# Charmless Three-body $B$ Decays at BABAR 

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#### Abstract

We present Dalitz-plot analyses of $B^{+} \rightarrow K^{+} \pi^{-} \pi^{+}$and $B^{0} \rightarrow K^{+} \pi^{-} \pi^{0}$ using the data sample collected at the $\Upsilon(4 S)$ by the $B A B A R$ detector. We have found evidence for $\operatorname{direct} C P$-violation in the decay $B^{ \pm} \rightarrow \rho^{0} K^{ \pm}$, with a $C P-$ violation parameter $\mathcal{A}_{C P}=\frac{\Gamma_{B^{+}}-\Gamma_{B^{-}}}{\Gamma_{B+}+\Gamma_{B-}}=\left(+44 \pm 10 \pm 4_{-13}^{+5}\right) \%$, where $\Gamma_{B^{ \pm}}$are the decay rates. The uncertainties are statistical, systematic, and model-dependent, respectively. We also search for the suppressed decays $B^{+} \rightarrow K^{-} \pi^{+} \pi^{+}$ and $K^{+} K^{+} \pi^{-}$and improve upper limits on the decay branching fractions.


## 1. INTRODUCTION

In the Standard Model (SM), violation of $C P$ symmetry is a consequence of the complex phase of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Comprehensive tests of the SM CP-violation mechanism require precise measurements of the three sides and three angles of the CKM unitarity triangle. Although CPviolation in the neutral $K^{0}$ meson [2] and $B^{0}$ meson [3] has been well-established, it is known to be too small to account for the matter-dominated Universe, direct $C P$-violation would help to explain the dominance of matter in the Universe [4]. Direct $C P$-asymmetry in $B^{ \pm} \rightarrow \rho^{0} K^{ \pm}$has been suggested [5] and searched at BABAR and BELLE [6] through Dalitz-plot analysis of $B^{+} \rightarrow K^{+} \pi^{+} \pi^{-}$(charge conjugate decay is implied throughout this paper.) Direct $C P$-asymmetries in $B \rightarrow K^{*} \pi, K_{0}^{*} \pi$, and $K_{2}^{*} \pi$ are expected to be small in the SM. Moreover, the relative weak phase between tree and penguin diagrams in $B \rightarrow K \pi \pi$ decays is the CKM angle $\gamma \equiv \arg \left(-V_{u d} V_{u b}^{*} / V_{c d} V_{c b}^{*}\right)$. Therefore a set of Dalitz-plot analyses of $B \rightarrow K \pi \pi$ can provide a relatively clean determination of $\gamma$ [7].

Compared to the penguin transitions $\bar{b} \rightarrow q \bar{q} \bar{d}$ and $\bar{b} \rightarrow q \bar{q} \bar{s}$, the decay rates for the wrong sign decays $B^{+} \rightarrow$ $K^{-} \pi^{+} \pi^{+}$and $K^{+} K^{+} \pi^{-}$via $\bar{b} \rightarrow \bar{d} \bar{d} s$ and $\bar{b} \rightarrow \bar{s} \bar{s} d$ transitions are further suppressed by $\left|V_{t d} V_{t s}^{*}\right|^{2} \simeq \mathcal{O}\left(10^{-7}\right)$, resulting in branching fractions of $\mathcal{O}\left(10^{-14}\right)$ and $\mathcal{O}\left(10^{-11}\right)$, respectively [8]. Observations of these decays would be clear evidence of the $\bar{b} \rightarrow \bar{d} \bar{d} s$ and $\bar{b} \rightarrow \bar{s} \bar{s} d$ transitions.

## 2. ANALYSIS TECHNIQUE

A number of intermediate states can contribute to 3-body $B \rightarrow K \pi \pi$ decays. Their individual contributions are obtained from a maximum likelihood (ML) fit to the distribution of events in the Dalitz-plot formed by two invariant masses squared $x$ and $y$ of particle pairs. The total amplitudes for 3 -body $B$ and $\bar{B}$ decays are given [9] by:

$$
\begin{equation*}
A \equiv A(x, y)=\sum_{j} c_{j} F_{j}(x, y) ; \quad \bar{A} \equiv \bar{A}(x, y)=\sum_{j} \bar{c}_{j} \bar{F}_{j}(x, y) \tag{1}
\end{equation*}
$$

