Charmless hadronic B decays with BaBar

Eugenia Maria Teresa Puccio
on behalf of the BaBar collaboration
Talk outline

- The experiment
- Analysis techniques
- The results:
  - $B^+ \rightarrow \rho^0 K^*$; $B^+ \rightarrow f_0 K^*$
  - $B^+ \rightarrow \phi \phi K^*$; $B^0 \rightarrow \phi \phi K_S$
  - $B^0 \rightarrow K^+ \pi^- \pi^0$
  - $B^+ \rightarrow K^+ \pi^0 \pi^0$
- Conclusion
PEP-II and BaBar

- PEP-II B-Factory collided $e^+e^-$ asymmetric beams at $\Upsilon(4S)$ energy threshold

- BaBar in operation from 1999 – 2008
- All analyses presented use full BaBar $\Upsilon(4S)$ dataset
  - 432 fb$^{-1}$ at the $\Upsilon(4S)$
  - 467M $\bar{B}B$ pairs
Why charmless B decays?

- Charmless B decays probe dynamics of weak and strong interactions
  - Contributions from both penguin and trees can lead to direct CP violation
  - Time dependent measurements and interferences between intermediate states allow to measure all CKM angles
- Allow searching for New Physics from new particles in loops – look for enhanced BF or CP asymmetry ($A_{CP}$)
Analysis techniques

- Use precise kinematical information from beam: $m_{ES}$ and $\Delta E$
- Distinguish light $q\bar{q}$ from $b\bar{b}$ using event topology:
  - $B$ mesons produced almost at rest in the $\Upsilon(4S)$ frame – isotropic event
  - continuum produced with large kinetic energy – jet-like event
- Combine event topology variables in a Neural Network or Fisher discriminant and use output:
  - apply selection to reject continuum
  - as variable in ML fit

$$m_{ES} = \sqrt{E_{\text{beam}}^* - p_B^*}$$

$$\Delta E = E_B^* - E_{\text{beam}}^*$$
**B^+ → ρ^0K^{*+}, f_0K^{*+} : Motivation**

- Model independent predictions give large longitudinal polarisation fractions ($f_L$) in $B \rightarrow VV$ decays
  - Experimental results give $f_L \approx 0.5$ in penguin dominated $b \rightarrow s$ decays
- $B^+ → ρ^0K^{*+}$ not yet observed
  - Predictions from QCD give $BF \approx (5 \pm 1) \times 10^{-6}$
B$^+ \rightarrow \rho^0 K^{**}, f_0 K^{**} : Results


- Reconstruct $\rho^0/f_0$ in decay to $\pi^+\pi^-$
- Reconstruct $K^{**}$ to $K_S\pi^+$ and $K^+\pi^0$
- ML fit with 7 variables
- Results consistent with previous BaBar upper limit
- First observation of $B^+ \rightarrow \rho^0 K^{**}$ with $5.3\sigma$ significance
- $f_L$ compatible with current experimental results in $b \rightarrow s$ decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>$N_{signal}$</th>
<th>BF (x10$^{-6}$)</th>
<th>$A_{CP}$ (%)</th>
<th>$f_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \rho^0 K^{**}$</td>
<td>85 ± 24 ($K_S\pi^+$)</td>
<td>4.6 ± 1.0 ± 0.4</td>
<td>31 ± 13 ± 3</td>
<td>0.78 ± 0.12 ±0.003</td>
</tr>
<tr>
<td></td>
<td>67 ± 31 ($K^+\pi^0$)</td>
<td></td>
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</tr>
<tr>
<td>$B^+ \rightarrow f_0 K^{**}$</td>
<td>69 ± 14 ($K_S\pi^+$)</td>
<td>4.2 ± 0.6 ± 0.3</td>
<td>-15 ± 12 ± 3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>91 ± 20 ($K^+\pi^0$)</td>
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</tbody>
</table>

21 July 2011

EPS HEP 2011
**B→φφK: Motivations**

- SM tree and penguin have similar weak phase
  - No direct CP violation expected
- Significant direct CP asymmetry could be produced by a non-zero CP violating phase
  - Sign of New Physics
- Only $J^P = 0^-$ component of $(φφ)K$ interferes with $η_c$
  - Angular analysis is helpful

