B_s^0 Decays at Belle

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for the Belle collaboration

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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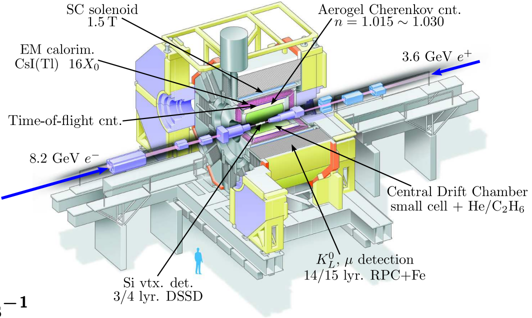
The Belle Experiment

The Belle detector

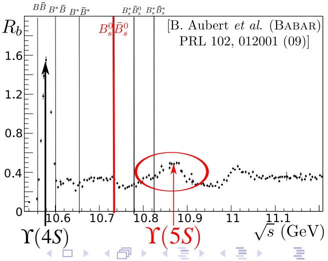
- e^+e^- collisions
- Located at KEK B factory (Tsukuba, Japan)
- Large-solid-angle ($\sim 92\%$)
- Efficient particle ID (p, $\pi^\pm$, $K^\pm$, γ, μ, e, K^0_L)
- World luminosity record

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



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

Study of $\mathbf{B^0_s}$ 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

[G.S. Huang *et al.* (CLEO) PRD 75, 012002 (07)
+ A. Drutskoy *et al.* (Belle) PRL 98, 052001 (07)]

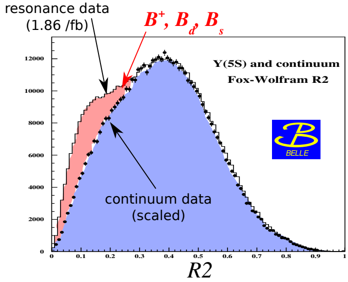
- $b\bar{b}$ cross section: subtraction of data taken below open-beauty threshold

On resonance data

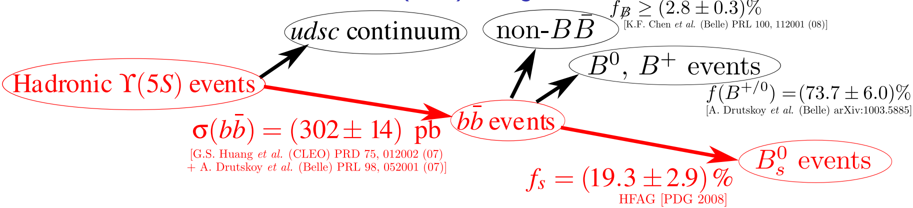
continnum data below open-beauty threshold

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

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:

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

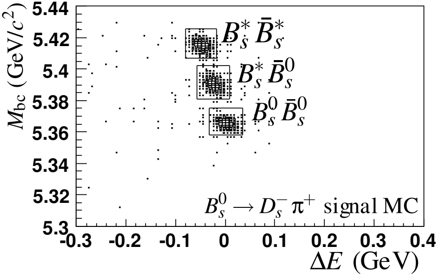
  - 15% uncertainty, mainly due to model-dependent estimates.
  - **Dominant systematics for our branching fractions.**
  - Current normalization, in 23.6 fb^{-1} (today's data set):

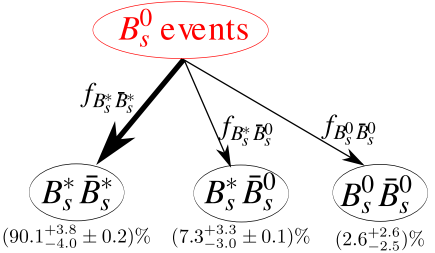
$$\boxed{\mathbf{N_{B_s^0} = 2 \cdot L_{int} \cdot \sigma(b\bar{b}) \cdot f_s = (2.75 \pm 0.43) \cdot 10^6}}$$

  - 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 di-lepton signs [Sia & Stone, PRD 74, 031501 (06)]

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

- Full reconstruction of the B_s^0. Observables: $(2 \times E_{\rm b}^* = \sqrt{s})$
  - 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 ($B_s^* \to B_s^0 \gamma$):
  $\Upsilon(5S) \to B_s^* \bar{B}_s^*$, $\Upsilon(5S) \to B_s^* \bar{B}_s^0$ and $\Upsilon(5S) \to B_s^0 \bar{B}_s^0$.
  - 3 signal regions in $(M_{\rm bc}, \Delta E)$ plane (B_s^* can't be reconstructed):





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

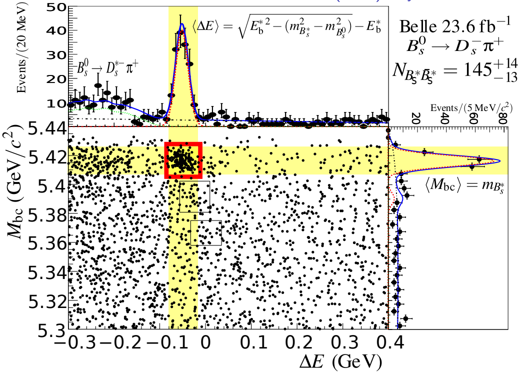
- Signal yield extraction: 2D unbinned maximum likelihood fit

Why B_s^0 decay modes with large statistics?

