Studies of Charmless Two-Body, Quasi-Two-Body and Three-Body $B$ Decays

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for the $BABAR$ Collaboration
Introduction

We consider channels mediated by $b \to u$ tree diagrams or $b \to d,s$ penguins

<table>
<thead>
<tr>
<th>Two-body</th>
<th>Quasi-two-body</th>
<th>Three-body</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \pi^{\pm}\pi^{\mp}$</td>
<td>$B^+ \to \omega h^+, \omega \to \pi^0\pi^+\pi^-$</td>
<td>$(B \to 3h, h=\pi,K)$</td>
</tr>
<tr>
<td>$B^0 \to K^{\pm}\pi^\mp$</td>
<td>$B^0 \to \omega K^0_s$</td>
<td>$B^+ \to K^{*0}\pi^+$</td>
</tr>
<tr>
<td>$B^0 \to K^{\pm}K^{\mp}$</td>
<td>$B^+ \to \eta' K^+, \eta' \to \eta \pi^+\pi^-$</td>
<td>$B^+ \to \rho^{0}\pi^+$</td>
</tr>
<tr>
<td></td>
<td>$B^0 \to \eta' K^0_s \gamma \gamma$</td>
<td>$B^0 \to \rho^{\pm}\pi^{\mp}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$B^+ \to \pi^+\pi^+\pi^-$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$B^+ \to K^+\pi^+\pi^-$</td>
</tr>
</tbody>
</table>

These channels are interesting because:

- many have yet to be discovered
- some offer potential for CP violation studies:
  - Study of penguins, model validation
  - Direct CP violation
  - Indirect CP violation: measurement of $\alpha, \beta$ and $\gamma$
Analysis Overview

• Data Set:
  7.7 fb\(^{-1}\) at \(\Upsilon(4S)\) (on resonance)
  1.2 fb\(^{-1}\) below BB threshold (off resonance)

• Analysis Method

  “Blind”: signal region hidden until analysis complete

  Cut-based (all modes)
  channel-dependent cuts, selected by optimising BR sensitivity

  Global Likelihood fit (Two-body modes)

• Analysis Details
  See BaBar-CONF-00/14, BaBar-CONF-00/15

• Beam-energy-substituted mass
  \(m_{ES} = \sqrt{E_{beam}^2 - p_B^*}^2\)

• Energy difference
  \(\Delta E = E_B^* - E_{beam}\)
Event Selection: Kaon Identification

Excellent kaon identification is essential for the decay modes of interest

DIRC (ring-imaging Cerenkov detector) :
Cerenkov angle $\theta_c$
Drift Chamber: $dE/dx$
Silicon Vertex Tracker: $dE/dx$

K/$\pi$ separation $>2\sigma$ at momenta up to 4GeV/c

separation = $<\theta(\pi)> - <\theta(K)>$

$<\sigma_{\theta}>$

pure sample of
$D^* \rightarrow D^0\pi^+ \rightarrow (K\pi)\pi^+$

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Event Selection: Quasi-two-body modes

Background suppression:

Fisher Discriminant
9 energy cones around B decay axis

$B^+ \rightarrow \omega h^+$
$B^0 \rightarrow \omega K^0$
$B^+ \rightarrow \eta' K^+$
$B^0 \rightarrow \eta' K^0$

$\omega \rightarrow \pi^0 \pi^+ \pi^-$

$\eta' \rightarrow \eta \pi^+ \pi^-$
$\eta \rightarrow \gamma \gamma$
Event Selection: Three-body modes

- $\rho, K^{*0}$ helicity angle
- $B^+ \rightarrow K^{*0}\pi^+$
- $B^+ \rightarrow \rho^0 K^+$
- $B^0 \rightarrow \rho^0 \pi^+$
- $B^+ \rightarrow \pi^+\pi^+\pi^-$
- $B^+ \rightarrow K^+\pi^+\pi^-$

Phase space cuts
- $J/\psi$, $D^0$ veto
- Cosine angle between axes of $B$ decay and rest-of-event

