B_s^0 Decays at Belle

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for the Belle collaboration

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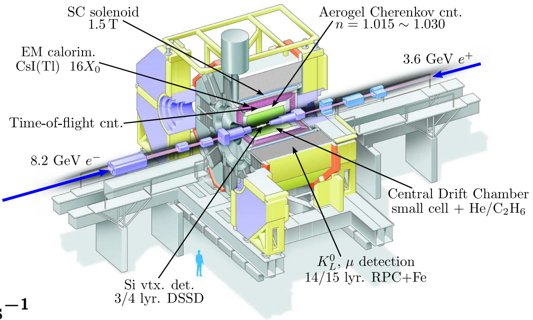
The Belle Experiment

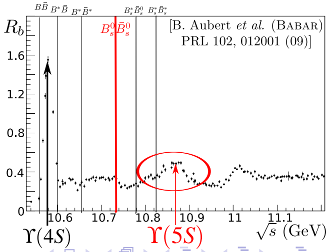
The Belle detector

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



$$\mathbf{L_{peak} = 2.11 \cdot 10^{34} cm^{-2} s^{-1}}$$

- Data taken at $\Upsilon(5S)$ ($\sqrt{s} = 10867 \pm 1$ MeV)
- The only large data sample at this energy:
  - Total sample: $\boxed{\sim \mathbf{121\ fb^{-1}}}$
- $\Upsilon(5S)$ is above $B_s^0\bar{B}_s^0$ threshold
  Study of $\mathbf{B_s^0}$ meson possible !



Physics at $\Upsilon(5S)$: B_s^0 Production

udsc continuum

Hadronic $\Upsilon(5S)$ events

$b\bar{b}$ events

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

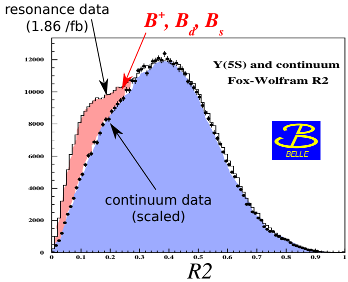
Cleo (PRD 75, 012002)
+Belle (PRL 98, 052001)

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

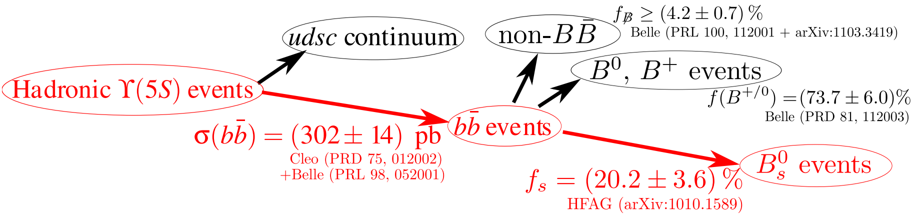
On resonance data; continnum data below open-beauty threshold

$$\sigma(b\bar{b}) = \frac{N_{5S}^{b\bar{b}}}{\mathcal{L}_{5S}} = \frac{1}{\mathcal{L}_{5S}} \frac{1}{\epsilon_{5S}^{b\bar{b}}} \left(N_{5S}^{\rm had} - N_{\rm cont}^{\rm had} \underbrace{\frac{\mathcal{L}_{5S}}{\mathcal{L}_{\rm cont}} \frac{E_{\rm cont}^2}{E_{5S}^2} \frac{\epsilon_{5S}^{\rm rec}}{\epsilon_{\rm cont}^{\rm rec}}}_{\text{scaling factor}} \right)$$

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



- f_s = fraction of B_s. Inclusive measurements:

$$\frac{1}{2}\overbrace{\mathcal{B}(\Upsilon(5S) \to D_s X)}^{\Upsilon(5S)\text{ data}} = f_s \times \overbrace{\mathcal{B}(B_s \to D_s X)}^{\textbf{THEORY estimate}} + (1 - f_s) \times \frac{1}{2}\overbrace{\mathcal{B}(\Upsilon(4S) \to D_s X)}^{\Upsilon(4S)\text{ data}}$$

(+ similar measurements with D^0 and ϕ rates)

