$B_s$ and $\Upsilon(5S)$ decays at Belle

きぼう (kibō) means hope

Jean Wicht (KEK)
Beauty 2011
April 4$^{th}$ 2011
Data samples at $\Upsilon(5S)$

$\Upsilon(4S)$ above $B_s^*B_s^*$ threshold

$B_s$ can be produced and studied at B-factory was established by CLEO

$\Upsilon(5S)$ does also of course decay to $B^+$ and $B^0$

Can be excited and produced with pions

$\Rightarrow B^*(n\pi)$

And to $\Upsilon(nS)\pi\pi$, etc...

Belle took about $\sim140$ fb$^{-1}$ around the $\Upsilon(5S)$

121.4 fb$^{-1}$ at the resonance

$\sim20$ fb$^{-1}$ in scans

Much larger than CLEO, BaBar: <1 fb$^{-1}$

Compared to 711 fb$^{-1}$ at the $\Upsilon(4S)$

J. Wicht: $B_s$ and $\Upsilon(5S)$ decays at Belle
Absolute BF measurement

J. Wicht: $B_s$ and $\Upsilon(5S)$ decays at Belle

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

**Number of $b\overline{b}$**: $\Upsilon(4S)$ off-resonance data (continuum) subtraction

$$N_{b\overline{b}}^{\Upsilon(5S)} = \frac{1}{\epsilon_{b\overline{b}}^{\Upsilon(5S)}} \left( N_{\text{hadr}}^{\Upsilon(5S)} - N_{\text{cont}}^{\Upsilon(5S)} \frac{L_{\text{hadr}}}{L_{\text{cont}}} \frac{E_{\Upsilon(5S)}^2}{E_{\text{cont}}^2} \frac{\epsilon_{\text{rec}}^{\Upsilon(5S)}}{\epsilon_{\text{cont}}^{\text{rec}}} \right)$$

$B_s$ production fraction ($f_s$)

Take advantage of $\mathcal{B}(B_s \rightarrow D_s X) \gg \mathcal{B}(B \rightarrow D_s X)$

$$\mathcal{B}(B \rightarrow D_s X) = (8.3 \pm 0.7\%)$$

$$\mathcal{B}(B_s \rightarrow D_s X) = (92 \pm 11\%)$$

We measure with $\Upsilon(5S)$ data

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

BaBar@$\Upsilon(4S)$

In 121.4 fb$^{-1}$: 14 million $B_s$ mesons (~18% uncertainty)
Reconstruction of $B_s$ 

Using well-known $M_{bc}$ and $\Delta E$ variables taking advantage of $e^+e^-$ annihilation to two $B$

$$M_{bc} = \sqrt{(E_{CM}^2/2) - (p_{B_s}^{CM})^2}$$

$$\Delta E = E_{B_s}^{CM} - E_{CM}/2$$

Three possible $\Upsilon(5S)$ decays: $B_s^*B_s^*$, $B_s^*B_s$ and $B_sB_s$

We don't reconstruct the $\sim$50MeV photon from $B_s^*$ decay to $B_s$.

Three regions in $M_{bc}$-$\Delta E$ plane (well separated)

\[\text{Diagram showing regions labeled } B_s^*B_s^*, B_s^*B_s, \text{ and } B_sB_s\]

\[\sim90\% \text{ of } B_s \text{ are produced through } B_s^*B_s^*\]
Observation of $B_s \rightarrow J/\psi \ f_0(980)$
and evidence of $B_s \rightarrow J/\psi \ f_0(1370)$

PRL 106 121802 (2011)
121.4 fb$^{-1}$
\[ \mathcal{B}_s \rightarrow J/\psi f_0(980) \]

- **Silver mode for LHCb** to measure $\beta_s$, the CP-violating phase in the $B_s$ mixing  

- BF 2-5 times smaller than $B_s \rightarrow J/\psi \phi$ BUT $J/\psi f_0$ is a **pure CP-eigenstate** ($S \rightarrow VS$ versus $S \rightarrow VV$)
  - No angular analysis required

- **Branching fraction**

  - Extrapolation from $B_s \rightarrow J/\psi \phi$
    \[
    \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi f_0) \mathcal{B}(f_0 \rightarrow \pi^+ \pi^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \mathcal{B}(\phi \rightarrow K^+ K^-)} \approx 0.2 \]
    
    \[= 0.42 \pm 0.11\]

