$B_s^0$ Decays at Belle

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The Belle Experiment

The Belle detector

- $e^+ e^-$ collisions
- Located at KEK $B$ factory (Tsukuba, Japan)
- Large-solid-angle ($\sim 92\%$)
- Efficient particle ID ($p$, $\pi^\pm$, $K^\pm$, $\gamma$, $\mu$, $e$, $K^0_L$)
- World luminosity record

$$L_{\text{peak}} = 2.11 \cdot 10^{34} \text{cm}^{-1}\text{s}^{-1}$$

- Data taken at $\Upsilon(5S)$ ($\sqrt{s} = 10867 \pm 1 \text{ MeV}$)
- The only large data sample at this energy:
  - $\sim 23.6 \text{ fb}^{-1} \rightarrow$ this talk
  - Total sample: $\sim 120 \text{ fb}^{-1}$
- $\Upsilon(5S)$ is above $B^0_s \bar{B}^0_s$ threshold

  Study of $B^0_s$ meson possible!

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$B^0_s$ Decays at Belle
Physics at $\Upsilon(5S)$: $B^0_s$ Production

$\sigma(b\bar{b}) = (302 \pm 14) \text{ pb}$

$b\bar{b}$ cross section: subtraction of data taken below open-beauty threshold

$R_2$: 2nd Fox-Wolfram moment $\sim$ event “jettiness”
$\rightarrow$ smaller values for $B\bar{B}$ events (more spherical)
Physics at $\Upsilon(5S)$: $B_{s}^{0}$ Production

Hadronic $\Upsilon(5S)$ events

$\sigma(b\bar{b}) = (302 \pm 14)$ pb

Cleo (PRD 75, 012002)
+ Belle (PRL 98, 052001)

$B_{s}^{0}$ events

$B_{s}^{0}$, $B^{0}$, $B^{+}$ events

$fb \geq (2.8 \pm 0.3)\%$
Belle (PRL 100, 112001)

$15\%$ uncertainty, mainly due to model-dependent estimates.

Dominant systematics for our branching fractions.

Current normalization, in 23.6 fb$^{-1}$ (today's data set):

$$N_{B_{s}^{0}} = 2 \cdot L_{\text{int}} \cdot \sigma(b\bar{b}) \cdot f_{s} \approx 2.8 \cdot 10^{6}$$

Alternative methods under consideration. The most promising:

$B_{s}^{0}$ oscillate faster than $B^{0}$: informations on $N(B_{s}^{0})/N(B^{+/0})$ from fraction of same sign dileptons [Sia & Stone, PRD 74, 031501 (06)]
Physics at $\Upsilon(5S)$: $B_s^0$ Production

- Full reconstruction of the $B_s^0$. Observables: $(E_b^* = \sqrt{s}/2)$
  - Beam-constrained mass: $M_{bc} = \sqrt{E_b^{*2} - p_{B_s^0}^{*2}}$
  - Energy difference: $\Delta E = E_{B_s^0}^* - E_b^*$
- 3 production modes:
  $\Upsilon(5S) \to B_s^* \bar{B}_s^*$, $\Upsilon(5S) \to B_s^* \bar{B}_s^0$ and $\Upsilon(5S) \to B_s^0 \bar{B}_s^0$.
- $B_s^* \to B_s^0 \gamma$ cannot be reconstructed ($\gamma$ too soft)
- In the $(M_{bc}, \Delta E)$ plane, $B_s^0$ candidates are in 3 signal regions
A “standard candle” for $B_0^s$: $B_0^s \to D_s^- \pi^+$

RL et al. (Belle) Phys. Rev. Lett. 102, 021801 (2009)

$B_0^s \to D_s^- \pi^+$

$\langle M_{bc} \rangle = m_{B_s}$

$\langle \Delta E \rangle = \sqrt{E_b^2 - (m_{B_s}^2 - m_{B_s}^2)} - E_b$

Belle 23.6 fb$^{-1}$

$B_0^s \to D_s^- \pi^+$

$N_{B_s^* B_s^*} = 145^{+14}_{-13}$

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

$m_{B_s^*} = (5416.4 \pm 0.4 \pm 0.5) \text{ MeV}/c^2$

$m_{B_0^s} = (5364.4 \pm 1.3 \pm 0.7) \text{ MeV}/c^2$

$\mathcal{B}(B_0^s \to D_s^- \pi^+) = \left(3.67^{+0.35}_{-0.33} \text{(stat.)}^{+0.43}_{-0.42} \text{(syst.)} \pm 0.49(f_s)\right) \times 10^{-3}$