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B→φφK: Results

- ML fit to 5 variables: $m_{ES}$, $ΔE$, Fisher, $m_{φ1}$ and $m_{φ2}$
- At $m_{φφ}<2.85$ GeV/c²:
  - $BF(B^+→φφK^+)=(5.6±0.5±0.3)\times10^{-6}$
  - $A_{CP} = -0.10 ± 0.08 ± 0.02$
  - First observation of $BF(B^0→φφK_S)=(4.5±0.8±0.3)\times10^{-6}$
- In $η_c$ region ($2.94<m_{φφ}<3.02$ GeV/c²)
  - $A_{CP} = -0.09 ± 0.10 ± 0.02$ is consistent with SM expectations
Measuring $\gamma$ in $B \rightarrow K \pi \pi$

- Form isospin triangles from $K^*\pi$ modes: $^1$
  - From $B^0 \rightarrow K^+\pi^-\pi^0$ $^2$
  - From $B^0 \rightarrow K_S\pi^+\pi^-$ $^3$

- Resultant amplitude:
  $$3A_3 = A\left( B^0 \rightarrow K^*\pi^- \right) + \sqrt{2}A\left( B^0 \rightarrow K^{0}\pi^0 \right)$$

- Phase $\Phi_{3/2}$ determined from combinations of phases and amplitudes

- $\Phi_{3/2}$ is related to $\gamma$ up to corrections for EW penguins

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$^2$Phys.Rev.D83:112010,2011 (results shown here)

$^3$B.Aubert et al., Phys. Rev. D80, 112001
The $K^+\pi^-\pi^0$ Dalitz plot

- Overlap region of resonances small
  - Effect on event density is subtle
  - Crucial to understand backgrounds and efficiencies in interference regions.

- ML fit with $m_{ES}$, $\Delta E'$, $NN_{out}$ and DP
  - Maximise separation between signal and background
  - Signal category includes signal from misreconstructed events
Results from $B^0 \rightarrow K^+\pi^-\pi^0$


- $BF(B^0 \rightarrow K^+\pi^-\pi^0) = (38.5\pm1.0\pm3.9) \times 10^{-6}$
- $3.1\sigma$ evidence of direct CP violation in $B^0 \rightarrow K^{*+}\pi^-$
- Poor sensitivity to $\Phi_{3/2}$ since $\bar{A}_{3/2}(K^*\pi)$ close to zero.
- $\Phi_{3/2}(\rho K) = (-10^{+10}_{-20}^{+7}_{-22})^\circ$

<table>
<thead>
<tr>
<th>Isobar</th>
<th>$B \times 10^{-6}$</th>
<th>$\bar{\Phi}$ [°]</th>
<th>$\Phi$ [°]</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)^-K^+$</td>
<td>6.6 ± 0.5 ± 0.8</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
<td>0.20 ± 0.09 ± 0.08</td>
</tr>
<tr>
<td>$\rho(1450)^-K^+$</td>
<td>2.4 ± 1.0 ± 0.6</td>
<td>75 ± 19 ± 9</td>
<td>126 ± 25 ± 26</td>
<td>-0.10 ± 0.32 ± 0.09</td>
</tr>
<tr>
<td>$\rho(1700)^-K^+$</td>
<td>0.6 ± 0.6 ± 0.4</td>
<td>18 ± 36 ± 16</td>
<td>50 ± 38 ± 20</td>
<td>-0.36 ± 0.57 ± 0.23</td>
</tr>
<tr>
<td>$K^{*+}(892)^+\pi^-$</td>
<td>8.0 ± 1.1 ± 0.8</td>
<td>33 ± 22 ± 20</td>
<td>39 ± 25 ± 20</td>
<td>-0.29 ± 0.11 ± 0.02</td>
</tr>
<tr>
<td>$K^{*+}(892)^0\pi^0$</td>
<td>3.3 ± 0.5 ± 0.4</td>
<td>29 ± 18 ± 6</td>
<td>17 ± 20 ± 8</td>
<td>-0.15 ± 0.12 ± 0.04</td>
</tr>
<tr>
<td>$(K\pi)^+\pi^-$</td>
<td>34.2 ± 2.4 ± 4.1</td>
<td>-167 ± 16 ± 37</td>
<td>-130 ± 22 ± 22</td>
<td>0.07 ± 0.14 ± 0.01</td>
</tr>
<tr>
<td>$(K\pi)^0\pi^0$</td>
<td>8.6 ± 1.1 ± 1.3</td>
<td>13 ± 17 ± 12</td>
<td>10 ± 17 ± 16</td>
<td>-0.15 ± 0.10 ± 0.04</td>
</tr>
<tr>
<td>NR</td>
<td>2.8 ± 0.5 ± 0.4</td>
<td>48 ± 14 ± 6</td>
<td>90 ± 21 ± 15</td>
<td>0.10 ± 0.16 ± 0.08</td>
</tr>
</tbody>
</table>
Search for $B^+ \rightarrow K^+\pi^0\pi^0$: Motivations