  - HFAG's average (with correlations, CLEO+Belle): $f_s = (20.2 \pm 3.6)\%$ [arXiv:1010.1589]
  - 18% uncertainty, mainly due to model-dependent estimates.
  - **Dominant systematics for our branching fractions.**
  - Number of B_s^0, in 121 fb^{-1}:

$$\boxed{N_{B_s^0} = 2 \cdot L_{\text{int}} \cdot \sigma(b\bar{b}) \cdot f_s = 14.8 \pm 0.7 \pm 2.6(f_s) \cdot 10^6}$$

Model-independent measurement of f_s with dileptons

- Alternative Model-independent f_s measurement with dileptons. proposed by R. Sia and S. Stone [PRD **74**, 031501 (2006), **80**, 039901(E) (2009)]
- Based on the difference between fast B_s^0 oscillation ($\chi_s = 50\%$), slow B^0 oscillation ($\chi_d = 19\%$) and no B^+ oscillation.
- Look at semi-leptonic decays $B \to l^+ \nu X$, $\bar{B} \to l^- \bar{\nu} X$
- Measure the number of same-sign and opposite-sign dileptons.

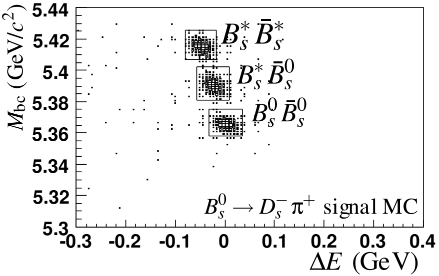
		Probabilities	
$B^{(*)}\bar{B}^{(*)}(X)$ events	100%	l^+l^+, l^-l^-	l^+l^-
B^+B^-	46%	0%	100%
$B^0\bar{B}^0$ $(C=-1)$	35%	19%	81%
$B^0\bar{B}^0$ $(C=+1)$	11%	42%	58%
B^0B^-	4%	19%	81%
$B_s^{(*)}\bar{B}_s^{(*)}$ events		50%	50%

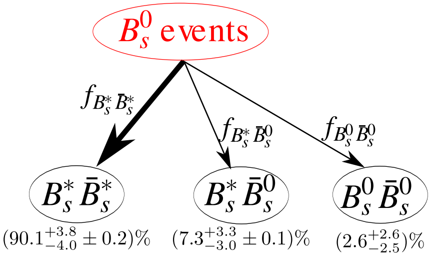
- The ratio $f_s/f(B^{+/0})$ can be measured from the number of SS and OS lepton pairs.
- Expected sensitivity: $5-10\%$ relative error on f_s

[RL, O. Schneider and T. Aushev, Belle note 1140, http://lphe.epfl.ch/louvot/bnote_1140.pdf]

Physics at $\Upsilon(5S)$: B_s^0 Reconstruction

- Full reconstruction of the B_s^0. Observables: ($E_{\rm b}^* = \sqrt{s}/2$)
  - Beam-constrained mass: $M_{\rm bc} = \sqrt{{E_{\rm b}^*}^2 - {p_{B_s^0}^*}^2}$
  - Energy difference: $\Delta E = E_{B_s^0}^* - E_{\rm b}^*$
- 3 production modes:
  $\Upsilon(5S) \to B_s^* \bar{B}_s^*$, $\Upsilon(5S) \to B_s^* \bar{B}_s^0$ and $\Upsilon(5S) \to B_s^0 \bar{B}_s^0$.
- $\boldsymbol{B_s^*}$ $\to B_s^0\gamma$ **cannot be reconstructed** (γ too soft)
- In the ($M_{\rm bc}, \Delta E$) plane, $\boldsymbol{B_s^0}$ candidates are in **3 signal regions**

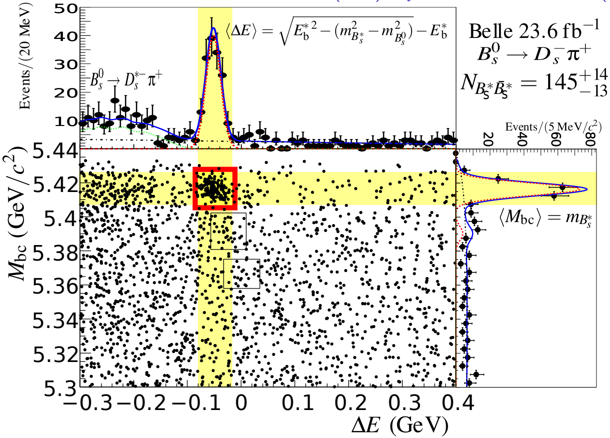




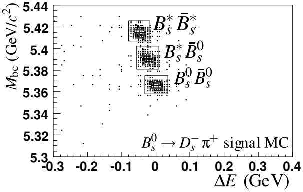
[RL *et al.* (Belle) PRL 102, 021801 (09)]