Where $c_{j}$ is the complex coefficient for a given intermediate state $j$ with all the weak phase dependence. The normalized distributions $F_{j}$ describe the dynamics of the decay amplitudes and are the product of an invariant mass term (relativistic Breit-Wigner in general), two Blatt-Weisskopf barrier form factors 10], and an angular function. In the case of $f_{0}(980)\left(K_{0}^{*}\right)$, the mass term is replaced by the Flatté (LASS) lineshape 11]. The fit fraction $F F$ of a given intermediate state $j$ with a partial decay width $\Gamma_{j}$ is given by:

Insert PSN Here

$$
\begin{equation*}
F F_{j} \equiv \frac{\Gamma_{j}}{\Gamma}=\frac{\iint\left(\left|c_{j} F_{j}\right|^{2}+\left|\bar{c}_{j} \bar{F}_{j}\right|^{2}\right) d x d y}{\iint\left(|A|^{2}+|\bar{A}|^{2}\right) d x d y} \tag{2}
\end{equation*}
$$

The sum of all contributions is not necessarily unity due to the interference. The $C P$-asymmetry for a given intermediate state is defined as

$$
\begin{equation*}
\mathcal{A}_{C P, j} \equiv \frac{\Gamma_{\bar{B}, j}-\Gamma_{B, j}}{\Gamma_{\bar{B}, j}+\Gamma_{B, j}}=\frac{\left|\bar{c}_{j}\right|^{2}-\left|c_{j}\right|^{2}}{\left|\bar{c}_{j}\right|^{2}+\left|c_{j}\right|^{2}} \tag{3}
\end{equation*}
$$

The signal Dalitz-plot probability density function (PDF) is constructed as

$$
\begin{equation*}
\mathcal{P}_{\text {sig }}\left(x, y, q_{B}\right)=\frac{\frac{1+q_{B}}{2}|A|^{2} \epsilon+\frac{1-q_{B}}{2}|\bar{A}|^{2} \bar{\epsilon}}{\iint\left(|A|^{2} \epsilon+|\bar{A}|^{2} \bar{\epsilon}\right) d x d y} \tag{4}
\end{equation*}
$$

where $q_{B}$ is the charge of $B$ candidate, $\epsilon \equiv \epsilon(x, y)$ and $\bar{\epsilon}=\bar{\epsilon}(x, y)$ are the signal reconstruction efficiencies for $B$ and $\bar{B}$ events. The Dalitz-plot PDFs for continuum and $B \bar{B}$ backgrounds are constructed through two-dimensional histograms from simulated continuum and $B \bar{B}$ samples.

A $B$ candidate is reconstructed through the desired decay chains of interest. Charged kaon and pion candidates are identified by energy loss $d E / d x$ information measured in a five-layer silicon vertex detector and a 40-layer drift chamber, and the Cherenkov angle and number of photons measured in a detector of internally reflected Cherenkov radiation. A $\pi^{0}$ candidate is formed from photon pairs measured in a $\operatorname{CsI}(\mathrm{Tl})$ crystal electromagnetic calorimeter. The BABAR detector is described in detail elsewhere [12].

A $B$ candidate is characterized by two kinematic variables: the energy-substituted mass $m_{\mathrm{ES}} \equiv \sqrt{s / 4-\left(p_{B}^{*}\right)^{2}}$ and the energy difference $\Delta E \equiv E_{B}^{*}-\sqrt{s} / 2$, where $E_{B}^{*}$ and $p_{B}^{*}$ are the center-of-mass (CM) energy and momentum of the $B$ candidate, respectively, $\sqrt{s}$ is the total CM energy. Signal events peak at the nominal $B$ mass for $m_{\mathrm{ES}}$ and at zero for $\Delta E$.

The dominant background comes from continuum production $e^{+} e^{-} \rightarrow q \bar{q}$, where $q=u, d, s, c$. This background is suppressed by requirements on event-shape variables calculated in the CM frame. The continuum background is further suppressed by exploring a neural network (NN) algorithm based on a set of kinematical variables.

Standard extended unbinned maximum likelihood method is used to fit data. The likelihood function has the form

$$
\begin{equation*}
\mathcal{L}=\exp \left(-\sum_{k} n_{k}\right) \prod_{i=1}^{N}\left[\sum_{k} n_{k} \mathcal{P}_{k}^{i}\left(x, y, m_{\mathrm{ES}}, \Delta E, N N\right)\right] \tag{5}
\end{equation*}
$$

where $N=\sum_{k} n_{k}$ is the total number of events, $n_{k}$ is the fit yield of component $k$ ( $k=\operatorname{signal}, B \bar{B}$, and continuum). $\mathcal{P}_{k}^{i}$ is the PDF for event $i$ to be identified as component $k$.