Monte Carlo
- Signal
- $B^g$-dominated data

$0.0$ $0.2$ $0.4$ $0.6$ $0.8$ $1$

$m_{12}^2/m_B^2$

$0$ $0.2$ $0.4$ $0.6$ $0.8$ $1$

$m_{13}^2/m_B^2$

$0$ $0.2$ $0.4$ $0.6$ $0.8$ $1$

$\cos(\delta_{\pi K})$

$0$ $0.1$ $0.2$ $0.3$ $0.4$ $0.5$ $0.6$ $0.7$ $0.8$ $0.9$ $1$

$\cos(\delta_{\mathrm{mm}})$

$0$ $50$ $100$ $150$ $200$ $250$

$0$ $50$ $100$ $150$ $200$ $250$

$0$ $100$ $200$ $300$

$0$ $100$ $200$ $300$

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Calibration Modes

Measure BRs (x10^{-4}):

\[ \text{B}^+ \rightarrow \overline{D}^0\pi^+ \rightarrow (K\pi)\pi \]
\[ 2.21 \pm 0.11 \text{ (stat)} \]
\[ [2.03 \pm 0.20]_{\text{PDG}} \]

\[ \text{B}^+ \rightarrow \overline{D}^0\pi^+ \rightarrow (K\pi\pi^0)\pi \]
\[ 6.79 \pm 0.32 \text{ (stat)} \]
\[ [7.37 \pm 0.84]_{\text{PDG}} \]
Background Characterisation

$\Delta E$ vs. $m_{ES}$ plane

Measure number of events in: sidebands ($N_2$), extrapolating to signal region ($N_1$)

Find ratio $\mathcal{R} = N_1/N_2$

Linear fit to $\Delta E$
Argus Function fit to $m_{ES}$

$$dN/dx = Ax\sqrt{1-x^2} \exp[-\xi(1-x^2)],$$
where $x = m_{ES}/E_{beam}$

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Results: Quasi-two-body Modes

\[ B = \frac{N_1 - \Re N_2}{N_{B\epsilon}} = \frac{N}{N_{B\epsilon}} \]

\[ N(\eta^{'\eta\pi\pi}K^\pm) = 12 \pm 4 \]

\[ N(\eta^{'\eta\pi\pi}K^0) = 1 \pm 1 \]

\[ N(\omega h^\pm) = 6 \pm 4 \]

\[ N(\omega K^0) = 0 \]

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Results: Three-body Modes

\[ B = \frac{N_1 - \Re N_2}{N_B \varepsilon} = \frac{N}{N_B \varepsilon} \]

\[ N( K^*0\pi^\pm) = 10 \pm 5 \]

\[ N( \rho^0K^\pm) = 11 \pm 5 \]

\[ N( \rho^0\pi^\pm) = 25 \pm 8 \]

\[ N( \rho^\pm\pi^\mp) = 36 \pm 10 \]
Results: Three-body Final States (non-resonant + higher resonances)

\[ B = \frac{N_1 - NK N_2}{N_B \varepsilon} = \frac{N}{N_B \varepsilon} \]

\[ N(\pi^+\pi^+\pi^-) = 5 \pm 6 \]

\[ N(K^+\pi^+\pi^-) = 19 \pm 6 \]

K$^+\pi^+\pi^-$ Dalitz plot
Cut-based $B^0 \rightarrow h^+h^-$ Analysis

Cut on event topology to reduce background
Signal yield from a fit to $m_{ES}$ in the region $|\Delta E| < 140$ MeV

Signal for $h^+h^-$

Evidence for kaons

After sideband subtraction
Cut-based Analysis with Kaon Selection

Fit mass distribution to determine signal yields

\[ N(\pi\pi) = 25 \pm 8 \]
\[ N(K\pi) = 26 \pm 8 \]
\[ N(KK) = 1 \pm 4 \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\pi\pi)</th>
<th>(K\pi)</th>
<th>(KK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi\pi)</td>
<td>0.853 (\pm 0.005)</td>
<td>0.109 (\pm 0.008)</td>
<td>0.0029 (\pm 0.0002)</td>
</tr>
<tr>
<td>(K\pi)</td>
<td>0.121 (\pm 0.004)</td>
<td>0.775 (\pm 0.006)</td>
<td>0.051 (\pm 0.004)</td>
</tr>
<tr>
<td>(KK)</td>
<td>0.0112 (\pm 0.0006)</td>
<td>0.231 (\pm 0.008)</td>
<td>0.704 (\pm 0.007)</td>
</tr>
</tbody>
</table>