A "standard candle": $B_s^0 \to D_s^- \pi^+$

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



$$f_{B_s^* \bar{B}_s^*} = (90.1 \pm 3.9)\%$$
$$f_{B_s^* \bar{B}_s^0} = (7.3 \pm 3.2)\%$$
$$f_{B_s^0 \bar{B}_s^0} = (2.6 \pm 2.6)\%$$



$$\mathcal{B}(B_s^0 \to D_s^- \pi^+) = \left(3.67^{+0.35}_{-0.33}(\mathrm{stat.})^{+0.43}_{-0.42}(\mathrm{syst.}) \pm 0.49(f_s)\right) \times 10^{-3}$$

- 18% systematics, f_s limits the precision for all B_s^0 branching fraction.

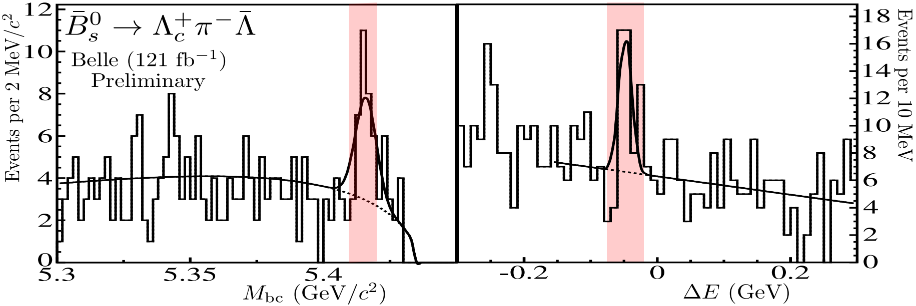
Observation of $\bar{B}^0_s \to \Lambda_c^+ \pi^- \bar{\Lambda}$

Presented for the first time

- baryonic multi-body B decays tends to have larger BF than 2-body decays
- three-body baryonic B decays exhibit near-threshold baryon-antibaryon mass peak.
- $\bar{B}^0_s \to \Lambda_c^+ \pi^- \bar{\Lambda}$ is the counterpart of the already-observed $B^- \to \Lambda_c^+ \pi^- \bar{p}$
- Full reconstruction of $\bar{B}^0_s \to \Lambda_c^+ \pi^- \bar{\Lambda}$, $\Lambda_c^+ \to p K^- \pi^+$, $\bar{\Lambda} \to \bar{p} \pi^+$
- fit of the Λ_c^+ and $\bar{\Lambda}$ vertices
- $M(\Lambda_c^+)$ required to be within 10MeV$/c^2$ from the PDG value.
- $M(\bar{\Lambda})$ required to be within 4MeV$/c^2$ from the PDG value.
- continuum rejected with $R_2 < 0.5$ and cos(thrust angle) < 0.85
- 2D binned fit on $M_{\rm bc}$ and ΔE.

Observation of $\bar{B}_s^0 \to \Lambda_c^+ \pi^- \bar{\Lambda}$

Presented for the first time



- 24±7 signal events (5.0σ stat. significance incl. systematics)

First Observation of a baryonic B_s^0 decay!

- $\mathcal{B}(\bar{B}_s^0 \to \Lambda_c^+ \pi^- \bar{\Lambda}) = \left(4.8 \pm 1.4(\text{stat.}) \pm 0.9(\text{syst.}) \pm 1.3(\Lambda_c^+)\right) \times 10^{-4}$
- Comparable with B^- partner: PDG value $\mathcal{B}(B^- \to \Lambda_c^+ \pi^- \bar{p}) = (2.8 \pm 0.8) \times 10^{-4}$
- Plans: Add more Λ_c^+ modes ($\to \Lambda\pi^+, \to pK_S^0$, etc.) & extract $M(\Lambda_c\bar{\Lambda})$ distribution

Search for CP-eigenstate B_s^0 Decays

- B_s^0 CP-eigenstate are important for CKM-related measurements.
- $b \to c\bar{c}s$ transition are small in the SM $\longrightarrow$ NP may be sizeable