- 20% uncertainties, $f_s$ is a crucial source of systematics
- large $f_{B_s^* B_s^*}$ confirmed (1st Belle value: $(93^{+7}_{10}) \pm 1)\%$ [PRD 76, 012002 (07)]
- $m_{B_s^*}$ is $2.6\sigma$ larger than CLEO [O. Aquines et al. (CLEO) PRL 96, 152001 (06)].
- $m_{B_s^*}$ ($m_{B_0^s}$) is the 1st (2nd) most precise measurement so far.
Study of $B_s^0 \rightarrow D_s^{*-} \rho^+$


- Scalar → Vector + Vector: Longitudinal and Transverse polarizations are possible.
- Decay width depends on the “longitudinal polarization fraction” $f_L$

$$
\frac{d^2\Gamma}{d \cos \theta_{D_s^*} d \cos \theta_{\rho}} \propto 4f_L \sin^2 \theta_{D_s^*} \cos^2 \theta_{\rho} + (1 - f_L) \left( 1 + \cos^2 \theta_{D_s^*} \right) \sin^2 \theta_{\rho}
$$

- Need to measure $f_L$
- Simultaneous extraction of $B(B_s^0 \rightarrow D_s^{*-} \rho^+)$ and $f_L(B_s^0 \rightarrow D_s^{*-} \rho^+)$ with a 4D fit

In signal simulations: Longitudinal ($f_L = 1$) and transverse ($f_L = 0$) events have different $M_{bc}/\Delta E$ distributions
Observation of $B^0_s \to D^{*-}_s \rho^+$


$N(B^*_s \bar{B}^*_s) = 77.8^{+14.5}_{-13.4} \text{(stat.)} \pm 3.3 \text{(fit)}$ events (7.4σ significance)

$\mathcal{B}(B^0_s \to D^{*-}_s \rho^+) = \left(11.8^{+2.2}_{-2.0} \text{(stat.)} \pm 1.7 \text{(syst.)} \pm 1.8(f_s)\right) \times 10^{-3}$

$f_L = 1.05^{+0.08 +0.03}_{-0.10 -0.04}$ or $f_L \in [0.93, 1.00]$ at 68% C.L.
**CP violation in $B^0_s$ decays**

- $B^0_s$ decays are interesting for SM tests and for NP searches. They can provide tests of the CKM source of CP violation.


- Non-flavor specific tree decay (not sensitive to NP). For instance $B^0_s \rightarrow D_s^\mp K^\pm$, $\mathcal{B} \sim \mathcal{O}(10^{-4})$, can be used
  - to measure $\gamma$


  to resolve the ambiguity on the $\Delta\Gamma_s$ sign.


\[
|\lambda| = \left| \frac{q \langle D_s^- K^+ | B^0_s \rangle}{p \langle D_s^- K^+ | B^0_s \rangle} \right| \sim 0.3 - 0.4
\]
B_s^0 \to CP\text{-eigenstate Decays}

- Charmless B_s^0 \to K^+K^- decay (penguin)
  - may be sensitive to NP
  - can measure \( \phi_1(\beta) \) and \( \phi_3(\gamma) \) (with \( B^0 \to \pi^+\pi^- \))

- \( b \to c\bar{c}s \) transition are very small in the SM \( \rightarrow \) NP may be sizeable

\[
B_s^0 \to D_s^{(*)+}D_s^{(*)-}, \; B_s^0 \to J/\psi \phi, \; B_s^0 \to J/\psi K_s^0, \; B_s^0 \to J/\psi \eta('), \; B_s^0 \to J/\psi f_0, \ldots
\]

- \( B_s^0 \to D_s^{(*)+}D_s^{(*)-} \) dominates \( \Delta \Gamma_s \)

\[
\Delta \Gamma^{CP} = \Gamma(CP\text{--even}) - \Gamma(CP\text{--odd}) \approx \Gamma\left( B_{s,\text{short}}^0 \to D_s^{(*)}D_s^{(*)}\right)
\]

The first step is to establish these modes!

- Decays with \( \pi^0 \) and/or \( \gamma \) are hard for hadron-colliders experiments
  - Belle can contribute!