- Measurements of precise exclusive modes
  $\longrightarrow$ 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
  $\longrightarrow$ tests of HQET, factorization, etc.
- Measurements of $\Upsilon(5S) \to B_s^{(*)} \bar{B}_s^{(*)}$ properties.

Measurement of $B_s^0 \to D_s^- \pi^+$

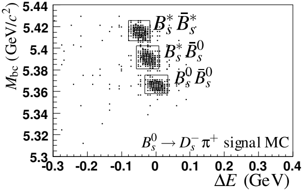
RL *et al.* (Belle) Phys. Rev. Lett. **102**, 021801 (2009)



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

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

$$m_{B_s^0} = (5364.4 \pm 1.3 \pm 0.7)\ \mathrm{MeV}/c^2$$



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

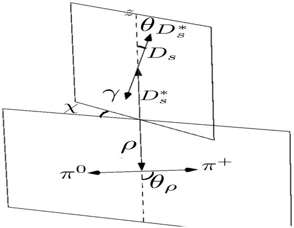
- 20% uncertainties, f_s is a crucial source of systematics
- large $f_{B_s^* B_s^*}$ confirmed (1st Belle value: $(93^{+7}_{-9} \pm 1)\%$ [PRD 76, 012002 (07)])

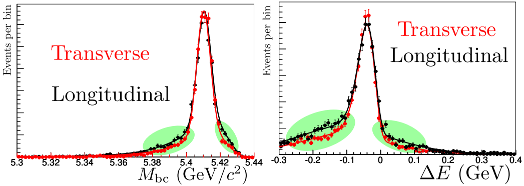
- $m_{B_s^*}$ is 2.6σ larger than CLEO [O. Aquines *et al.* (CLEO) PRL 96, 152001 (06)].
- $m_{B_s^*}$ ($m_{B_s^0}$) is the 1st (2nd) most precise measurement so far.

Study of $B_s^0 \to D_s^{*-}\rho^+$

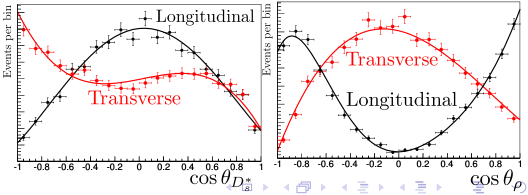
- Scalar $\to$ Vector + Vector: Longitudinal and Transverse polarizations are possible.
- Decay width depends on the "longitudinal polarization fraction" f_L

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





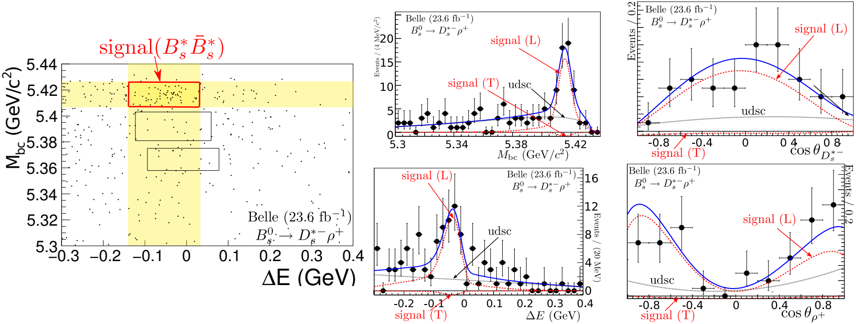
In signal simulations: **Longitudinal ($f_L = 1$) and transverse ($f_L = 0$) events have different $M_{bc}/\Delta E$ distributions**



- Need to know f_L
- Simultaneous extraction of $\mathcal{B}(B_s^0 \to D_s^{*-}\rho^+)$ and $f_L(B_s^0 \to D_s^{*-}\rho^+)$ with a 4D fit
- $(M_{bc}, \Delta E, \cos\theta_{D_s^*}, \cos\theta_\rho)$

Observation of $B_s^0 \to D_s^{*-}\rho^+$

RL *et al.* (Belle) Phys. Rev. Lett. (in press), arXiv:1003.5312



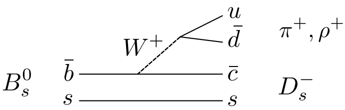
- $N(B_s^* \bar{B}_s^*) = 77.8^{+14.5}_{-13.4}(\text{stat.}) \pm 3.3(\text{fit})$ events (7.4σ significance)

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

$\boxed{f_L = 1.05^{+0.08}_{-0.10}{}^{+0.03}_{-0.04}}$ or $f_L \in [0.93, 1.00]$ at 68% C.L.

