from the yields and the efficiencies, the third is the model uncertainty, and the fourth is the uncertainty due to interference.

Channel	BF $\times 10^{-6}$
$K^{*0}(892)\pi^+$	$15.5 \pm 1.8 \pm 1.1_{-3.8}^{+0.6} \pm 0.9$
“higher K^{*0} ”, π^+ , $K^{*0} \rightarrow K^+\pi^-$	$25.1 \pm 2.0 \pm 2.9_{-0.5}^{+9.4} \pm 4.9$
$\bar{D}^0\pi^+$, $\bar{D}^0 \rightarrow K^+\pi^-$	$184.6 \pm 3.2 \pm 9.7$
$\rho^0(770)K^+$	$3.9 \pm 1.2_{-0.6}^{+0.3+0.3} \pm 1.2$
$f_0(980)K^+$, $f_0 \rightarrow \pi^+\pi^-$	$9.2 \pm 1.2 \pm 0.6_{-1.9}^{+1.2} \pm 1.6$
“higher f ” K^+ , $f \rightarrow \pi^+\pi^-$	$3.2 \pm 1.2 \pm 0.5_{-2.4}^{+5.8} \pm 1.5$
Nonresonant	$5.2 \pm 1.9_{-1.8}^{+0.8+3.3} \pm 6.4$
$\chi_{c0}K^+$, $\chi_{c0} \rightarrow \pi^+\pi^-$	$1.5 \pm 0.4 \pm 0.1$

Dalitz plots with all the contributions having random phases and observing how the interference between the contributions affects the measured branching fractions. The branching fractions and uncertainties of intermediate resonances are given in Table III.

Figure 3 shows the Dalitz plot for data events within a signal-region, $5.2715 < m_{ES} < 5.2865 \text{ GeV}/c^2$, that have a per event signal-to-background likelihood ratio, formed from the ΔE and \mathcal{F} PDFs, greater than 5. Both signal and background events appear in the plot. The $\bar{D}^0\pi^+$ signal is the narrow band in the $m_{K\pi}$ spectrum. To illustrate the expected background distribution, events passing the same likelihood selection but having a value of m_{ES} between $5.25 < m_{ES} < 5.26 \text{ GeV}/c^2$ are also shown. The size of this sideband is chosen to contain approximately the expected number of background events that will enter the signal-region plot.

Figure 4 shows background-subtracted, efficiency-corrected projections of the two-body invariant mass spectra, $m_{K\pi}$ and $m_{\pi\pi}$, from $0.6 \text{ GeV}/c^2$ to $1.8 \text{ GeV}/c^2$ and from $0.2 \text{ GeV}/c^2$ to $1.5 \text{ GeV}/c^2$ respectively. The signal events and background distributions are obtained

by the same method as for Fig. 3 and again the \bar{D}^0 , J/ψ and $\Psi(2S)$ vetoes are applied. Peaks at the $K^{*0}(892)$ and $f_0(980)$ masses are clearly visible.

The invariant mass $m_{K\pi}$ or $m_{\pi\pi}$, and helicity angle between the resonance decay and flight directions, θ_H , are not used in the likelihood fit. However, to illustrate our findings, we show, in Fig. 5, resonant mass and $\cos\theta_H$ projections for Regions I, IV and II after background subtraction and efficiency corrections. Figures 5(a)–5(d) have been overlaid with the distribution of the expected dominant resonance: Breit-Wigner line shapes for the mass distributions in Figs. 5(a) and 5(c), $\cos^2\theta_H$ for the $K^{*0}(892)$ $\cos\theta_H$ distribution in Fig. 5(b), and a uniform distribution for the scalar $f_0(980)$ $\cos\theta_H$ distribution in Fig. 5(d). There is good agreement between the overlaid and observed distributions indicating that the expected resonances are indeed dominant in these regions. The $f_0(980)$ $\cos\theta_H$ distribution suggests a linear dependence that is most likely due to interference with the vector $\rho(770)$, which is taken into account in our interference systematic uncertainty.

We can see in Fig. 4, there is a large signal in the region $1.1 < m_{K\pi} < 1.4 \text{ GeV}/c^2$ (Region II). This is shown in more detail in Fig. 5(e), resonant mass, and Fig. 5(f), the $\cos\theta_H$ projections for Region II. The complex behavior of this signal is similar to that observed by LASS [16] and precludes an interpretation as a single resonance.

In conclusion, we have made branching fraction measurements, summarized in Table III, for a number of charm and charmless B decay channels with the final state $K^+\pi^-\pi^+$. This analysis has taken into account the uncertainty in the knowledge of the nature and parametrization of the intermediate resonances on all the branching fractions assuming a nonresonant contribution with kinematics defined by phase space. The results also take account of the unknown levels of interference between the different contributions. The $B^+ \rightarrow \bar{D}^0\pi^+$ and $B^+ \rightarrow \chi_{c0}K^+$ results agree with previous measurements

