Recent Charmonium Results from Belle

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- Brief overview of KEKB and Belle
- First observation of $B^\pm \to \chi_{c1} \pi^\pm$
- First observation of $B^0 \to J/\psi \eta$
- Search for $B \to J/\psi \eta' K$
- Charmonium branching fractions through $B \to \phi \phi K$
- Conclusions
$L_{\text{peak}} = 1.65 \times 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1}$

$\int L \, dt = 649 \, \text{fb}^{-1}$

The analyses presented here are based on 388-449 million B-pairs.
Recent Charmonium Results from Belle

**The Belle Detector**

SVD vertex resolution:

SVD1: $\sigma_{dz} = (42 \pm 44 / p \beta \sin(\theta)^{5/2}) \mu m$, $\sigma_{d_1} = (19 \pm 54 / p \beta \sin(\theta)^{3/2}) \mu m$

SVD2: $\sigma_{dz} = (28 \pm 32 / p \beta \sin(\theta)^{5/2}) \mu m$, $\sigma_{d_1} = (22 \pm 36 / p \beta \sin(\theta)^{3/2}) \mu m$

CDC + SVD momentum resolution: $\sigma_{p_t} / p_t = (0.19 p_t \pm 0.30 / \beta) \%$

ECL energy resolution: $\sigma_E / E(\text{GeV}) = \left[ \begin{array}{c} 0.066 E^{1/4} + 0.81 + 1.34 \end{array} \right] \%$ [1.6% at 1 GeV]

ECL position resolution: $\sigma = (0.27 + \frac{3.4}{E^{1/2}} + \frac{1.8}{E^{1/4}}) \text{mm}$

<table>
<thead>
<tr>
<th>Kaon ID</th>
<th>Electron ID</th>
<th>Muon ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel ACC, TOF, CDC $(0.5 &lt; p &lt; 4.0) \text{GeV}/c$</td>
<td>$(1.0 &lt; p &lt; 3.0) \text{GeV}/c$</td>
<td>$(1.0 &lt; p &lt; 3.0) \text{GeV}/c$</td>
</tr>
<tr>
<td>$\epsilon(K) = (87.99 \pm 0.12) %$</td>
<td>$\epsilon(e) = (92.4 \pm 0.4) %$</td>
<td>$\epsilon(\mu) = (92.5 \pm 0.8) %$</td>
</tr>
<tr>
<td>$\epsilon(\pi) = (8.53 \pm 0.10) %$</td>
<td>$\epsilon(\pi) = (0.25 \pm 0.02) %$</td>
<td>$\epsilon(\pi) = (2.76 \pm 0.09) %$</td>
</tr>
<tr>
<td>Endcap ACC, CDC $(0.8 &lt; p &lt; 4.0) \text{GeV}/c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\epsilon(K) = (82.67 \pm 0.43) %$</td>
<td>$\epsilon(K) = (0.43 \pm 0.07) %$</td>
<td>$\epsilon(K) = (3.3 \pm 0.8) %$</td>
</tr>
<tr>
<td>$\epsilon(\pi) = (7.81 \pm 0.29) %$</td>
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</table>
First Observation of $B^\pm \rightarrow \chi_{c1} \pi^\pm$

The decay $B^\pm \rightarrow \chi_{c1} K^\pm$ has recently been measured by both Belle and BaBar:

$B^- \rightarrow \left\{ \begin{array}{c} b \\ \bar{u} \end{array} \right\} \chi_{c1}$

$B^+ \rightarrow \left\{ \begin{array}{c} \bar{c} \\ \bar{u} \end{array} \right\} K^+$

$B^\pm \rightarrow \chi_{c1} \pi^\pm$, the Cabbibo-suppressed counterpart of $B^\pm \rightarrow \chi_{c1} K^\pm$, is expected to occur with a relative branching fraction of $|V_{cd}/V_{cs}|^2 \approx 5\%$

A $b \rightarrow d \ c \ \bar{c}$ penguin contribution may lead to direct CP-violation in $B^\pm \rightarrow \chi_{c1} \pi^\pm$
First Observation of $B^\pm \rightarrow \chi_{c1} \pi^\pm$

- $\chi_{c1}$ candidates are reconstructed through the decay $\chi_{c1} \rightarrow \gamma J/\psi$

- B-candidates are selected using the kinematic variables $M_{bc} \equiv \sqrt{E_{cm}^2 - p_B^*}$
  and $\Delta E \equiv E_B^* - E_{cm}$

\[\Delta M \equiv M(\ell^+\ell^-\gamma) - M(\ell^+\ell^-)\]
First Observation of $B^\pm \rightarrow \chi_{c1} \pi^\pm$

- Perform a binned maximum likelihood fit to the $\Delta E$ distribution.