Ball & Fleischer, Phys. Lett. B 475, 111 (2000)

$$B_s^0 \to J/\psi\,\eta^{(\prime)},\ B_s^0 \to J/\psi\, f_0,\ B_s^0 \to D_s^{(*)+} D_s^{(*)-},\ B_s^0 \to J/\psi\,\phi,\ \ldots$$

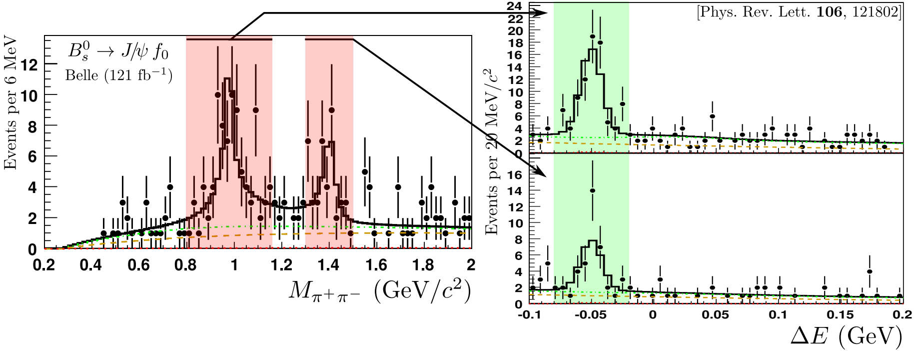
- $B_s^0 \to J/\psi f_0$ is a CP-odd mode with a final state with only 4 charged particles
  - expectations: $\mathcal{B}(B_s^0 \to J/\psi\, f_0; f_0 \to \pi^+\pi^-) \approx (1.3 - 2.7) \times 10^{-4}$

[RL PoS(FPCP2010)015])

- Our analysis of $B_s^0 \to J/\psi f_0$:
  - $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, $R_2 < 0.4$
  - $B_s^0 \to J/\psi f_0, f_0 \to \pi^+\pi^-$ candidates with consistent J/ψ and $\pi^+\pi^-$ vertices. Best-candidate selection based on $M_{\rm bc}$. $(\Delta E, M_{\pi^+\pi^-})$ 2D fit in -0.1 GeV$< \Delta E < 0.2$ GeV and $M_{\pi^+\pi^-} < 1.8$ GeV$/c^2$
  - Two f_0 resonances included in the fit: $f_0(980)$ and $f_0(1370)$
  - includes backgrounds from continuum and other J/ψ modes.

Search for $B_s^0 \to J/\psi\, f_0(980)$ and $B_s^0 \to J/\psi\, f_0(1370)$

J. Li *et al.* (Belle) Phys. Rev. Lett. **106**, 121802 (2011)



- Observation of 63^{+16}_{-10} $B_s^0 \to J/\psi f_0(980)$ events (8.4σ incl. syst.)
- First evidence for 19^{+6}_{-8} $B_s^0 \to J/\psi f_0(1370)$ events (4.2σ incl. syst.)

$$\mathcal{B}(B_s^0 \to J/\psi f_0(980); f_0(980) \to \pi^+\pi^-) = [1.16^{+0.31}_{-0.19}(\text{stat.})^{+0.15}_{-0.17}(\text{syst.})^{+0.26}_{-0.18}(N(B_s^0))] \times 10^{-4}$$
$$\mathcal{B}(B_s^0 \to J/\psi f_0(1370); f_0(1370) \to \pi^+\pi^-) = [0.34^{+0.11}_{-0.14}(\text{stat.})^{+0.03}_{-0.02}(\text{syst.})^{+0.08}_{-0.05}(N(B_s^0))] \times 10^{-4}$$

- Comparable results with LHCb [PLB 698, 115], CDF [arXiv: 1106.3682] and D0 [conf. note 6152].