- \( CP \)-violation analysis need more statistics and better time resolution
  \( \sim 0.06 \text{ ps (} \sim 30 \text{ times better than for } B^0 \text{!)} \)

Prospects and workarounds: arXiv:1008.1541 (SuperB), arXiv:1005.5012 (Belle II)
Evidence for $B_s^0 \rightarrow D_s^{\mp} K^{\pm}$

RL et al. (Belle) Phys. Rev. Lett. 102, 021801 (2009)

- reco. similar to $B_s^0 \rightarrow D_s^- \pi^+$
- Replace the $\pi^+$ by a $K^+$.
- Cabbibo suppressed
  $\rightarrow \mathcal{O}(10)$ times less signal
- $\pi$ misidentification !

$N(\text{Signal}) \sim N(B_s^0 \rightarrow D_s^- \pi^+, \pi \text{ misid.})$

- Fit Result: $N(\text{Signal}) = 6.7^{+3.4}_{-2.7}$
  3.5$\sigma$ evidence (w/ systematics) !

- Direct measurement of branching fraction:
  
  $\mathcal{B}(B_s^0 \rightarrow D_s^{\mp} K^{\pm}) = (2.4^{+1.2}_{-1.0}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.3(f_s)) \times 10^{-4}$

- Ratio with $B_s^0 \rightarrow D_s^- \pi^+$: $\mathcal{B}(B_s^0 \rightarrow D_s^{\mp} K^{\pm})/\mathcal{B}(B_s^0 \rightarrow D_s^- \pi^+) = (6.5^{+3.5}_{-2.9})\%$
  $\rightarrow$ compatible with CDF (102 events): $(9.7 \pm 2.0)\%$

[T. Aaltonen et al. (CDF) PRL 103, 191802 (09)]

- Better precision expected with 120 /fb . . .
$B_s^0 \rightarrow KK$

C.C. Peng et al. (Belle) Phys. Rev. D 82, 072007 (2010)

First limit on $\mathcal{B}(B_s^0 \rightarrow K^0 K^0) < 6.6 \times 10^{-5}$

- Observation of $23.4^{+5.5}_{-6.3} B_s^0 \rightarrow K^+ K^- \text{ events (5.8}\sigma)$

Direct BR measurement:

$\mathcal{B}(B_s^0 \rightarrow K^+ K^-) = \left(3.8^{+1.0}_{-0.9} \pm 0.5 \pm 0.5 (f_s)\right) \times 10^{-5}$

confirms CDF results (102 events): $(2.44 \pm 0.14 \pm 0.46) \times 10^{-5}$ [M. Morello, Nucl. Phys. B (Proc. Suppl.) 170, 39 (07)]
Observation of $B^0_s \rightarrow J/\psi \eta$


First Observation of $14.9 \pm 4.1$ events ($7.3\sigma$)

$$\mathcal{B}(B^0_s \rightarrow J/\psi \eta) = (3.32 \pm 0.87^{+0.32}_{-0.28} \pm 0.42(f_s)) \times 10^{-4}$$

$\eta \rightarrow \gamma\gamma + \eta \rightarrow \pi^0\pi^+\pi^-$ channels

Remi Louvot (EPFL)
Observation of $B^0_s \to J/\psi \eta'$


First Evidence of $10.7 \pm 4.6$ events ($3.8\sigma$)

$B(\mathcal{B}^0_s \to J/\psi \eta') = (3.1 \pm 1.2^{+0.5}_{-0.6} \pm 0.4(f_s)) \times 10^{-4}$

- 3 \eta' channels: $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$, $\eta' \to \eta(\to \pi^0\pi^+\pi^-)\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$
The $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ Analysis


- CKM-favored and $CP$-even eigenstate (in heavy-quark limit).
- Dominates $\Delta \Gamma$ (this relation has $\sim 3\%$ theoretical uncertainty):

$$\frac{\Delta \Gamma_s^{CP}}{\Gamma_s} = \frac{2 \times \mathcal{B} \left( B_s^0 \to D_s^{(*)+} D_s^{(*)-} \right)}{1 - \mathcal{B} \left( B_s^0 \to D_s^{(*)+} D_s^{(*)-} \right)}$$