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Likelihood Fit for Two-body Analysis

Global likelihood fit: using \( m_{ES}, \Delta E, \text{Fisher, Cerenkov angles for tracks} \)

\[
\mathcal{L} = e^{-N'} \prod_{i=1}^{N} \mathcal{P}_i(m_{ES}, \Delta E, F, \theta_1, \theta_2 | N_{\pi\pi}, N_{K\pi}, N_{\pi K}, N_{KK}, N_{bkg})
\]

to determine signal and background yields

PDFs obtained from data where possible

PDFs for \( \theta_c \) for kaons in 8 bins of momentum

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Results: Two-body Analysis

<table>
<thead>
<tr>
<th>Mode</th>
<th>N</th>
<th>BR(10^{-6})</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>π^{±}π^{±}</td>
<td>29 ± 8</td>
<td>9.3 ± 2.3</td>
<td>5.7</td>
</tr>
<tr>
<td>K^{±}π^{±}</td>
<td>38 ± 9</td>
<td>12.5 ± 3.0</td>
<td>6.7</td>
</tr>
<tr>
<td>K^{±}K^{±}</td>
<td>7 ± 5</td>
<td>&lt; 6.6</td>
<td>2.1</td>
</tr>
</tbody>
</table>

B(ππ) (10^{-6}) vs B(Kπ) (10^{-6})

(statistical only)
Summary of Results

We have provided several competitive measurements of BRs and upper limits, and anticipate further results in the near future:

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>BaBar BR/10^-6</th>
<th>CLEO BR/10^-6</th>
</tr>
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<tbody>
<tr>
<td>π⁺π⁻</td>
<td>9.3 +2.6 +1.2</td>
<td>4.3 +1.6 ± 0.5</td>
</tr>
<tr>
<td>K⁺π⁻</td>
<td>12.5 +3.0 +1.3</td>
<td>17.2 +2.5 ± 1.2</td>
</tr>
<tr>
<td>K⁺K⁻</td>
<td>&lt; 6.6</td>
<td>&lt; 1.9</td>
</tr>
<tr>
<td>ωh⁺</td>
<td>&lt; 24</td>
<td>14.3 ± 3.6</td>
</tr>
<tr>
<td>ωK⁰</td>
<td>&lt; 14</td>
<td>&lt; 21</td>
</tr>
<tr>
<td>η⁺ηππK⁺</td>
<td>62 ± 18 ± 8</td>
<td>80 ± 10</td>
</tr>
<tr>
<td>η⁺ηππK⁰</td>
<td>&lt; 112</td>
<td>89 ± 18</td>
</tr>
<tr>
<td>K⁺π⁺π⁻</td>
<td>&lt; 66</td>
<td>&lt; 28</td>
</tr>
<tr>
<td>ρ⁺K⁺</td>
<td>&lt; 29</td>
<td>&lt; 17</td>
</tr>
<tr>
<td>ρ⁺π⁺</td>
<td>&lt; 39</td>
<td>10.4 ± 3.4</td>
</tr>
<tr>
<td>π⁺π⁺π⁻</td>
<td>&lt; 22</td>
<td>&lt; 41</td>
</tr>
<tr>
<td>ρ⁺⁺π⁻</td>
<td>48.5 ± 13.4+5.8</td>
<td>27.6 ± 8.4</td>
</tr>
</tbody>
</table>

All analyses are statistics-limited. Main sources of systematics are: tracking eff.: 2.5% /track; π⁰ eff.: 5% /π⁰; Monte Carlo statistics: 2-7%