  - CDF's $J/\psi \phi \Rightarrow \mathcal{B}(B_s^0 \rightarrow J/\psi f_0) \mathcal{B}(f_0 \rightarrow \pi^+ \pi^-) = (1.3 - 2.7) \times 10^{-4}$

  - **Theory (QCD@LO)**
    \[
    \mathcal{B}(B_s^0 \rightarrow J/\psi f_0) \mathcal{B}(f_0 \rightarrow \pi^+ \pi^-) = (3.4 \pm 2.4) \times (50^{+7}_{-9})\% \]
    
    \[= (1.6 \pm 1.3) \times 10^{-4}\]
**B_s \rightarrow J/\psi f_0** results

J/\psi \rightarrow e^+e^-, \mu^+\mu^- and f_0 \rightarrow \pi^+\pi^-; select B_s with M_{bc}; fit M_{\pi\pi} and \Delta E distributions

In the f_0(980) mass region
- all bkg
- B \rightarrow J/\psi X

M_{\pi\pi}:
- f_0(980) parameters fixed from BES (Flatté function)
- f_0(1370) parameters floated (BW function)

The two f_0 can interfere

Non-resonant B \rightarrow J/\psi \pi^+\pi^- signal (non interfering)
B \rightarrow J/\psi X bkg (MC), continuum bkg (sideband data)

<table>
<thead>
<tr>
<th>F</th>
<th>Yield</th>
<th>Significance</th>
<th>( \mathcal{B}(B_s^0 \rightarrow J/\psi F; F \rightarrow \pi\pi) \times 10^{-4} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_0(980)</td>
<td>63^{+16}_{-10}</td>
<td>8.4</td>
<td>1.16^{+0.31}<em>{-0.19},(\text{stat.}) + 0.15^{+0.26}</em>{-0.18},(N_{B_s^0})</td>
</tr>
<tr>
<td>f_0(1370)</td>
<td>19^{+6}_{-8}</td>
<td>4.2</td>
<td>0.34^{+0.11}<em>{-0.14},(\text{stat.}) + 0.03^{+0.08}</em>{-0.05},(N_{B_s^0})</td>
</tr>
</tbody>
</table>

BF in good agreement with predictions
B_s → J/ψ f_0 results

Observation of B_s → J/ψ f_0(980)
First evidence of B_s → J/ψ f_0(1370)
LHCb has also observed J/ψ f_0(980): PLB 698, 115 (2011)

Mass and width of f_0(1370) in good agreement with PDG

Helicity angle distribution is consistent with f_0 being scalars

M = 1.405 ± 0.015^{+0.001}_{-0.007} \text{ GeV}/c^2
Γ = 0.054 ± 0.033^{+0.014}_{-0.003} \text{ GeV}
Observation of $h_b(1P)$ and $h_b(2P)$

arXiv:1103.3419 [hep-ex]
preliminary
contributed to La Thuile 2011
121.4 fb$^{-1}$
\( \Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi \) decays

K.F. Chen et al. (Belle), PRL 100, 112001 (2008); PRD 82, 091106(R) (2010)

- Anomalously large \( \Upsilon(nS)\pi\pi \) transitions at the \( \Upsilon(5S) \) (on-res)

<table>
<thead>
<tr>
<th>Process</th>
<th>( \Gamma_{\text{total}} )</th>
<th>( \Gamma_{e^+e^-} )</th>
<th>( \Gamma_{\Upsilon(1S)\pi^+\pi^-} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^- )</td>
<td>0.032 MeV</td>
<td>0.612 keV</td>
<td>0.0060 MeV</td>
</tr>
<tr>
<td>( \Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^- )</td>
<td>0.020 MeV</td>
<td>0.443 keV</td>
<td>0.0009 MeV</td>
</tr>
<tr>
<td>( \Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^- )</td>
<td>20.5 MeV</td>
<td>0.272 keV</td>
<td>0.0019 MeV</td>
</tr>
<tr>
<td>( \Upsilon(10860) \rightarrow \Upsilon(1S)\pi^+\pi^- )</td>
<td>110 MeV</td>
<td>0.31 keV</td>
<td>0.59 MeV</td>
</tr>
</tbody>
</table>

- 2007: 6-points scan (~1 fb\(^{-1}\) per point)

Maximum of hadrons' production

Does not agree well with the conventional \( \Upsilon(10860) \) line shape

1) \( Y_b \) particle: analog to \( \Upsilon(4260) \) that has anomalously large \( \Gamma(J/\psi\pi\pi) \)

2) Rescattering of \( \Upsilon(5S) \rightarrow BB\pi\pi \rightarrow \Upsilon(nS)\pi\pi \)
Discovery of $h_c$ by CLEO

- CLEO observed $e^+e^- \rightarrow h_c \pi^+ \pi^-$
  - $h_c$ production cross-section seems to be **enhanced near $Y(4260)$**

![Graph showing the production cross-section of $h_c$](image)

- Do we have more chance of seeing $h_b$ at $\Upsilon(5S)$?

