Hadronic B Decays at Belle

T’Mir D. Julius
Outline

- $\mathbf{B} \rightarrow \phi \pi$
  - arXiv:1206.4760v1
  - New upper limit

- $\mathbf{B} \rightarrow K\pi, KK, \pi\pi$
  - $K^+\pi^-, K^+\pi^0, K^0\pi^+, \pi^+\pi^-, K^+K^0, K^0K^0$ branching fraction and $A_{CP}$ using final Belle dataset
  - New $K^0\pi^0$ branching fraction using final Belle dataset
  - New $\pi^+\pi^-$ branching fraction using final Belle dataset

- $\mathbf{B} \rightarrow K K$
  - New $K^+K^-$ upper limit using final Belle dataset
Hadronic B Decays

- Charmless B decays provide an excellent probe into the accuracy of the Standard Model.

- Measurement of Branching Fractions and $A_{CP}$ can be used to measure CKM parameters.

- Measurements can confirm theoretical predictions, or indicate the presence of New Physics.
Dataset

- Using $\Upsilon(4S)$ data collected using the Belle detector at the KEKB asymmetric $e^+e^-$ collider

- $B \rightarrow \phi \pi$ is measured using $657 \times 10^6$ BB pairs after processing

- All other analyses are performed on the full Belle $\Upsilon(4S)$ dataset of $772 \times 10^6$ BB pairs
Event selection and analysis

- B meson candidates are identified using two kinematic variables
  - $M_{BC} = \sqrt{E_{Beam}^2 - \sum_i p_i^2}$
  - $\Delta E = \sum_i E_i - E_{Beam}$

- These analyses all make use of a continuum suppression variable made up of a combination of event properties combined in to a likelihood ratio (LR)
Continuum Suppression

- Typical continuum suppression variables include the:
  - Modified Super Fox Wolfram moments combined using a Fisher discriminant
  - The distance between the vertices of the reconstructed $B$ and the tag-side $B$ ($\Delta Z$) (charged track modes only)
  - The $B$ flight direction with respect to the beam axis ($\text{Cos}(B)$)
$B \rightarrow \phi \pi$

- $B \rightarrow \phi \pi$ is forbidden at tree level and can only proceed through penguin processes.

- Expected SM branching fraction:
  - $B^0 \rightarrow \phi \pi^0 \sim 6.8 \times 10^{-9}$
  - $B^+ \rightarrow \phi \pi^+ \sim 3.2 \times 10^{-8}$ (Y. Li et al. Phys. Rev. D 80, 014024 (2009))

- Upper limits from BaBar:
  - $B^0 \rightarrow \phi \pi^0 < 2.8 \times 10^{-7}$
  - $B^+ \rightarrow \phi \pi^+ < 2.4 \times 10^{-7}$

- A precise measurement provides a means to study SM from suppressed diagrams in other modes including non-perturbative effects.

- An enhanced branching fraction could indicate CMSSM, or the presence of a $Z'$ boson.
Analysis

- \( \Phi \) candidates are created from a pair of charged kaons with an invariant mass within 2.5\( \sigma \) of the \( \Phi \) full width.

- The \( K^+K^- \) is then combined with either a \( \pi^+ \) or a \( \pi^0 \) candidate.

- \( M_{BC} > 5.2 \text{GeV} \), and \( |\Delta E| < 0.1 \) for \( B^+ \rightarrow \phi \pi^+ \) and \( |\Delta E| < 0.4 \) for \( B^0 \rightarrow \phi \pi^0 \).

- The \( M_{BC}-\Delta E \) fit cannot distinguish signal from \( B \rightarrow K^+K^-\pi \).

- Additional background suppression is achieved through the use of \( B \) tagging algorithm.

<table>
<thead>
<tr>
<th>Source of systematic uncertainty</th>
<th>( B &gt; \phi \pi^+ ) (%)</th>
<th>( B &gt; \phi \pi^0 ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC Statistics</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>PID</td>
<td>2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.1</td>
<td>2.0</td>
</tr>
<tr>
<td>( \pi^0 ) eff</td>
<td>-</td>
<td>3.0</td>
</tr>
<tr>
<td>Continuum Likelihood</td>
<td>2.4</td>
<td>4.1</td>
</tr>
<tr>
<td>( N_{BB} )</td>
<td>1.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Results $B \rightarrow \varphi \pi^+$

Signal + Continuum (dotted)
Continuum (dashed)
Non-resonant $B \rightarrow K^+K^-\pi$
Other Background
Total