- Observe 1597 ± 48 events for $B^\pm \rightarrow \chi_{c1} K^\pm$, and 55 ± 10 events for $B^\pm \rightarrow \chi_{c1} \pi^\pm$:

$$B(B^\pm \rightarrow \chi_{c1} \pi^\pm) = (2.2 \pm 0.4 \pm 0.3) \times 10^{-5}$$

$$\frac{B(B^\pm \rightarrow \chi_{c1} \pi^\pm)}{B(B^\pm \rightarrow \chi_{c1} K^\pm)} = (4.3 \pm 0.8 \pm 0.3)\%$$

- Statistical significance: 6.3 $\sigma$

Based on $388 \times 10^6 B\bar{B}$ events
First Observation of $B^\pm \rightarrow \chi_{c1} \pi^\pm$

- Search for direct CP violation:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_-$</th>
<th>$N_+$</th>
<th>$A_{CP} = \frac{N_- - N_+}{N_- + N_+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow \chi_{c1} \pi^\pm$</td>
<td>$29 \pm 7$</td>
<td>$25 \pm 7$</td>
<td>$0.07 \pm 0.18 \pm 0.02$</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \chi_{c1} K^\pm$</td>
<td>$792 \pm 31$</td>
<td>$807 \pm 31$</td>
<td>$-0.01 \pm 0.03 \pm 0.02$</td>
</tr>
</tbody>
</table>

- This represents the first observation of $B^\pm \rightarrow \chi_{c1} \pi^\pm$

- Measured branching fraction:
  - is consistent with the factorization hypothesis
  - indicates that the tree-level diagram is dominant

- Published in PRD 74, 051103 (2006)
First Observation of $B^0 \to J/\psi \eta$

- CP eigenstate
- If the main contribution to this decay is the tree-level diagram, then, assuming factorization and a pseudoscalar mixing angle of $-17^\circ$, we can expect the branching fraction for $B^0 \to J/\psi \eta$ to be $\sim 63\%$ of that for $B^0 \to J/\psi \pi^0$,
  \[ B(B^0 \to J/\psi \pi^0) = (2.2 \pm 0.4) \times 10^{-5} \] (PDG 2006)
- Provides a test for higher-order contributions such as penguin pollution
- Previous studies were able to yield only upper limits, but the statistics available now make a branching-fraction measurement possible.
First Observation of $B^0 \to J/\psi \eta$

- Reconstruct $\eta$ through its decays $\eta \to \gamma \gamma$ and $\eta \to \pi^+ \pi^- \pi^0$
- Perform unbinned maximum likelihood fit to the $\Delta E$ spectrum
- Observe $43.1 \pm 8.9$ events with $\eta \to \gamma \gamma$, and $16.6 \pm 5.8$ events with $\eta \to \pi^+ \pi^- \pi^0$

$$B^0 \to J/\psi \eta(\eta \to \gamma \gamma)$$

double gaussian + Crystal Ball function + 2$^{\text{nd}}$-order polynomial

signal and background shapes fixed based on MC

statistical significance: $8.1 \sigma$

based on $449 \times 10^6 B \bar{B}$ events
First Observation of $B^0 \rightarrow J/\psi \eta$

- Measured branching fractions:
  - $B(B^0 \rightarrow J/\psi \eta) = (9.5 \pm 2.0) \times 10^{-6}$ for $\eta \rightarrow \gamma \gamma$
  - $B(B^0 \rightarrow J/\psi \eta) = (10.1 \pm 3.5) \times 10^{-6}$ for $\eta \rightarrow \pi^+ \pi^- \pi^0$
  - combined: $B(B^0 \rightarrow J/\psi \eta) = (9.6 \pm 1.7 \pm 0.7) \times 10^{-6}$

- This represents the first observation of $B^0 \rightarrow J/\psi \eta$

- Branching fraction is $(44 \pm 12)\%$ of that for $B^0 \rightarrow J/\psi \pi^0$
  - consistent with expectations based on factorization and the quark model
  - tree-level contribution appears to be dominant

- posted as hep-ex/0609047
Search for $B \rightarrow J/\psi \eta' K$

- This decay requires the creation of an $s \bar{s}$ quark pair in the final state.

- Two possible mechanisms for such a decay:
  - Three-body decay:
    $$
    \overline{B}^0 \rightarrow b \rightarrow W^{+} \rightarrow c + \bar{c} \rightarrow J/\psi, \eta' \rightarrow s+\bar{s} \rightarrow K^0
    $$
  - $B^\pm \rightarrow \psi_g K, \psi_g \rightarrow J/\psi \eta'$, where $\psi_g$ is a hybrid charmonium state (i.e., $c\bar{c}g$)

- The similar decay $B \rightarrow J/\psi \phi K$ was observed by CLEO in 2000, with a branching fraction $B(B \rightarrow J/\psi \phi K) = (8.8^{+3.5}_{-3.0} \pm 1.3) \times 10^{-5}$ [PRL 84, 1393 (2000)]

- More recently, BaBar measured the branching fractions:
  $$
  B(B^\pm \rightarrow J/\psi \eta K^\pm) = (10.8 \pm 2.3 \pm 2.4) \times 10^{-5}
  $$
  $$
  B(B^0 \rightarrow J/\psi \eta K^0_S) = (8.4 \pm 2.6 \pm 2.7) \times 10^{-5}
  $$

  Note that these include $B \rightarrow \psi(2S)K, \psi(2S) \rightarrow J/\psi \eta$.

