ϒ(5S) Decays at Belle

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KEK

Lausanne, 14. September 2009
KEKB and Belle detector

**KEKB**: asymmetric $e^+e^-$ collider (3.5 on 8.0 GeV): Tsukuba, Japan

**B meson factory**: $e^+e^- \rightarrow \Upsilon(4S), \Upsilon(5S) \rightarrow BB$

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**Luminosity**

- **Peak**: $2.11 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (World record with crab cavities (06/2009))
- **Integrated**
  - Total: 950 fb$^{-1}$
  - $\Upsilon(4S)$: 710 fb$^{-1}$ (≈772M BB pairs, $B=B^+$ or $B^0$)
  - $\Upsilon(5S)$: 100 fb$^{-1}$

**Today's results**: 23.6 fb$^{-1}$

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Solid angle coverage $\sim$92%
Particle identification $\pi,K,e,\mu,p$
Events at the \( \Upsilon(5S) \)

- **e\(^+\)e\(^-\) collisions at \( \Upsilon(5S) \) energy**
  - bb events
  - uu, dd, ss, cc (continuum)
  - QED (ee, \( \mu \mu, \tau \tau \)) ISR
  - \( \Upsilon \) + hadrons (eg. \( \Upsilon(1S) \pi \pi \))

- Bs events
  - \( B^*_s \) events
    - \( B^*_sB^*_s \), \( B^*_sB_s \), \( B_sB_s \)
  - \( B (B^+ \text{ or } B^0) \) events
    - \( B^*B^* \), \( B^*B \), \( BB \), \( B^*B^\pi \), \( B^*B_\pi \), \( BB_\pi \), \( BB_\pi \pi \)

- Today
  - Bs decays

- \( B_s \) excited states decay to \( B_s \) \( \gamma \)
**B** \(_{(s)}\) reconstruction

- \(B\)\(_{(s)}\) selected using the \(M_{bc}\) (\(M_{ES}\)) and \(\Delta E\) variables:

\[
M_{bc} = \sqrt{(E_{CM}/2)^2 - (p_B^{CM})^2}
\]

\[
\Delta E = E_B^{CM} - E_{CM}/2
\]

- Difficult to fully reconstruct \(B\)\(_{(s)}\)* mesons:
  de-excitation \(\gamma\) too soft
- But the different B production decays are well separated

\(B_s \rightarrow D_s \pi\)
\(B \rightarrow D \pi\)
(one B is reconstructed)
Continuum suppression

- $B_s$ produced with low momentum
- Continuum produced with a lot

- Fox-Wolfram moments: $R_2$, SFW (Super Fox-Wolfram)

Fox, Wolfram, PRL 41, 1581 (1978)
Recent $B_s$ results from Belle
B_s at the $\Upsilon(5S)$

bb cross-section measured by continuum subtraction

2 fb$^{-1}$ at $\Upsilon(5S)$

Drutskoy et al. (Belle), PRL 98, 052001 (2007)

e$^+e^-$ collisions at $\Upsilon(5S)$

$\sigma_{\Upsilon(5S)} = (0.302 \pm 0.015)$ nb

$\sigma_{\Upsilon(4S)} \sim 1.1$ nb

$B_s, B^+, B^0$

$\Upsilon(5S)$

continuum (scaled)
$B_s$ at the $\Upsilon(5S)$

$B_s$ meson production fraction ($f_s$) measured with inclusive D and $D_s$

$$\mathcal{B}(\Upsilon(5S) \rightarrow D_s X)/2 = f_s \times \mathcal{B}(B_s \rightarrow D_s X) + (1 - f_s) \times \mathcal{B}(B \rightarrow D_s X)$$

We measure

We measure absolute branching fractions!

$$(19.5^{+3.0}_{-2.3})\%$$

In 23.6 fb$^{-1}$, 2.8 millions $B_s$ mesons

$\sim$15% uncertainty, mainly due to $f_s$

September 14, 2009
$B_s$ at the $\Upsilon(5S)$

$B_s^{(*)}B_s^{(*)}$ production fractions measured with fully reconstructed $B_s \to D_s \pi$ decays

$$f_{B_s^*B_s^*} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$$
$$f_{B_s^*B_s} = (7.3^{+3.3}_{-3.0} \pm 0.1)\%$$

Louvot, Wicht, Schneider et al. (Belle), PRL 100, 021801, 2009
CKM-favored modes

- We have studied:
  - $B_s \rightarrow D_s^* \pi^+, D_s^* \rho^+$ and $D_s \rho^+$