<table>
<thead>
<tr>
<th></th>
<th>Statistic</th>
<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>4.5</td>
<td>+5.1, -4.3</td>
</tr>
<tr>
<td>$\epsilon$(data)</td>
<td>8.4%</td>
<td>-</td>
</tr>
<tr>
<td>$B \times 10^{-7}$</td>
<td>0.8</td>
<td>+0.9, -0.8</td>
</tr>
<tr>
<td>$B_{UL} \times 10^{-7}$</td>
<td>3.3</td>
<td>-</td>
</tr>
</tbody>
</table>

Projection of fits in the fit region with $\Delta E$ on the left and $M_{BC}$ on the right.
Results $B \rightarrow \phi \pi^0$

<table>
<thead>
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<th></th>
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<th>Systematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>-2.2</td>
<td>+2.1, -1.2</td>
</tr>
<tr>
<td>$\epsilon$ (data)</td>
<td>4.9%</td>
<td>-</td>
</tr>
<tr>
<td>$B \times 10^{-7}$</td>
<td>-0.7</td>
<td>+0.6, -0.4</td>
</tr>
<tr>
<td>$B_{UL} \times 10^{-7}$</td>
<td>1.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Projection of fits in the fit region with $\Delta E$ on the left and $M_{BC}$ on the right.
B $\rightarrow \pi\pi$, K$\pi$, and KK

- Theoretical calculations for these BF have large uncertainties

- These errors will cancel out in ratios of measurements

- The $A_{\text{CP}}$ measurements will help observe SM quantities

- Improved experimental uncertainties can help our understanding of the standard model and help identify New Physics
Analysis

- K⁰ candidates are created from a pair of charged pions with an invariant mass within 5.2σ of the K⁰ full width

\[ \vec{p}_B = \vec{p}_h + \frac{p_{\pi^0}}{|p_{\pi^0}|} \sqrt{(E_{\text{Beam}} - E_h)^2 - m_{\pi^0}^2} \]

- Decays with a π⁰ in the final state use an M_{BC} that accounts for the shower leakage in the ECL

- In the case of modes similar to each other (B⁰→K⁺π⁻ and B⁰→π⁺π⁻, B⁺→K⁺π⁰ and B⁺→π⁺π⁰, and B⁺→K⁰π⁺ and B⁺→K⁰K⁺) a simultaneous fit was performed on both modes at once

- Other modes were fitted separately

- Shapes were fitted in 3 dimensions - M_{BC}, ΔE and the continuum suppression variable
\[ \Delta A_{K\pi} = A_{CP}(K\pi^0) - A_{CP}(K\pi) \]

- As \( B \rightarrow K^+\pi^0 \) and \( B^0 \rightarrow K^+\pi^- \) have very similar leading order Feynman diagrams, we would expect them to have similar \( A_{CP} \)

- A difference could indicate the enhancement of the colour suppressed tree diagram

- However, the previous Belle result found the sign and magnitude of these asymmetries to be different

- The difference in these could indicate new Physics, such as a difference between direct CP in neutral and charged B decays
# B → K$^+\pi^-$ and B → $\pi^+\pi^-$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Branching Fraction x 10$^{-6}$</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B → K$^{+/−}$</td>
<td>7525 ± 127</td>
<td>20.00 ± 0.34 ± 0.63</td>
<td>-0.069 ± 0.014 ± 0.007</td>
</tr>
<tr>
<td>B → $\pi^+\pi^-$</td>
<td>2111 ± 89</td>
<td>5.04 ± 0.21 ± 0.19</td>
<td>$Update$ $coming$ $soon$</td>
</tr>
</tbody>
</table>

Previous Belle Result $A_{CP}$ B → K$\pi$:

-0.094 ± 0.018 ± 0.008

Using 535 x 10$^6$ BB pairs


Current Results:

- BaBar: -0.107 ± 0.016

arXiv:0807.4226

- CDF: -0.086 ± 0.023 ± 0.009

PRL 106, 181802 (2011)

- LHCb: -0.088 ± 0.011 ± 0.008

PRL 108, 201601 (2012)
**B → K\(^+\)\(\pi^0\) and B → \(\pi^+\)\(\pi^0\)**

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<tr>
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<th>Branching Fraction x 10(^{-6})</th>
<th>(A_{CP})</th>
</tr>
</thead>
<tbody>
<tr>
<td>B → K(^+)(\pi^0)</td>
<td>3731 ± 92</td>
<td>12.62 ± 0.31 ± 0.56</td>
<td>+0.043±0.024±0.002</td>
</tr>
<tr>
<td>B → (\pi^+)(\pi^0)</td>
<td>1846 ± 82</td>
<td>5.86 ± 0.26 ± 0.38</td>
<td>+0.025±0.043±0.007</td>
</tr>
</tbody>
</table>

**Previous Belle Result**

\(A_{CP} B \rightarrow K\pi^0\):

0.07±0.03 ±0.01

Using 535 x 10\(^6\) BB pairs


\(A_{CP} B \rightarrow \pi\pi^0\):