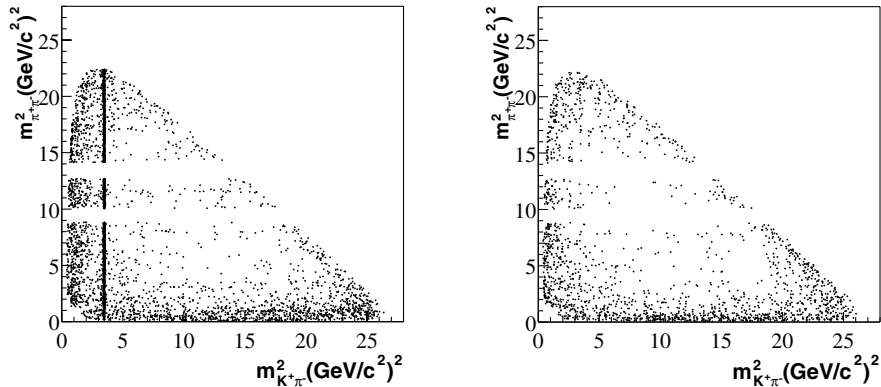


FIG. 3. Dalitz plots showing (left) the observed distribution in a signal m_{ES} region (defined in the text) and (right) the distribution for continuum background from the m_{ES} sideband. Vetoes reject events with J/ψ and $\psi(2S)$.

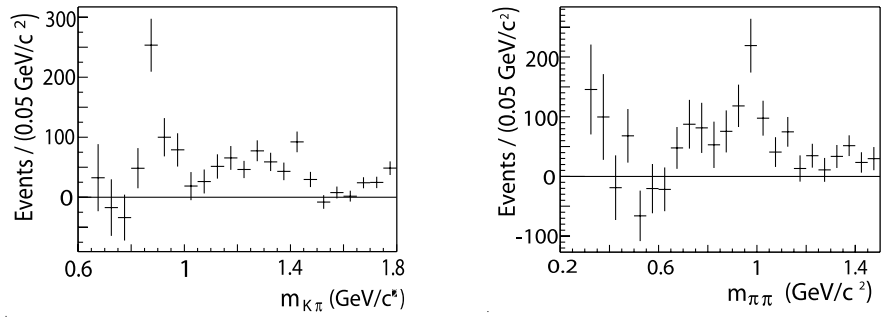


FIG. 4. Background-subtracted and efficiency-corrected projections of the Dalitz plot in $m_{K\pi}$ and $m_{\pi\pi}$.

[19,20]. The $B^+ \rightarrow K^{*0}(892)\pi^+$ [21] and $B^+ \rightarrow f_0(980)K^+$ branching fractions are consistent with, and more precise than, previous measurements [22]. The $B^+ \rightarrow K^{*0}(892)\pi^+$ result is significantly higher than predicted by many factorization models [3]. The observation of the decay $B^+ \rightarrow f_0(980)K^+$ provides hints about the nature of the $f_0(980)$ [7]. A large signal is seen for $B^+ \rightarrow$ “higher K^{*0} ” π^+ where “higher K^{*0} ” means any combination of $K_0^{*0}(1430)$, $K_2^{*0}(1430)$ and $K_1^{*0}(1680)$.

We also give 90% confidence-level upper limits for the branching fractions of the following channels: $\mathcal{B}[B^+ \rightarrow \rho^0(770)K^+] < 6.2 \times 10^{-6}$, $\mathcal{B}[B^+ \rightarrow K^+\pi^-\pi^+ \text{ nonresonant}] < 17 \times 10^{-6}$, $\mathcal{B}[B^+ \rightarrow \text{“higher } f\text{”}K^+] < 12 \times 10^{-6}$. The tight limit on the non-resonant component means that its γ -dependent interfer-

ence with the $\chi_{c0}K$ final state will be very hard to measure.

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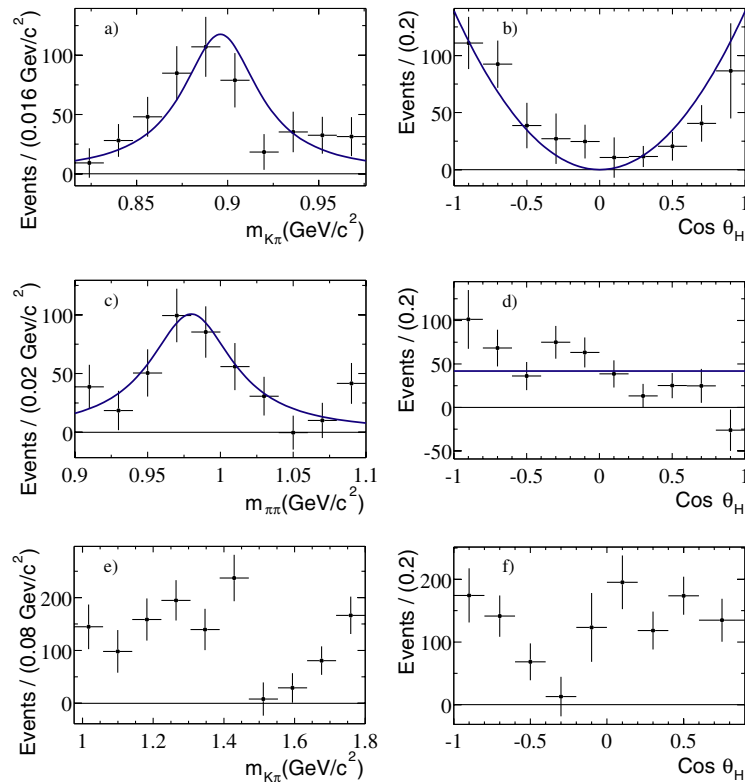


FIG. 5 (color online). Projection plots of the two-body invariant mass and $\cos\theta_H$ for, from top to bottom, Regions I, V and II.

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