- With these high-statistics modes, we can:
  - Measure absolute branching fractions
    - proton colliders can't!
  - $B_s$ and $B_s^*$ masses
    - Intrinsically interesting and can also be compared with $B^0$ and $B^*$.
  - $B_s^{(*)}B_s^{(*)}$ production fractions

- Was done with $B_s \rightarrow D_s \pi^+$ already

Louvot, Wicht, Schneider et al. (Belle), PRL 100, 021801, 2009

- These modes are difficult at hadron colliders ($D_s^*, \rho$)
Analysis strategy

- Sub-modes
  - $\rho^+ \to \pi^+ \pi^0$
  - $D_s \to \phi \pi, K^*(892)K, K_SK$
    - $\phi \to KK$
    - $K^*(892) \to K\pi$
    - $K_S \to \pi\pi$
  - $D_s^* \to D_s \gamma$
- PID to separate $K$ and $\pi$
- Mass cuts
- Continuum suppression
- Best candidate selection: masses and PID
$B_s \rightarrow D_{s}^{*} \rho^{+}$

Preliminary, EPS09, 23.6 fb$^{-1}$

Background from continuum only
~73 signal events are observed in the $B_s^{*}B_s^{*}$ region (8.6σ)

First observation!

\[
\mathcal{B}(B_s^0 \rightarrow D_{s}^{*-} \rho^{+}) = (13.0^{+2.3}_{-2.1}(\text{stat.})\pm1.7(\text{syst.})\pm1.7(\text{pol.})\pm1.9(f_s)) \times 10^{-3}
\]

pol. means polarization (decay to two vector-particles), will be measured for the final result

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Background from $B_s \rightarrow D_s^* \rho^+$

~87 signal events are observed in the $B_s^*B_s^*$ region (10.1σ)

First observation!

\[ \mathcal{B}(B_s^0 \rightarrow D_s^- \rho^+) = (8.5^{+1.3}_{-1.2}\text{(stat.)} \pm 1.1\text{(syst.)} \pm 1.3(f_s)) \times 10^{-3} \]
$B_s \to D_s^* \pi^+$

Preliminary, EPS09, 23.6 fb$^{-1}$

Background from $B_s \to D_s \pi^+$ and $D_s \rho^+$

$\sim$54 signal events are observed

in the $B_s^*B_s^*$ region (8.4$\sigma$)

First observation!

$\mathcal{B}(B_s^0 \to D_s^{*-}\pi^+) = (2.4^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.4(f_s)) \times 10^{-3}$

September 14, 2009
### Some systematics

<table>
<thead>
<tr>
<th>( N_{B_s^+B_s^-} )</th>
<th>( B_s^0 \rightarrow D_s^- \pi^+ ) [6, 8]</th>
<th>( B_s^0 \rightarrow D_s^+ K^\mp ) [6, 8]</th>
<th>( B_s^0 \rightarrow D_s^{*-} \pi^+ )</th>
<th>( B_s^0 \rightarrow D_s^- \rho^+ )</th>
<th>( B_s^0 \rightarrow D_s^{*-} \rho^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sum \varepsilon \mathcal{B} ) ((10^{-3}))</td>
<td>15.8 ± 0.2 ± 1.0</td>
<td>11.2 ± 0.2 ± 0.7</td>
<td>9.13 ± 0.15 ± 0.59</td>
<td>4.40 ± 0.10 ± 0.28</td>
<td>2.69 ± 0.07 ± 0.18</td>
</tr>
<tr>
<td>( \mathcal{B} ) ((10^{-3}))</td>
<td>3.7^{+0.4}_{-0.3} ± 0.4 ± 0.6</td>
<td>0.24^{+0.12}_{-0.10} ± 0.03 ± 0.03</td>
<td>2.4^{+0.5}_{-0.4} ± 0.3 ± 0.4</td>
<td>8.5^{+1.3}_{-1.2} ± 1.1 ± 1.3</td>
<td>13.0^{+2.3}_{-2.1} ± 1.7 ± 1.7 ± 1.9</td>
</tr>
<tr>
<td>( m_{B_s^0} ) ((\text{MeV}/c^2))</td>
<td>5364.4 ± 1.3</td>
<td>—</td>
<td>5364.4^{+5.5}<em>{-3.4}^{+0.6}</em>{-0.8}</td>
<td>5372.3^{+4.2}_{-4.1} ± 0.7</td>
<td>5376.4^{+6.1}<em>{-3.2}^{+0.6}</em>{-0.4}</td>
</tr>
<tr>
<td>( m_{B_s^*} ) ((\text{MeV}/c^2))</td>
<td>5416.4 ± 0.4</td>
<td>—</td>
<td>5416.7 ± 0.6^{+0.2}_{-0.1}</td>
<td>5416.1 ± 0.7 ± 0.1</td>
<td>5416.1 ± 0.8 ± 0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative systematics: (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-f_s ) [5]</td>
</tr>
<tr>
<td>(-S \rightarrow VV) polarization</td>
</tr>
<tr>
<td>Others: ( L_{\text{int}} ) [22]</td>
</tr>
<tr>
<td>( \sigma_{\text{bb}} ) [3, 4]</td>
</tr>
<tr>
<td>( f_{B_s^+B_s^-} ) [6]</td>
</tr>
<tr>
<td>Branch. frac. [5]</td>
</tr>
<tr>
<td>Efficiency (cut)</td>
</tr>
<tr>
<td>Efficiency (MC stat.)</td>
</tr>
<tr>
<td>Tracking [23]</td>
</tr>
<tr>
<td>( \pi^\pm/K^\mp) ID [24]</td>
</tr>
<tr>
<td>( \gamma ) ID [25]</td>
</tr>
<tr>
<td>( \pi^0 ) ID [21]</td>
</tr>
<tr>
<td>PDF shape</td>
</tr>
</tbody>
</table>
CP eigenstates