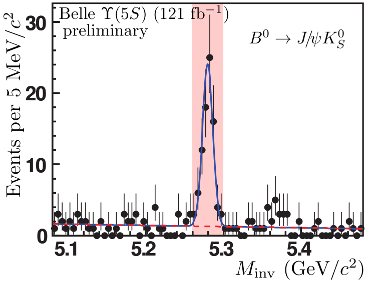
Measurement of $\sin 2\phi_1$ with B-π Tagging

Presented for the first time

- $\Upsilon(5S)$ energy above $B^*\bar{B}^*\pi$ threshold
- Three body decay $\Upsilon(5S) \to B^{(*)}\bar{B}^{(*)}\pi^\pm$
- $\Upsilon(5S) \to \boldsymbol{B^{(*)0}} B^{(*)-}\boldsymbol{\pi^+}$ or
  $\Upsilon(5S) \to \boldsymbol{\bar{B}^{(*)0}} B^{(*)+}\boldsymbol{\pi^-}$

Pion's sign indicates the initial B^0 flavor

- Select $B^0 \to J/\psi(\to l^+l^-)K^0_S(\to \pi^+\pi^-)$:
  Signal yield: 75.9 ± 9.5
  keep candidates with $m(B^0) \pm 20$ MeV$/c^2$



- $\phi_1(\beta)$ can be measured with the asymmetry ($x = \Delta m/\Gamma$)

$$A_{BB\pi} = \frac{N_{BB\pi^-} - N_{BB\pi^+}}{N_{BB\pi^-} + N_{BB\pi^+}} = \frac{\mathcal{S}x + \mathcal{A}}{1 + x^2}$$

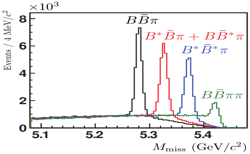
Within the standard model, $\mathcal{A} = 0$, $\mathcal{S} = -\eta_{CP}\sin 2\phi_1$:

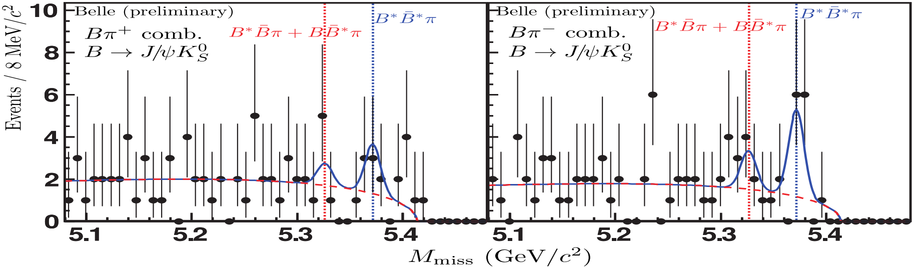
$$\sin 2\phi_1 = -\eta_{CP}\frac{1+x^2}{x} \times A_{BB\pi}$$

Measurement of $\sin 2\phi_1$ with B-π Tagging

Presented for the first time

- Fit of missing mass of $B^0\pi$: $M_{\rm miss} = |P_{\rm tot.} - (P_{B^0} + P_\pi)|$
- Two signal components $B\bar{B}^*\pi$ and $B^*\bar{B}^*\pi$ events
- Simultaneous fit of $B\pi^+$ and $B\pi^-$, with same shapes





- Result: 21.5 ± 6.8 signal events, $A_{BB\pi} = 0.28 \pm 0.28(\rm stat.)$

$$\sin 2\phi_1 = 0.57 \pm 0.58(\rm stat.) \pm 0.06(\rm syst.)$$

Clear lack of statistics, but **it is possible to measure ϕ_1 with B-π tagging!**

Conclusion:

- Belle has recorded ~ 15 M of B_s^0 (and ~ 54 M of $B^{+/0}$) at $\Upsilon(5S)$ energy
- Several results using all the whole Belle $\Upsilon(5S)$ sample (121 /fb) are ready:
- Observation of $\bar{B}_s^0 \to \Lambda_c^+ \pi^- \bar{\Lambda}$

First baryonic B_s^0 decay!,

$$\mathcal{B}(B_s^0 \to \Lambda_c^+ \pi^- \bar{\Lambda}) = (4.8 \pm 1.4 \pm 0.9 \pm 1.3(\Lambda_c^+)) \cdot 10^{-4}$$

- Observation of $B_s^0 \to J/\psi f_0(980)$ and Evidence for $B_s^0 \to J/\psi f_0(1370)$

[J. Li *et al.* (Belle collab.), Phys. Rev. Lett. **106**, 121802]

- Measurement of ϕ_1 (β) using B-π tagging in $\Upsilon(5S) \to B^{(*)} B \pi^{\pm}$ events

It's possible!, but needs more statistics

- More to come this summer, stay tuned!
- Good B_s^0 prospects at Belle2/superB

Thank you.