- Possible hints of New Physics in measurements of rates and asymmetries in $B \rightarrow K\pi^{1,2}$.
- More precise measurements needed for all observables in $B \rightarrow K\pi$ or look at $B \rightarrow K^*\pi$ decays$^3$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$BF \times 10^{-6}$</th>
<th>$A_{\text{cp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{*+}\pi^-$</td>
<td>10.3 ± 1.1</td>
<td>-0.23±0.08</td>
</tr>
<tr>
<td>$K^{*+}\pi^0$</td>
<td>6.9 ± 2.3</td>
<td>0.04±0.29±0.05$^4$</td>
</tr>
<tr>
<td>$K^{0}\pi^+$</td>
<td>9.9 + 0.8 - 0.9</td>
<td>-0.02+0.067-0.061</td>
</tr>
<tr>
<td>$K^{0}\pi^0$</td>
<td>2.4 ± 0.7</td>
<td>-0.15±0.12±0.02</td>
</tr>
</tbody>
</table>

- Improved measurement of $K^{*+}\pi^0$ needed.
- Only 3-body $K\pi\pi$ Dalitz plot not measured.
- Study light mesons in $\pi^0\pi^0$ spectrum eg. $f_0(980)$.

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$^1$ B.Aubert et al. (BABAR), Phys. Rev. D76, 091102 (2007), 0707.2798


$^4$ B.Aubert et al. (BABAR), Phys. Rev. D71, 111101 (2005), hep-ex/0504009
Search for $B^+ \rightarrow K^+ \pi^0 \pi^0$: Inclusive results

Preliminary results – To be submitted to Phys. Rev. D

- ML fit to two variables $m_{ES}$ and $NN_{out}$:
  - DP analysis not possible at present
    - Large fractions of misreconstructed signal events – difficult to model
  - $\Delta E$ dependent on DP position, not included in fit to avoid biases
  - Signal component includes also misreconstructed signal events
- $BF(B^+ \rightarrow K^+ \pi^0 \pi^0) = (16.2 \pm 1.2 \pm 1.5) \times 10^{-6}$ with more than 10$\sigma$ significance
- $A_{CP} = -0.06 \pm 0.06 \pm 0.04$

$N_{sig} = 1220 \pm 85$

![Graph showing events vs $m_{ES}$]
Search for $B^+ \rightarrow K^+ \pi^0 \pi^0$: resonances

Preliminary results – To be submitted to Phys. Rev. D

- Select resonance signal region in corresponding signal invariant mass reproduced from sWeights
- Yields from nonresonant and other resonances estimated as a normalised average of two sideband regions

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Results</th>
<th>Previous world average</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow f_0 (\rightarrow \pi^0 \pi^0) K^+$</td>
<td>$BF = (2.79 \pm 0.57 \pm 0.51) \times 10^{-6}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A_{CP} = (18 \pm 18 \pm 4)%$</td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+}(892) \pi^0$</td>
<td>$BF = (8.2\pm1.5\pm1.1) \times 10^{-6}$</td>
<td>$BF = (6.9\pm2.3) \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$A_{CP} = (-6\pm24\pm4)%$</td>
<td>$A_{CP} = (4\pm29)%$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \chi_{c0} K^+$</td>
<td>$BF = (182\pm78\pm32) \times 10^{-6}$</td>
<td>$BF = (133^{+19}_{-16}) \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$A_{CP} = (-96\pm37\pm4)%$</td>
<td>$A_{CP} = (-11\pm12)%$</td>
</tr>
</tbody>
</table>