- We have studied
  - $B_s \rightarrow K^+ K^-, K_s K_s, \pi^+ \pi^-, K^- \pi^+$
  - $B_s \rightarrow J/\psi \eta, J/\psi \eta'$

- CP eigenstates are used to measure CP violation parameters: $\beta_s$, $\Delta \Gamma_s$, ...
  
  Dunietz, Fleischer, Nierste, PRD 63, 114015 (2001)

  - At Belle, we are not able to resolve the fast $B_s$ oscillations (SVD resolution is insufficient, or $B_s$ don't have enough momentum).
    However, $\Delta \Gamma_s/\Gamma_s$ is accessible.

- $B_s \rightarrow K^+ K^-$ is related to $B^0 \rightarrow \pi^+ \pi^-$ by SU(3)
  
  - Can test the presence of New Physics by comparing CP asymmetries
  
  - Can measure the CKM angle $\gamma$ using the U-spin symmetry.
$B_s \rightarrow hh$ analysis

- Not much to say
- Continuum suppression uses (high-momentum) lepton tag
  - Leptons at Belle are more frequently produced in B decays than by continuum
    - Harder cut when no lepton is found
- Background is continuum only. Except in $B_s \rightarrow K\pi$: small $B_s \rightarrow KK$ background (misidentification)
$B_s \to K^+ K^-$

23 candidates observed, 5.8$\sigma$

Improved limit!

$B(B_s^0 \to K^+ K^-) = (3.8^{+1.0}_{-0.9} \pm 0.7) \times 10^{-5}$

$B(B_s^0 \to K^0 \bar{K}^0) < 6.6 \times 10^{-5}$ (90% CL)


$B(B_s^0 \to K^+ K^-) = (2.4 \pm 0.1 \pm 0.5) \times 10^{-5}$ 1.3k events...

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$B_s \rightarrow \pi^+ \pi^-, K^- \pi^+$

Suppressed decays compared to $B_s \rightarrow K K$

No significant signals in both modes

$B_s \rightarrow \pi^+ \pi^-$

$B_s \rightarrow K^- \pi^+$

$\mathcal{B}(B_s^0 \rightarrow \pi^+ \pi^-) < 1.2 \times 10^{-5} \ (90\% \ CL)$

$\mathcal{B}(B_s^0 \rightarrow K^- \pi^+) < 2.6 \times 10^{-5} \ (90\% \ CL)$

CDF
PRL 103, 031801 (2009)

$\mathcal{B}(B_s^0 \rightarrow \pi^+ \pi^-) = (0.49 \pm 0.28 \pm 0.36) \times 10^{-6} (< 1.2 \times 10^{-6})$

$\mathcal{B}(B_s^0 \rightarrow K^- \pi^+) = (5.0 \pm 0.7 \pm 0.8) \times 10^{-6}$
\( B_s \rightarrow J/\psi \ \eta, \ J/\psi \ \eta' \) strategy