- Hybrid charmonium states may also be involved in $X(3872), Y(4260)$, etc.
Search for $B \rightarrow J/\psi \eta' K$

$B^\pm \rightarrow J/\psi \eta' K^\pm$

- Results of 2-D unbinned maximum-likelihood fit to $\Delta E$ and $M_{bc}$:

- $B(B^\pm \rightarrow J/\psi \eta' K^\pm) < 8.8 \times 10^{-5}$ at 90\% confidence level
- based on $388 \times 10^6 B \bar{B}$ events
- worth revisiting in two years with $\sim 1 \text{ab}^{-1}$
Search for $B \rightarrow J/\psi \eta' K$.

$B^0 \rightarrow J/\psi \eta' K^0_S$

- Results of 2-D unbinned maximum-likelihood fit to $\Delta E$ and $M_{bc}$:
  - $B(B^0 \rightarrow J/\psi \eta' K^0_S) < 2.5 \times 10^{-5}$ at 90% confidence level
  - based on $388 \times 10^6 B \bar{B}$ events
  - unlikely to see anything even with twice as much data

The results are to be submitted to PRL.
Charmonium via $B \rightarrow \phi \phi K$

- A high-statistics analysis has been performed for $B^\pm \rightarrow \phi \phi K^\pm$

Based on $449 \times 10^6 B \bar{B}$ events
Fitting the spectra and using the known branching fractions for $B^\pm \to \eta_c K^\pm$ and $B^\pm \to J/\psi K^\pm$ yields the following charmonium branching fractions:

<table>
<thead>
<tr>
<th>mode</th>
<th>measured branching fraction</th>
<th>PDG 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c \to \phi \phi$</td>
<td>$(2.7^{+0.6}_{-0.5} \pm 0.4) \times 10^{-3}$</td>
<td>$(2.7 \pm 0.9) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta_c \to \phi K^+ K^-$</td>
<td>$(3.9^{+0.7}_{-0.6} \pm 0.6) \times 10^{-3}$</td>
<td>$(2.9 \pm 1.4) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta_c \to 2(K^+ K^-)$</td>
<td>$(2.6^{+0.5}_{-0.4} \pm 0.4) \times 10^{-3}$</td>
<td>$(1.5 \pm 0.7) \times 10^{-3}$</td>
</tr>
<tr>
<td>$J/\psi \to \phi K^+ K^-$</td>
<td>$(1.2 \pm 0.3 \pm 0.1) \times 10^{-3}$</td>
<td>$(1.83 \pm 0.24) \times 10^{-3}$</td>
</tr>
<tr>
<td>$J/\psi \to 2(K^+ K^-)$</td>
<td>$(9.7^{+1.7}_{-1.6} \pm 1.0) \times 10^{-4}$</td>
<td>$(7.08 \pm 1.4) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- contributed to ICHEP 2006
Conclusions

- We have observed several Cabbibo-suppressed B decays to charmonium.
  - First observation of $B^\pm \to \chi_{c1} \pi^\pm$:
    \[
    \frac{B(B^\pm \to \chi_{c1} \pi^\pm)}{B(B^\pm \to \chi_{c1} K^\pm)} = (4.3 \pm 0.8 \pm 0.3)\% , \text{ consistent with S. M. prediction}
    \]
  - First observation of $B^0 \to J/\psi \eta$:
    \[
    B(B^0 \to J/\psi \eta) = (9.6 \pm 1.7 \pm 0.7) \times 10^{-6} , \text{ consistent with S. M. prediction}
    \]
  - So far, no significant direct CP-violation observed.
Conclusions

- Various multi-body B decays to charmonium have also been studied:
  - Upper limits at 90% confidence level for $B \rightarrow J/\psi \eta' K$:
    
    $B(B^+ \rightarrow J/\psi \eta' K^\pm) < 8.8 \times 10^{-5}$
    $B(B^0 \rightarrow J/\psi \eta' K^0_s) < 2.5 \times 10^{-5}$
  - Branching fractions have been obtained for $\eta_c$ and $J/\psi$ decays to $\phi \phi$, $\phi K^+ K^-$, and $2(K^+ K^-)$ by studying $B^\pm \rightarrow 2(K^+ K^-) K^\pm$

- See also A. Imoto's poster presentation on $B^0 \rightarrow J/\psi \pi^+ \pi^-$. 

- Stay tuned for more charmonium results from Belle!