2.5σ significance measured from $\chi_{c} \rightarrow \pi^{+}\pi^{-}$
Conclusion

- BaBar continues to produce many new physics results in charmless B decays
- Most of these results agree with Standard Model prediction but some puzzles still remain
  - polarisation puzzle
  - “Kπ” puzzle
- More statistics are needed to see if these discrepancies are an indication of New Physics
- Need data from current and future experiments
$\boldsymbol{B \to \phi \phi K}$: Angular analysis

Definition of angles:
• angle between $K^+$ momentum from $\phi_i$ decay wrt to the boost in the $\phi \phi$ rest frame
• dihedral angle between $\phi_1$ and $\phi_2$ in $\phi \phi$ rest frame
• angle between a $\phi$ meson wrt to the boost from $B^+$ rest frame

In $\eta_c$ region consistent with $J^p = 0^-$

Below $\eta_c$ more consistent with $J^p = 0^+$
**$K^* \pi$ Amplitudes and penguins**

\[ A_{\frac{3}{2}} = \frac{1}{\sqrt{2}} A(B^0 \rightarrow K^{*+}\pi^-) + A(B^0 \rightarrow K^{*0}\pi^0) \]

- Tree component expected to be small compared to dominant QCD penguin in $K^*\pi$ amplitudes
- QCD penguin contributions cancel in the sum of $A_{K^*\pi}$
  - $A_{3/2}$ is QCD penguins free (not EWP penguin free)

\[ A_{K^{*0}\pi^0} = \frac{1}{\sqrt{2}} A_{K^{*+}\pi^-} \]
$K^+\pi^-\pi^0$ DP: $K^*\pi$ vs $\rho K$ amplitudes

- $\bar{A}_{3/2}(K^*\pi)$ found to be consistent with 0:
  - Uncertainties on $\Phi_{3/2}$ too large

$$\bar{A}^3 = \frac{1}{\sqrt{2}} A(B^0 \to \rho^+K^-) + \bar{A}(B^0 \to \rho^0K^0)$$

From $B^0 \to K^+\pi^-\pi^0$ DP

- Situation in $\rho K$ decays found to be more favorable.

$$\bar{A}_3(K^*\pi) = \frac{1}{\sqrt{2}} \bar{A}_{K^*\pi}$$

$$A_{3/2}(\rho K) = \frac{1}{\sqrt{2}} A_{\rho K^0}$$

All from $B^0 \to K^+\pi^-\pi^0$ DP
Results from time dependent $B^0 \rightarrow K_S \pi^+ \pi^-$

- BaBar result from 383 million $B\bar{B}$
  - $\Delta \phi = (58.3 \pm 32.7 \pm 4.6 \pm 8.1)^\circ$
  - $\Delta \phi = (176.6 \pm 28.8 \pm 4.6 \pm 8.1)^\circ$
  (errors are stat, syst, model)

- Belle results from 657 million $B\bar{B}$:
  - $\Delta \phi = (-0.7 \pm 24.2 \pm 11 \pm 18)^\circ$
  - $\Delta \phi = (+14.6 \pm 19.2 \pm 11 \pm 18)^\circ$
  (errors are stat, syst, model)

- Difference between solutions is interference between $K_0^{*\pm}(1430)$ and NR

- This phase difference includes the $B^0\bar{B}^0$ mixing phase (-2$\beta$)

B.Aubert et al., Phys. Rev. D80, 112001
J.Dalseno et al., Phys. Rev. D79, 072004
$K^{*+} \pi^- \text{ and } K^{*-} \pi^+ \text{ phase difference}$

$B^0 \rightarrow K^+_S \pi^+ \pi^-$

$$\Delta \phi_{K^* \pi} = \bar{\phi}_{K^{*-} \pi^+} - \phi_{K^{*+} \pi^-}$$

- Measure $K^* \pi$ phases relative to each other due to mixing
  - Additional phase of $-2\beta$ needs to be accounted for.
Issue 1 - Phase conventions