## 3. RESULTS

### 3.1. Results on $B^{+} \rightarrow K^{+} \pi^{-} \pi^{+}$

A Dalitz-plot analysis of the decay $B^{+} \rightarrow K^{+} \pi^{-} \pi^{+}[14]$ is based on a data sample of $347.5 \mathrm{fb}^{-1}$, containing $(383.2 \pm 4.2) \times 10^{6} B \bar{B}$ pairs recorded by the $B A B A R$ detector at the $\Upsilon(4 S)$ resonance at the Stanford Linear Accelerator Center. The Dalitz-plot variables are $x \equiv m_{K^{+} \pi^{-}}^{2}$ and $y \equiv m_{\pi^{+} \pi^{-}}^{2}$. A phase-space non-resonant component and nine intermediate states $K^{* 0} \pi^{+}, K_{0}^{* 0} \pi^{+}, \rho^{0} K^{+}, f_{0}(980) K^{+}, \chi_{c 0} K^{+}, K_{2}^{* 0} \pi^{+}, \omega K^{+}, f_{2}(1270) K^{+}$, and $f_{X} K^{+}$are included in the ML fit. The fit to 12,753 selected candidate events yield $4585 \pm 90 \pm 297 \pm 63$ signal events and the overall direct $C P$-asymmetry of $(2.8 \pm 2.0 \pm 2.0 \pm 1.2) \%$, where the uncertainties are statistical, systematic, and model-dependent, respectively. The intermediate state $\omega K^{+}$with $\omega \rightarrow \pi^{+} \pi^{-}$has noticeable effect on the $\rho^{0}$ lineshape and is included in the fit although its contribution is small. A scalar particle $f_{X}$ and $f_{2}(1270)$ are necessary to provide better fit to the data. The mass and width of $f_{X}$ are determined to be $m_{f_{X}}=1479 \pm 8 \mathrm{MeV} / \mathrm{c}^{2}$ and $\Gamma_{f_{X}}=80 \pm 10 \mathrm{MeV}$, respectively, where the uncertainties are statistical only. The fit results are summarized in Table The statistical significance of the direct $C P$-violation is evaluated from the differnce $-2 \Delta \ln \mathcal{L}$ of the nagative log-likelihood of the
nominal fit and that of a fit where $C P$-violation parameters for the given component are set to zero, the number of degrees of freedom (two in this case) is taken into account.

The total branching fraction in Table $\mathbb{1}$ is consistent with BELLE's measurement 13]. We see evidence of direct $C P$-asymmetry of $\mathcal{A}_{C P}=\left(+44 \pm 10 \pm 4_{-13}^{+5}\right) \%$ in $B^{+} \rightarrow \rho^{0} K^{+}$, consistent with the previous findings 6]. The statistical significance of the direct $C P$-violation effect is found to be $3.7 \sigma$ from the change in likelihood as described above. As experimental systematic uncertainties are much smaller than the statistical errors, they do not affect this conclusion. We have cross-checked the effect of the choice of the Dalitz-plot models on the significance. We find that the significance remains above $3 \sigma$ with alternative models. The statistical significance of direct $C P$-violation in $B^{+} \rightarrow f_{2}(1270) K^{+}$is also above $3 \sigma$, but it suffers from large model uncertainties. The direct $C P$-asymmetries in $B^{+} \rightarrow K^{* 0} \pi^{+}, K_{0}^{* 0} \pi^{+}$, and $K_{2}^{* 0} \pi^{+}$are all consistent with the SM expectations.

Table I: Summary of measurements of branching fractions (averaged over charge conjugate states) and CP asymmetries. Note that these results are not corrected for secondary branching fractions. The first uncertainty is statistical, the second is systematic, and the third represents the model dependence. The final column is the statistical significance of direct $C P$ violation (DCPV) determined as described in the text.