0.07±0.06 ±0.01

Using 535 x 10\(^6\) BB pairs

\[ \Delta A_{K\pi} = A_{CP}(K\pi^0) - A_{CP}(K\pi) \]

- Previous Belle Result:
  \[ \Delta A_{K\pi} = +0.164 \pm 0.037 \quad 4.4 \sigma \]

- New Result:
  \[ \Delta A_{K\pi} = +0.112 \pm 0.028 \quad 4 \sigma \]
**B → K^{0}π^{+/0} and B → K^{0}K^{+/0}**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>Branching Fraction x 10^{-6}</th>
<th>A_{CP}</th>
</tr>
</thead>
<tbody>
<tr>
<td>B → K^{0}π^{+}</td>
<td>3229 ± 71</td>
<td>23.97^{+0.53}_{-0.52} ± 0.69</td>
<td>-0.014±0.021 ± 0.006</td>
</tr>
<tr>
<td>B → K^{0}K^{+}</td>
<td>134 ± 23</td>
<td>1.11^{+0.19}_{-0.18} ± 0.05</td>
<td>+0.017±0.168±0.002</td>
</tr>
<tr>
<td>B → K^{0}K^{0}</td>
<td>103 ± 15</td>
<td>1.26^{+0.19}_{-0.18} ± 0.06</td>
<td>-</td>
</tr>
<tr>
<td>B → K^{0}π^{0}</td>
<td>961 ± 45</td>
<td>9.68 ±0.46 ±0.50</td>
<td>-</td>
</tr>
</tbody>
</table>

**Graphs:**

- **K^{0}π^{+}**
- **K^{0}π^{0}**
- **K^{0}K^{+}**
- **K^{0}K^{0}**
- **M_{bc}(GeV/c^2)**
- **ΔE(GeV)**

ICHEP 2012
T. D. Julius
The branching fraction of $B \rightarrow K^+K^-$ is expected to be 2 orders of magnitude smaller than $B \rightarrow K^+\pi^-$. $B \rightarrow K^+\pi^-$ is a large background for this mode. $B \rightarrow \pi^+\pi^-$ also makes a contribution.
$$B \rightarrow K^+K^-$$

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<tr>
<th>Mode</th>
<th>Yield</th>
<th>Branching Fraction x 10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow K^+K^-$</td>
<td>35 ± 29</td>
<td>$0.10 \pm 0.08 \pm 0.04$ (&lt; 0.20) to 1.2σ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>BF x 10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle 2007</td>
<td>$0.09^{+0.18}_{-0.13} \pm 0.01$ (&lt; 0.41)</td>
</tr>
<tr>
<td>Babar 2007</td>
<td>$0.04 \pm 0.15 \pm 0.08$ (&lt; 0.5)</td>
</tr>
<tr>
<td>PDG 2010</td>
<td>$0.15^{+0.11}_{-0.10}$ (&lt; 0.41)</td>
</tr>
<tr>
<td>LHCb 2012 (Preliminary)</td>
<td>$0.11^{+0.05}_{-0.04} \pm 0.06$ (&lt; 0.18)</td>
</tr>
</tbody>
</table>
The $A_{CP}$ Sum rule

- While $A_{K\pi}$ asymmetry can be explained by colour suppressed tree diagrams, the $A_{CP}$ sum rule is a model independent, and should hold (Gronau et al. hep-ph/0608040)

- The $A_{CP}$ sum rule is found to be non-zero to $2\sigma$

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_2}{\tau_+} = A_{CP}(K^+\pi^0) \frac{2B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_2}{\tau_+} + A_{CP}(K^0\pi^0) \frac{2B(K^0\pi^0)}{B(K^+\pi^-)}$$

$$A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+) \frac{\Gamma(K^0\pi^+)}{\Gamma(K^+\pi^-)} = A_{CP}(K^+\pi^0) \frac{2\Gamma(K^+\pi^0)}{\Gamma(K^+\pi^-)} + A_{CP}(K^0\pi^0) \frac{2\Gamma(K^0\pi^0)}{\Gamma(K^+\pi^-)}$$

Left side - right side = $-0.270 \pm 0.142$

Using $A_{cp}(K^0\pi^0=+0.14+-0.13+-0.06)_{PRD 81, 011101, (2010) Belle.}$
Conclusion

- New branching fractions and direct $A_{CP}$ are available for $B \rightarrow hh$ the final Belle dataset with improved analyses (Publication coming soon!!)

- A new, improved upper limit is available for $B \rightarrow \phi \pi$ from Belle

- The ratios present in $B \rightarrow hh$ are consistent with the expected theoretical values, and have errors that are comparable with theoretical errors

- $K^+K^-$ upper limits were improved by a factor of 2