- Each quasi-two body subsystem of $K\pi\pi$ in the vector meson rest frame contains:
  - Two pseudoscalar decay products with momentum $q$ and $-q$
  - The bachelor pseudoscalar with momentum $p$
- Choice of which resonance daughter is defined to have positive momentum defines the phase convention
- Alternative choice induces a $180^\circ$ flip of the phase
- Whichever choice is made it must be correctly accounted for when combining amplitudes to obtain the constraint on the UT apex
\[ A_3 = \frac{1}{2} T e^{i\gamma} - P_{EWP} \]

\[ A_3 \propto \left( \rho + i\eta \right) \left( 1 + \frac{r_3}{2} \right) + C \left( 1 - \frac{r_3}{2} \right) \]

Wilson coeff, \( \lambda \approx -0.27 \)

**SU(3) decomposition of operators gives good approximation:**

**Ratio of hadronic matrix elements**

\[ r_3 = \frac{A_{\rho^+\pi^0} - A_{\rho^0\pi^+}}{A_{\rho^+\pi^0} + A_{\rho^0\pi^+}} - \sqrt{2} \left[ A_{K^+\bar{K}^0} - A_{K^+\bar{K}^*0} \right] \]

Gronau et al., Phys.Rev.D75, 014002
Estimating $r_{3/2}$

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>BF(x10⁻⁶)</th>
<th>$A_{CP}$</th>
</tr>
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<tbody>
<tr>
<td>$B^+ \rightarrow \rho^0\pi^+$</td>
<td>8.3 $^{+1.2}_{-1.3}$</td>
<td>0.18 $^{+0.09}_{-0.17}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^+\pi^0$</td>
<td>10.9 $^{+1.4}_{-1.5}$</td>
<td>0.02 ± 0.11</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\bar{K}$</td>
<td>0.68 ± 0.19</td>
<td>-</td>
</tr>
<tr>
<td>$B^+ \rightarrow K_SK_S\pi^+$</td>
<td>&lt; 0.51</td>
<td>-</td>
</tr>
</tbody>
</table>

BFs are well measured
Amplitudes small but relative phases unknown


Strategy – Separate into well-measured components and systematic uncertainty

\[
r_{\frac{3}{2}} = \frac{A_{\rho^+\pi^0} - A_{\rho^0\pi^+}}{A_{\rho^+\pi^0} + A_{\rho^0\pi^+}} \pm \sqrt{2} \frac{A_{K^+\bar{K}^0} - A_{K^0\bar{K}^0}}{A_{K^+\bar{K}^0} + A_{K^0\bar{K}^0}} \pm 30\% SU(3)
\]

$m_s \approx 30\% \Lambda_{QCD}$
Measurement of $r_{3/2}$

$3\%$ SU(3) breaking

$30\%$ SU(3) breaking

$\pm \text{Im}(r_{3/2})$ vs $\text{Re}(r_{3/2})$

$A_{\rho^+\pi^0} - A_{\rho^0\pi^+}$

$\frac{r_3}{2} \equiv \frac{A_{\rho^+\pi^0} - A_{\rho^0\pi^+}}{A_{\rho^+\pi^0} + A_{\rho^0\pi^+}}$

Contours darkest to lightest: 1, 2, 3, 4, 5σ

A. Wagner, PhD Thesis, SLAC-R-942

- K*K contribution added as a systematic.
Determining \( \gamma \) from \( B \to \rho K \)

- Another method involves using \( B \to \rho K \) with \( K^+\pi^-\pi^0 \) and \( K_S\pi^+\pi^- \)
- Subtle difference with \( K^*\pi \): relative phase not measured directly:
  - \( \rho^+K^- \) measured from \( K^+\pi^-\pi^0 \)
  - \( \rho^0K_S \) measured from \( K_S\pi^+\pi^- \)
- \( A_{3/2} \) determined from difference between the phases relative to \( K^{*+}\pi^- \)

EW penguin contributions follow again from \( \rho\pi \) like in \( K^{*}(892)\pi \) case
Interference fractions

\[ FF_{ij} = \frac{\int_{DP} 2 \text{Re} \left[ c_i c_j^* F_i(m_+^2, m_-^2) F_j^*(m_+^2, m_-^2) \right] d(m_+^2) d(m_-^2)}{\int_{DP} \left| \sum_j c_j F_j(m_+^2, m_-^2) \right|^2 d(m_+^2) d(m_-^2)} \]

- Gives the extent of the interference effect between two resonances as measured in the fit.
- It’s a convention independent representation of the event population of the DP
  - +\( FF_{ij} \) = constructive interference
  - -\( FF_{ij} \) = destructive interference