J. Wicht: $B_s$ and $\Upsilon(5S)$ decays at Belle
$h_b(nP)$ properties

- $b\bar{b}$ states, spin 0, $L=1$, $J^{PC}=1^{+-}$.
- Expected mass of $h_b(nP)$ at the Center of Gravity (CoG) of $\chi_b$ states
  - Test of hyperfine splitting
- Radiative transition to $\eta_b(1S)$
  - BaBar has obtained evidence ($3.0\sigma$) of $h_b(1P)$ in $\Upsilon(3S)\rightarrow\pi^0h_b(1P)\rightarrow\pi^0\gamma\eta_b(1S)$

arXiv:1102.4565
Analysis procedure

- **Similar to CLEO's $h_c$ analysis: missing mass (MM) technique**
  - Implicit reconstruction of $h_b$ thanks to $e^+e^-$ annihilation
    - $e^+e^- \rightarrow \Upsilon(5S) \rightarrow h_b \pi^+\pi^-$

\[
MM = \sqrt{(P_{\Upsilon(5S)} - P_{\pi^+\pi^-})^2}
\]

- $P_{\Upsilon(5S)}$: CM-energy and boost (accelerator information)
- $P_{\pi^+\pi^-}$: we reconstruct and measure

- Search for peaks in MM when $h_b(nP)$, $\Upsilon$(1-3S), etc... are produced:
  \[
  MM \equiv M_{h_b}
  \]

- **Selection is simple**
  - Pions with opposite charges
    - track originating from IP and particle identification
  - Continuum suppression with event shape
Signal calibration

• Use the large exclusive “ϒ(5S) → ϒ(nS) π⁺π⁻ with ϒ(nS) → μ⁺μ⁻” as reference
  • Signal: CrystalBall tail due to ISR
  • Reflections are also calibrated

ϒ(5S) → ϒ(1S) π⁺π⁻  
ϒ(5S) → ϒ(2S) π⁺π⁻

J. Wicht: B_s and ϒ(5S) decays at Belle
Background

- Most background is random combination of pions that can be described by polynomial function
- At $MM \sim M_{\Upsilon(3S)}$ region: contribution from real $K_S \rightarrow \pi^+\pi^-$ explodes
  - Near threshold: $M_{\Upsilon(3S)} \sim E_{CM} - M_{K_S}$

$K_S$ yield fitted in data as a function of $MM$
Will be used as PDF in the fit
Fit procedure

- **Three** independent fit are performed to MM distribution
  - signals and reflections (calibrated with exclusive decays)
  - combinatorial background: order of polynomial: max of C.L.
- $K_S$ background (3rd region only)

![Graph](image)