| Mode | Fit fraction (\%) | $\mathcal{B}\left(B^{+} \rightarrow\right.$ Mode $)\left(10^{-6}\right)$ | $\mathcal{A}_{C P}(\%)$ | DCPV sig. |
| :--- | :---: | :---: | :---: | :---: |
| $K^{+} \pi^{-} \pi^{+}$total |  | $54.4 \pm 1.1 \pm 4.5 \pm 0.7$ | $2.8 \pm 2.0 \pm 2.0 \pm 1.2$ |  |
| $K^{* 0} \pi^{+} ; K^{* 0} \rightarrow K^{+} \pi^{-}$ | $13.3 \pm 0.7 \pm 0.7_{-0.9}^{+0.4}$ | $7.2 \pm 0.4 \pm 0.7_{-0.5}^{+0.3}$ | $+3.2 \pm 5.2 \pm 1.1_{-0.7}^{+1.2}$ | $0.9 \sigma$ |
| $K_{0}^{* 0} \pi^{+} ; K_{0}^{* 0} \rightarrow K^{+} \pi^{-}$ | $45.0 \pm 1.4 \pm 1.2_{-0.2}^{+12.9}$ | $24.5 \pm 0.9 \pm 2.1_{-1.1}^{+7.0}$ | $+3.2 \pm 3.5 \pm 2.0_{-1.9}^{+2.7}$ | $1.2 \sigma$ |
| $\rho^{0} K^{+} ; \rho^{0} \rightarrow \pi^{+} \pi^{-}$ | $6.54 \pm 0.81 \pm 0.58_{-0.26}^{+0.69}$ | $3.56 \pm 0.45 \pm 0.43_{-0.15}^{+0.38}$ | $+44 \pm 10 \pm 4_{-13}^{+5}$ | $3.7 \sigma$ |
| $f_{0}(980) K^{+} ; f_{0}(980) \rightarrow \pi^{+} \pi^{-}$ | $18.9 \pm 0.9 \pm 1.7_{-0.6}^{+2.8}$ | $10.3 \pm 0.5 \pm 1.3_{-0.4}^{+1.5}$ | $-10.6 \pm 5.0 \pm 1.1_{-1.0}^{+3.4}$ | $1.8 \sigma$ |
| $\chi_{c 0} K^{+} ; \chi_{c 0} \rightarrow \pi^{+} \pi^{-}$ | $1.29 \pm 0.19 \pm 0.15_{-0.03}^{+0.12}$ | $0.70 \pm 0.10 \pm 0.10_{-0.02}^{+0.06}$ | $-14 \pm 15 \pm 3_{-5}^{+1}$ | $0.5 \sigma$ |
| $K^{+} \pi^{-} \pi^{+}$nonresonant | $4.5 \pm 0.9 \pm 2.4_{-1.5}^{+0.6}$ | $2.4 \pm 0.5 \pm 1.3_{-0.8}^{+0.3}$ | - | - |
| $K_{2}^{* 0} \pi^{+} ; K_{2}^{* 0} \rightarrow K^{+} \pi^{-}$ | $3.40 \pm 0.75 \pm 0.42_{-0.13}^{+0.99}$ | $1.85 \pm 0.41 \pm 0.28_{-0.08}^{+0.54}$ | $+5 \pm 23 \pm 4_{-7}^{+18}$ | $0.2 \sigma$ |
| $\omega K^{+} ; \omega \rightarrow \pi^{+} \pi^{-}$ | $0.17 \pm 0.24 \pm 0.03_{-0.08}^{+0.05}$ | $0.09 \pm 0.13 \pm 0.02_{-0.04}^{+0.03}$ | - | - |
| $f_{2}(1270) K^{+} ; f_{2}(1270) \rightarrow \pi^{+} \pi^{-}$ | $0.91 \pm 0.27 \pm 0.11_{-0.17}^{+0.24}$ | $0.50 \pm 0.15 \pm 0.07_{-0.09}^{+0.13}$ | $-85 \pm 22 \pm 13_{-2}^{+22}$ | $3.5 \sigma$ |
| $f_{X} K^{+} ; f_{X} \rightarrow \pi^{+} \pi^{-}$ | $1.33 \pm 0.38 \pm 0.86_{-0.14}^{+0.04}$ | $0.73 \pm 0.21 \pm 0.47_{-0.08}^{+0.02}$ | $+28 \pm 26 \pm 13_{-5}^{+7}$ | $0.6 \sigma$ |