- Full reconstruction of $B_s^0 \to D_s^{(*)} D_s^{(*)}$
- Large B.R. ($\sim 10^{-2}$) but low efficiency ($\sim 10^{-4}$)
- $D_s^+$ reconstructed in 6 final states: $\phi \pi^+$, $K_S^0 K^+$, $\bar{K}^* K^+$, $\phi \rho^+$, $K_S^0 K^{*+}$ and $\bar{K}^* K^{*+}$
- Selection of one candidate (all channels) per event.
- $D_s^{*+} \to D_s^+ \gamma$: photon energy is low ($E_\gamma < 150$ MeV)!
- Contamination between the 3 modes ("cross feed")

when a photon is missing or added by error.
$B^0_s \rightarrow D_s^* + D_s^*(*)^-$ Fit


- Simultaneous fit of the 3 modes. For one mode, cross feed from the 2 others is included
- Signal has 2 components: right and wrong combinations

Remi Louvot (EPFL)

$B^0_s$ Decays at Belle
Observation of $B^0_s \rightarrow D^{(*)}_s + D^{(*)}_s$  


$\Delta\Gamma^s_{CP} / \Gamma_s = \left(14.7^{+3.6}_{-3.0} +4.4_{-4.2}\right)\%$

CDF: $(12 \pm 10)\%$ [PRL 100, 121803]
D0: $(7.2 \pm 3.0)\%$ [PRL 102, 091801]

$\mathcal{B} (B^0_s \rightarrow D^{(*)}_s + D^{(*)}_s) = \left(6.9^{+1.5}_{-1.3} \pm 1.9\right)\%$

The 3 modes are seen separately (22.6 signal events).

$\mathcal{B} (B^0_s \rightarrow D^{*+}_s D_s^-) = \left(1.0^{+0.4}_{-0.3} +0.3\right)\%$
consistent with CDF [PRL 100, 021803]

$\mathcal{B} (B^0_s \rightarrow D^{*\pm}_s D_s^\mp) = \left(2.8^{+0.8}_{-0.7} \pm 0.7\right)\%$
first observation

$\mathcal{B} (B^0_s \rightarrow D^{*+}_s D_s^{-}) = \left(3.1^{+1.2}_{-1.0} \pm 0.8\right)\%$
first evidence

Competitive precision on $\Delta\Gamma / \Gamma$ with $23.6 \text{ fb}^{-1}$!
Search for $B^0_s \rightarrow J/\psi f_0(980)$

Contribution to FPCP 2010 (arXiv:1009.2605)

- CP-eigenstate (odd) mode with a final state with only 4 charged particles

- Expectations:
  - $\frac{B(B_s^0 \rightarrow J/\psi f_0)B(f_0 \rightarrow \pi^+\pi^-)}{B(B_s^0 \rightarrow J/\psi \phi)B(\phi \rightarrow K^+K^-)} \approx 0.2$ (Stone+Zhang [PRD 79, 074024])
  - $\frac{B(B_s^0 \rightarrow J/\psi f_0)B(f_0 \rightarrow \pi^+\pi^-)}{B(B_s^0 \rightarrow J/\psi \phi)B(\phi \rightarrow K^+K^-)} = 0.42 \pm 0.11$ (CLEO ($D_s \rightarrow f_0 e^+\nu_e$) [PRD 80, 052009])

- Our analysis:
  - $J/\psi \rightarrow e^+e^-$ or $\mu^+\mu^-$; $f_0 \rightarrow \pi^+\pi^-$
  - $(\Delta E, M_{\pi^+\pi^-})$ 2D fit in $-0.1$ GeV $< \Delta E < 0.2$ GeV and $M_{\pi^+\pi^-} < 1.8$ GeV/$c^2$
  - includes backgrounds from $B^0_s \rightarrow J/\psi \pi^+\pi^-$ (peaks in $\Delta E$) and others $J/\psi$ modes.
Search for $B_s^0 \rightarrow J/\psi f_0(980)$

Contribution to FPCP 2010 (arXiv:1009.2605)

$B_s^0 \rightarrow J/\psi f_0$

Belle preliminary (23.6 /fb)

$B_s^0 \rightarrow J/\psi f_0$

Signal: 6.0 ± 4.4 events (1.6σ)

$\mathcal{B}(B_s^0 \rightarrow J/\psi f_0) \times \mathcal{B}(f_0 \rightarrow \pi^+\pi^-) < 1.63 \times 10^{-4}$ (at 90% C.L.)

▷ We are sensitive to the region of interest!