$\Upsilon(1S)$  $\Upsilon(2S)$  $\Upsilon(3S)$

$h_b(1P)$  $h_b(2P)$

Fit of 1st region

$\Upsilon(1S)$

background subtracted

J. Wicht: $B_s$ and $\Upsilon(5S)$ decays at Belle
## Results

**Preliminary**

<table>
<thead>
<tr>
<th></th>
<th>Yield ([10^3])</th>
<th>Mass ([\text{MeV}/c^2])</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Upsilon(1S))</td>
<td>105.2 (\pm 5.8 \pm 3.0)</td>
<td>9459.42 (\pm 0.53 \pm 1.02)</td>
<td>18.2</td>
</tr>
<tr>
<td>(h_b(1P))</td>
<td>50.4 (\pm 7.8^{+4.5}_{-9.1})</td>
<td>9898.25 (\pm 1.06^{+1.03}_{-1.07})</td>
<td>5.5</td>
</tr>
<tr>
<td>(\Upsilon(3S) \rightarrow \Upsilon(1S))</td>
<td>55 (\pm 19)</td>
<td>9973.01</td>
<td>2.9</td>
</tr>
<tr>
<td>(\Upsilon(2S))</td>
<td>143.4 (\pm 8.7 \pm 6.8)</td>
<td>10022.25 (\pm 0.41 \pm 1.01)</td>
<td>16.6</td>
</tr>
<tr>
<td>(\Upsilon(1D))</td>
<td>22.1 (\pm 7.8)</td>
<td>10166.2 (\pm 2.4)</td>
<td>2.4</td>
</tr>
<tr>
<td>(h_b(2P))</td>
<td>84 (\pm 7^{+23}_{-10})</td>
<td>10259.76 (\pm 0.64^{+1.43}_{-1.07})</td>
<td>11.2</td>
</tr>
<tr>
<td>(\Upsilon(2S) \rightarrow \Upsilon(1S))</td>
<td>151.6 (\pm 9.7^{+9.0}_{-20.0})</td>
<td>10304.57 (\pm 0.61 \pm 1.03)</td>
<td>15.7</td>
</tr>
<tr>
<td>(\Upsilon(3S))</td>
<td>44.9 (\pm 5.1 \pm 5.1)</td>
<td>10356.56 (\pm 0.87 \pm 1.06)</td>
<td>8.5</td>
</tr>
</tbody>
</table>

J. Wicht: \(B_s\) and \(\Upsilon(5S)\) decays at Belle
Results

- Could the observed states be $\chi_{b1}(nP)$? No
  - Measured masses are $\sim 3\sigma$ off compared to $\chi_{b1}(nP)$
  - $\Upsilon(5S) \to \chi_{b1}(nP)\pi^+\pi^-$ violates isospin (strong interaction)

- Mass are in very good agreement with CoG of $\chi_b$ states
  - $h_b(1P)$: $\Delta M = 1.62 \pm 1.52$ MeV/$c^2$
  - $h_b(2P)$: $\Delta M = 0.48 \pm 1.57$ MeV/$c^2$

- Ratio of production rate

\[
\frac{\Gamma(\Upsilon(5S)\to h_b(1P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S)\to \Upsilon(2S)\pi^+\pi^-)} = 0.407 \pm 0.079^{+0.043}_{-0.076}
\]

\[
\frac{\Gamma(\Upsilon(5S)\to h_b(2P)\pi^+\pi^-)}{\Gamma(\Upsilon(5S)\to \Upsilon(2S)\pi^+\pi^-)} = 0.78 \pm 0.09^{+0.22}_{-0.10}
\]

- Spin of $h_b(nP)$ is 0 while $\Upsilon(nS)$'s are 1: decays to $h_b$ should be suppressed because of spin-flip.
  - $\Upsilon(5S) \to h_b(nP)\pi^+\pi^-$ decays seem exotic!

J. Wicht: $B_s$ and $\Upsilon(5S)$ decays at Belle
Search for $h_b$ at $\Upsilon(4S)$

- Using all our data: 711 fb$^{-1}$ (i.e., six times more data than at $\Upsilon(5S)$)

No significant $h_b$ signal

$\Upsilon(2S)$ decay to $h_b$ is not enhanced

$$\sigma(e^+e^- \rightarrow h_b(1P)\pi^+\pi^-)@\Upsilon(4S) < 0.28 \ (90\% \ CL)$$

\[ \frac{\sigma(e^+e^- \rightarrow h_b(1P)\pi^+\pi^-)@\Upsilon(4S)}{\sigma(e^+e^- \rightarrow h_b(1P)\pi^+\pi^-)@\Upsilon(5S)} < 0.28 \ (90\% \ CL) \]
Future plans