- Submodes:
  - \( J/\psi \rightarrow e^+e^-, \mu^+\mu^- \)
  - \( \eta \rightarrow \gamma\gamma \) and \( \eta \rightarrow \pi^+\pi^-\pi^0 \)
    - \( \pi^0 \rightarrow \gamma\gamma \)
  - \( \eta' \rightarrow \eta\pi^+\pi^- \) and \( \eta' \rightarrow \rho^0\gamma \)
    - \( \rho^0 \rightarrow \pi^+\pi^- \)
- Continuum subtraction but also important contribution from \( B \rightarrow J/\psi \) (irreducible)
  - \( B \rightarrow J/\psi \): yield and shape obtained from MC
  - Continuum: obtained from \( J/\psi \) sidebands
  - Background parameters fixed in the fit
- A simultaneous fit is performed on each \( \eta \) or \( \eta' \) submodes (\( J/\psi \) combined)
$B_s \to J/\psi \eta$

Preliminary, updated for Beauty09, 23.6 fb$^{-1}$

$J/\psi \to e^+e^-, \mu^+\mu^-$

$\eta \to \gamma\gamma$

$\eta \to \pi^+\pi^-\pi^0$

Combined

Simultaneous fit of the two $\eta$ decays

Very little background from continuum and $B \to J/\psi$

$\sim 15 \pm 4$ signal events in the $B_s^*B_s^*$ region (7.3$\sigma$)

First observation!

$\mathcal{B}(B \to J/\psi\eta) = (3.3 \pm 0.9\text{(stat.)} \pm 0.3\text{(syst.)} \pm 0.4(f_s)) \times 10^{-4}$

September 14. 2009
$\mathcal{B}(B \rightarrow J/\psi \eta') = (3.1 \pm 1.2{\text{(stat.)}}^{+0.5}_{-0.6}{\text{(syst.)}} \pm 0.38(f_s)) \times 10^{-4}$

First evidence!

11±5 total signal events in the $B_s^*B_s^*$ region (3.8σ)

Simultaneous fit of 3 $\eta'$ modes
Background: continuum and $B \rightarrow J/\psi$

$\eta' \rightarrow \eta\pi\pi$: very little background
$\eta' \rightarrow \rho^0\gamma$: dirty

September 14, 2009
$B^+$ and $B^0$ at the $\Upsilon(5S)$

$e^+e^-$ collisions at $\Upsilon(5S)$ energy

- $bb$ events
- $\Upsilon + \text{hadrons}$ (e.g., $\Upsilon(1S)\pi\pi$)
- $uu,dd,ss,cc$ (continuum)
- QED ($ee, \mu\mu, \tau\tau$, ISR)

$B_s$ events

$B$ ($B^+$ or $B^0$) events

- $B^*B^*$
- $B^*B$
- $BB$
- $B^*B\pi$
- $B^*\pi$
- $BB\pi$
- $BB\pi\pi$

2-body

3-body

4-body

Study these final states!
General strategy

Reconstruct well-known (BF uncertainties ~3-5%) and clean (only charged tracks) B decays

- \( B^+ \to J/\psi K^+ \), \( B^+ \to D^0(K^+\pi^-)\pi^+ \) and \( B^+ \to D^0(K^+3\pi)\pi^+ \)
- \( B^0 \to J/\psi K^* \) and \( B^0 \to D^-(K^+2\pi^-)\pi^+ \)

DATA: \( B^+ \to J/\psi K^+ \)
$B^+ \rightarrow D^0(K^+\pi^-)\pi^+$

$B^0 \rightarrow J/\psi K^{*0}$

$B^+ \rightarrow D^0(K^+3\pi)\pi^+$

$B^0 \rightarrow D^-(K^+2\pi^-)\pi^+$

$B^0 \rightarrow J/\psi K^{*0}$
**B⁺/₀ fractions**

The total signal yield is extracted from “Mᵦc+ΔE-5.28”.

\[ \text{B}^+ \rightarrow \text{D}^0(\text{K}^+\pi^-)\pi^+ \quad \text{B}^+ \rightarrow \text{D}^0(\text{K}^3\pi) \pi^+ \quad \text{B}^0 \rightarrow \text{D}^-\text{(K}^+2\pi^-)\pi^+ \quad \text{B}^+ \rightarrow \text{J}/\psi\text{K}^+ \quad \text{B}^0 \rightarrow \text{J}/\psi\text{K}^0 \]

Knowing the branching fractions and efficiency, one can compute the fraction of B⁺ and B₀.