▷ More to come with 120 fb$^{-1}$ + improved analysis ...
Conclusion:

- Belle has analysed $\sim 2.8$ millions of $B_s^0$ (total on tape: $\sim 14$ millions)
- Study of (experimentally) dominant CKM-favored decay modes.
  - Study of $B_s^0 \to D_s^- \pi^+$
  - First observations of $B_s^0 \to D_s^{*-} \pi^+$, $B_s^0 \to D_s^- \rho^+$ and $B_s^0 \to D_s^{*-} \rho^+$.
- B.F. precision suffers mainly from the imprecise fraction $f_s = N_{B_s^{(*)} \bar{B}_s^{(*)}} / N_{b\bar{b}}$
- Evidence for $B_s^0 \to D_s^{\mp} K^{\pm}$ but statistic is low!
- $CP$-eigenstate modes:
  - Analysis of $B_s^0 \to \eta \eta'$, but not competitive with Tevatron
  - Evidences for $B_s^0 \to J/\psi \eta'$
  - Competitive measurement of $\Delta \Gamma^{CP} / \Gamma$ with $B_s^0 \to D_s^{(*)} D_s^{(*)}$
  - Search for $B_s^0 \to J/\psi f_0$: First direct limit, very close to the expected signal!
- Our total $\Upsilon(5S)$ sample is 5 times larger $\rightarrow$ More to come soon!
- Good $B_s^0$ prospects at Belle2/superB $\rightarrow$ talks of A. Cervelli and S. Korpar

Thank you.
Rescale of existing results from Belle [PRD 73, 112002 (06)] and Babar [PRL 96, 251802 (06)] to the full Belle data sample (710 fb$^{-1}$ at $\Upsilon(4S)$ and 120 fb$^{-1}$ at $\Upsilon(5S)$)

$B_s^0$ mixed with 50% probability $\rightarrow$ 3 times more same-sign leptons than $B^0\bar{B}^0$.

\[ a_{Bs}^{B_s^0} \approx 1.2\% \]
\[ a_{sl}^{B_d^0} \approx 0.2\% \]
$B_s^0$ decay modes with large statistics?

- Measurements of precise exclusive modes
  $\rightarrow$ LHC experiments need a reference point for $B_s^0$

- Measurements of $B_s^0$, $B_s^*$ properties (masses, widths, angular distr.)

- Comparison between $B^0$ and $B_s^0$ is theoretically interesting
  $\rightarrow$ tests of HQET, factorization, etc.

- Comparison between $\Upsilon(5S) \rightarrow B_s^* \bar{B}_s^*$, $\Upsilon(5S) \rightarrow B_s^* \bar{B}_s^0 + \text{c.c.}$,
  $\Upsilon(5S) \rightarrow B_s^0 \bar{B}_s^0$
$B^0_s \rightarrow D_s^{(*)-} h^+$ Summary

- At LO: 1 tree-level diagram

\[ B^0_s \xrightarrow{\bar{b} \rightarrow \bar{c}} D_s^- \]

Measurements compatible with
- $B^0$ decays (as expected in the heavy-quark limit and small $W$-exchange ampl.)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B$ (Belle)</th>
<th>Theory (HQET)</th>
<th>$B^0$ partner (PDG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow D_s^- \pi^+$</td>
<td>$3.67^{+0.35+0.43}_{-0.33-0.42} \pm 0.49$</td>
<td>2.8</td>
<td>$2.68 \pm 0.13$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^{*-} \pi^+$</td>
<td>$2.4^{+0.5+0.4}_{-0.4} \pm 0.3 \pm 0.4$</td>
<td>2.8</td>
<td>$2.76 \pm 0.13$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^- \rho^+$</td>
<td>$8.5^{+1.3+1.1}_{-1.2} \pm 1.1 \pm 1.3$</td>
<td>7.5</td>
<td>$7.6 \pm 1.3$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D_s^{*-} \rho^+$</td>
<td>$11.9^{+2.2+2.0}_{-2.0} \pm 1.7 \pm 1.8$</td>
<td>8.9</td>
<td>$6.8 \pm 0.9$</td>
</tr>
</tbody>
</table>

- Large longitudinal polarization of $B^0_s \rightarrow D_s^{*-} \rho^+$
  - also expected from theory: 83% [Li et al. Phys. Rev. D 78, 014018 (08)]
  - comparable with $B^0 \rightarrow D^{*-} \rho^+$: 88.5 ± 2.0%, [CLEO PRD67, 112002].