### 3.2. Results on $B^{0} \rightarrow K^{+} \pi^{-} \pi^{0}$

A Dalitz-plot analysis of $B^{0} \rightarrow K^{+} \pi^{-} \pi^{0}[15]$ is based on a data sample of $413 \mathrm{fb}^{-1}$, corresponding to ( $454 \pm 5$ ) $\times 10^{6}$ $B \bar{B}$ pairs produced at the $\Upsilon(4 S)$ resonance. The Dalitz-plot variables are $x \equiv m_{K^{+} \pi^{-}}^{2}$ and $y \equiv m_{K^{+} \pi^{0}}^{2}$. A phase-space non-resonant component and seven intermediate states $\rho^{-}(770) K^{+}, \rho^{-}(1450) K^{+}, \rho^{-}(1700) K^{+}, K^{*+} \pi^{-}, K^{* 0} \pi^{0}$, $K_{0}^{*+} \pi^{-}$, and $K_{0}^{* 0} \pi^{0}$ are included in the ML fit. The fit to the data yields $4583 \pm 122$ signal events, where the uncertainty is statistical only. The results are preliminary. The decays $B^{0} \rightarrow \bar{D}^{0} \pi^{0}$ and $D^{-} K^{+}$with $\bar{D}^{0} \rightarrow K^{+} \pi^{-}$ and $D^{-} \rightarrow \pi^{+} \pi^{0}$ are included in the fit as calibration modes. The fit shows that the decay $B^{0} \rightarrow K^{+} \pi^{-} \pi^{0}$ is dominated by $K_{0}^{*} \pi$ and $\rho^{-}(770) K^{+}$.

Isospin symmetry relates the amplitudes of $B^{0} \rightarrow K^{*+} \pi^{-}$and $K^{* 0} \pi^{0}$ and $\bar{B}^{0} \rightarrow K^{*-} \pi^{+}$and $\bar{K}^{* 0} \pi^{0}$ which form two unitarity triangles. The orientation of the two triangles can be determined from a time-dependent Dalitz-plot analysis of $B^{0} \rightarrow K_{S}^{0} \pi^{+} \pi^{-}$. A Dalitz-plot analysis of $B^{0} \rightarrow K^{+} \pi^{-} \pi^{0}$ can extract the magnitudes and phases of $K^{*} \pi$ and $\bar{K}^{*} \pi$ in $B^{0}$ and $\bar{B}^{0}$ decays which are essential to determine the CKM angle $\gamma$ and will be updated soon.

### 3.3. Results on $B^{+} \rightarrow K^{-} \pi^{+} \pi^{+}$and $K^{+} K^{+} \pi^{-}$

The preliminary results on the search for the suppressed decays $B^{+} \rightarrow K^{-} \pi^{+} \pi^{+}$and $K^{+} K^{+} \pi^{-}$[16] are based on a data sample of $426 \mathrm{fb}^{-1}$ which contains $(467 \pm 5) \times 10^{6} B \bar{B}$ pairs. Since the signal yields for the two modes are expected to be small, no Dalitz-plot involves in the ML fit. We apply the ML fit to the $26,478 B^{+} \rightarrow K^{-} \pi^{+} \pi^{+}$
and $7,822 B^{+} \rightarrow K^{+} K^{+} \pi^{-}$candidate events and find no significant signal events. We set upper limits on the decay branching fractions to be $\mathcal{B}\left(B^{+} \rightarrow K^{-} \pi^{+} \pi^{+}\right)<9.5 \times 10^{-7}$ and $\mathcal{B}\left(B^{+} \rightarrow K^{+} K^{+} \pi^{-}\right)<1.6 \times 10^{-7}$ at $90 \%$ confidence level. These two upper limits have been improved by a factor of 2 and 8 , respectively.

## 4. SUMMARY

We have performed a Dalitz-plot analysis of $B^{+} \rightarrow K^{+} \pi^{-} \pi^{+}$. A scalar particle $f_{X}$ with $m_{f_{X}}=1479 \pm 8 \mathrm{MeV} / \mathrm{c}^{2}$ and $\Gamma_{f_{X}}=80 \pm 10 \mathrm{MeV}$ and $f_{2}(1270)$ are necessary to fit the data better. We find evidence for direct $C P$-asymmetry of $\mathcal{A}_{C P}=\left(+44 \pm 10 \pm 4_{-13}^{+5}\right) \%$ in the decay $B^{+} \rightarrow \rho^{0} K^{+}$with a statistical significance of $3.7 \sigma$. The direct $C P-$ asymmetries in $B^{+} \rightarrow K^{* 0} \pi^{+}, K_{0}^{* 0} \pi^{+}$, and $K_{2}^{* 0} \pi^{+}$are consistent with zero as expected.

We have improved the Dalitz-plot analysis of $B^{0} \rightarrow K^{+} \pi^{-} \pi^{0}$. The determination of the magnitudes and phases in $B^{0} \rightarrow K^{*} \pi$ and $\bar{B}^{0} \rightarrow \bar{K}^{*} \pi$ will be updated soon which are essential for the extraction of the CKM angle $\gamma$. We have improved the upper limits on the branching fractions for the SM-suppressed decays $B^{+} \rightarrow K^{-} \pi^{+} \pi^{+}$and $B^{+} \rightarrow K^{+} K^{+} \pi^{-}$by a factor of 2 and 8 , respectively.

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