Many results obtained with only one fifth of our data: 23.6 fb⁻¹

<table>
<thead>
<tr>
<th>Bs0 →</th>
<th>Type</th>
<th>B</th>
<th>Signif.</th>
<th>Status</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>φγ</td>
<td>Radiative penguin</td>
<td>(53⁺¹⁸⁻¹²)10⁻⁶</td>
<td>5.5</td>
<td>1st obs.</td>
<td>PRL 100, 121801</td>
</tr>
<tr>
<td>γγ</td>
<td>Radiative penguin</td>
<td>&lt; 8.7 10⁻⁶</td>
<td></td>
<td>Best UL</td>
<td>PRL 100, 121801</td>
</tr>
<tr>
<td>J/ψη</td>
<td>CP-eigenstate</td>
<td>(3.3 ± 0.9 ± 0.5)10⁻⁴</td>
<td>7.3</td>
<td>1st obs.</td>
<td>arXiv:0912.1434</td>
</tr>
<tr>
<td>J/ψη'</td>
<td>CP-eigenstate</td>
<td>(3.1 ± 1.2 ± 0.7)10⁻⁴</td>
<td>3.8</td>
<td>1st evid.</td>
<td>arXiv:0912.1434</td>
</tr>
<tr>
<td>DsDs</td>
<td>CP-eigenstate</td>
<td>(1.0⁺⁰.⁴⁻⁰.³⁻⁰.²)%</td>
<td>6.2</td>
<td></td>
<td>PRL 105, 201802</td>
</tr>
<tr>
<td>Ds*Ds</td>
<td>CP-eigenstate</td>
<td>(2.8⁻⁻⁰.⁷⁺⁺⁰.⁸ ± 0.⁷)%</td>
<td>6.6</td>
<td>1st obs.</td>
<td>PRL 105, 201802</td>
</tr>
<tr>
<td>Ds<em>Ds</em></td>
<td>CP-eigenstate</td>
<td>(3.1⁺⁺¹.²⁻⁻¹.⁰ ± 0.⁸)%</td>
<td>3.1</td>
<td>1st evid.</td>
<td>PRL 105, 201802</td>
</tr>
</tbody>
</table>

Measurement of ΔΓs with Bs → Ds(*)Ds(*)

Need to update!

J. Wicht: Bs and ϒ(5S) decays at Belle
Future plans

• Measure branching fractions as precisely as possible
  • Important for example for $B_s \rightarrow \mu\mu$ BF normalization at LHC
  • Need to improve precision on $f_s$ (fraction of $B_s$)
    - Using new method: dileptons
      • $\Upsilon(5S) \rightarrow B_s(\rightarrow X^- l^+ \nu) \overline{B}_s(\rightarrow X^+ l^- \nu)$
      • $B_s$ oscillate $\sim$40 times faster than $B^0$

<table>
<thead>
<tr>
<th>Lifetime $[10^{-12} \text{s}]$</th>
<th>$\Delta m$ $[10^{12} \bar{\text{h}} \text{s}^{-1}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$</td>
<td>$1.425 \pm 0.041$</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$1.525 \pm 0.009$</td>
</tr>
</tbody>
</table>

• Ratio of “same sign dileptons” to ”opposite sign dileptons” is sensitive to $f_s$
• Reach **5% precision** on $f_s$ according to: arXiv:hep-ph/0604201
Summary

- With 121.4 fb\(^{-1}\) at \(\Upsilon(5S)\)
- Observation of \(B_s \rightarrow J/\psi \ f_0(980)\) and first evidence of \(B_s \rightarrow J/\psi \ f_0(1370)\)
  - CP eigenstates to measure \(\beta_s\) without angular analysis
- First observation of two \(b\bar{b}\) states: \(h_b(1P)\) and \(h_b(2P)\)
  - Masses in agreement with expectations (CoG of \(\chi_b\))
  - Production ratio of \(h_b\) with respect to \(\Upsilon(2S)\) is not suppressed as expected due to the spin-flip
    - Production of \(h_b\) at \(\Upsilon(5S)\) is exotic
- No evidence of \(h_b\) in 711 fb\(^{-1}\) at \(\Upsilon(4S)\)
- Stay tuned for summer results!
## Systematics

<table>
<thead>
<tr>
<th>Polynomial order</th>
<th>Fit range</th>
<th>Signal shape</th>
<th>Selection requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N[h_b], 10^3$</td>
<td>±2.4</td>
<td>±3.6</td>
<td>±1.2</td>
</tr>
<tr>
<td>$M[h_b], \text{MeV/c}^2$</td>
<td>±.04</td>
<td>±.10</td>
<td>±0.04</td>
</tr>
<tr>
<td>$N[h_b(2P)], 10^3$</td>
<td>±2.2</td>
<td>±2.6</td>
<td>±9.0</td>
</tr>
<tr>
<td>$M[h_b(2P)], \text{MeV/c}^2$</td>
<td>±.10</td>
<td>±.20</td>
<td>±1.0</td>
</tr>
</tbody>
</table>

Results are stable

Significance w/ systematics

$h_b(1P) \quad 5.5\sigma$

$h_b(2P) \quad 11.2\sigma$

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$M_{\text{measured}} - M_{\text{PDG}}$ for reference channels

Deviations of reference channels from PDG

$\Rightarrow$ additional uncertainty $\pm 1\text{MeV}$

local variations of background shape?

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