\[ f(B) = \frac{Y}{(L_{\text{int}} \times \sigma_{\text{b\bar{b}}} \times \epsilon \times B)} \]

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Yield, events</th>
<th>Efficiency, %</th>
<th>( f(B^{+/0}) ), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^+ \rightarrow J/\psi K^+ )</td>
<td>221±16</td>
<td>3.62 ± 0.06</td>
<td>83.8±5.9 ± 7.2</td>
</tr>
<tr>
<td>( B^0 \rightarrow J/\psi K^*0 )</td>
<td>105 ± 11</td>
<td>1.44 ± 0.03</td>
<td>77.1±8.3 ± 7.9</td>
</tr>
<tr>
<td>( B^+ \rightarrow D^0(K\pi)\pi^+ )</td>
<td>215 ± 21</td>
<td>1.05 ± 0.03</td>
<td>59.2 ± 5.7 ± 5.1</td>
</tr>
<tr>
<td>( B^+ \rightarrow D^0(K3\pi)\pi^+ )</td>
<td>275 ± 32</td>
<td>1.28 ± 0.04</td>
<td>62.3±7.3 ± 7.5</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^-\pi^+ )</td>
<td>247 ± 25</td>
<td>1.98 ± 0.06</td>
<td>65.3 ± 6.7 ± 7.2</td>
</tr>
</tbody>
</table>

\[ f(B) = (68.5^{+3.0}_{-2.9} \pm 5.0)\% \]

Remember \( f_s = (19.5^{+3.0}_{-2.3})\% \)
Disentangle 2-body modes

Fit $M_{bc}$ distribution for $M_{bc} < 5.35$ (2-body threshold), all modes combined.

Background is subtracted using sidebands.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B\bar{B}$</td>
<td>5.1 ± 0.9 ± 0.4</td>
</tr>
<tr>
<td>$B\bar{B}^* + B^* \bar{B}$</td>
<td>12.6 ± 1.2 ± 1.0</td>
</tr>
<tr>
<td>$B^* \bar{B}^*$</td>
<td>34.5 ± 1.9 ± 2.7</td>
</tr>
<tr>
<td>3,4-body</td>
<td>16.4 ± 1.6 ± 1.2</td>
</tr>
</tbody>
</table>

Theory predicts 3,4-body fraction to be around (0.03-0.3) %

Lellouch et al, NPB 405, 55 (1993)
Disentangle 3-body modes

Reconstruct \( B_{\text{rec}} \) and \( \pi_{\text{rec}} \) → get missing B meson (\( B_{\text{miss}} \))

In CM: \( P(B_{\text{rec}}\pi_{\text{rec}}) = P(B_{\text{miss}}) \), \( E(B_{\text{rec}}\pi_{\text{rec}}) + E(B_{\text{miss}}) = E_{\text{CM}} \)

\[
M_{bc}^{\text{miss}} = \sqrt{(E_{CM}/2)^2 - (P(B_{\text{rec}}\pi_{\text{rec}}))^2}
\]

\[
\Delta E_{\text{miss}} = E(B_{\text{rec}}\pi_{\text{rec}}) - E_{CM}/2
\]

Only \( B^*B\pi \) is significantly seen
Knowing pion reconstruction efficiency, one can get the fractions.

The residual ($BB\pi\pi$) being half of the 3,4-body is also unexpected! $BB\pi\pi$ phasespace is really small! ($M_{Y(5S)} - M_{BB\pi\pi} \sim 37$ MeV)
Summary

- Many $B_s$ decays have been studied:
  - CKM-favored: $B_s \rightarrow D_s^* \pi^+, D_s^* \rho^+$ and $D_s \rho^+$
    - First observations, large signals seen (8-10σ)
  - CP eigenstates:
    - Charmless: $B_s \rightarrow K^+ K^-, K_s K_s, \pi^+ \pi^-, K^- \pi^+$
      - $B_s \rightarrow K^+ K^-$ observed
    - $B_s \rightarrow J/\psi \eta, J/\psi \eta'$: first observation and evidence
  - Many of these final states can only be studied at $e^+e^-$ collider!
- Study of $B^+$ and $B^0$ production at $\Upsilon(5S)$ energy for the first time
  - Theory cannot predict rate of 3 and 4-body decays!
- All results were based on 23.6 fb$^{-1}$: four times more on tape! More results in the pipeline!
  - Belle is also reprocessing its data! Tracking is new: you can even expect more than four times better.