$B_s^0 \to D_s^{(*)-} h^+$ Summary

- At LO: 1 tree-level diagram



- Measurements compatible with
  - HQET predictions [A. Deandrea *et al.*, Phys. Lett. B 318, 549 (93)]
  - B^0 decays (as expected in the heavy-quark limit and small W-exchange ampl.)

Mode	$\mathcal{B}$ (Belle)	Theory (HQET)	B^0 partner (PDG)
$B_s^0 \to D_s^- \pi^+$	$3.67^{+0.35}_{-0.33}{}^{+0.43}_{-0.42} \pm 0.49$	2.8	2.68 ± 0.13
$B_s^0 \to D_s^{*-} \pi^+$	$2.4^{+0.5}_{-0.4} \pm 0.3 \pm 0.4$	2.8	2.76 ± 0.13
$B_s^0 \to D_s^- \rho^+$	$8.5^{+1.3}_{-1.2} \pm 1.1 \pm 1.3$	7.5	7.6 ± 1.3
$B_s^0 \to D_s^{*-} \rho^+$	$11.9^{+2.2}_{-2.0} \pm 1.7 \pm 1.8$	8.9	6.8 ± 0.9

- Large longitudinal polarization of $B_s^0 \to D_s^{*-} \rho^+$
  - also expected from theory: 87% [Ali *et al.* Z.Phys.C 1, 269 (79)]
  - comparable with $B^0 \to D^{*-} \rho^+$: $88.5 \pm 2.0\%$, [CLEO PRD67, 112002].

$B_s^0 \to CP$-eigenstate Decay Modes

- Charmless $B_s^0 \to K^+K^-$ decay
  - may be sensitive to NP

    [London & Matias, PRD 70, 031502 (04)]
  - can measure CKM-angle γ via comparison with $B^0 \to \pi^+\pi^-$

    [R. Fleischer, PLB 459, 306 (99)]

- Generally, CP-eigenstates final states ($B_s^0 \to J/\psi\eta^{(\prime)}$, $B_s^0 \to J/\psi f_0$, $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$)
  - are useful for CP-violation parameters (β_s, $\Delta\Gamma_s/\Gamma_s$, ...)

    [I. Dunietz *et al.* PRD 63, 114015 (01)]
  - for instance, (heavy-quark limit + $m_b >> m_c$)

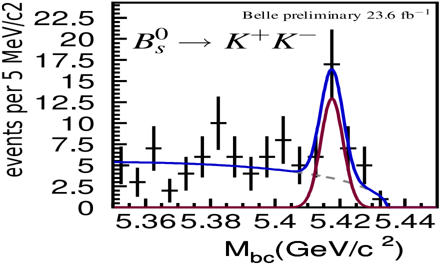
    $\Delta\Gamma^{CP} = \Gamma\left(CP-\mathrm{even}\right) - \Gamma\left(CP-\mathrm{odd}\right) \approx \Gamma\left(B^0_{s,\mathrm{short}} \to D_s^{(*)}D_s^{(*)}\right)$

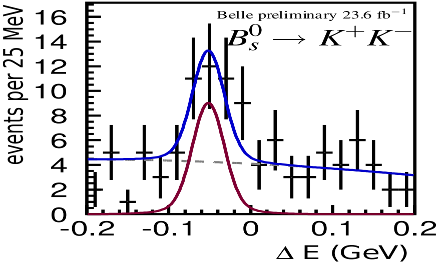
    [R. Aleksan *et al.* PLB 316, 567 (93)]

$B_s^0 \to KK$

Contribution to EPS-HEP09 [RL, PoS(EPS-HEP 2009)170]

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





First direct BR measurement:

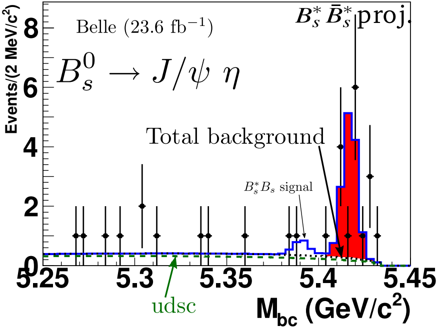
$$\mathcal{B}(\mathbf{B_s^0 \to K^+K^-}) = \left(\mathbf{3.8^{+1.0}_{-0.9} \pm 0.5 \pm 0.5(f_s)}\right) \times \mathbf{10^{-5}}$$

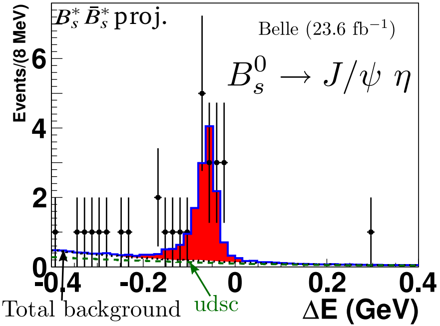
CDF: $(2.44 \pm 0.14 \pm 0.46) \times 10^{-5}$ [M. Morello, Nucl. Phys. B (Proc. Suppl.) 170, 39 (07)]

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

Observation of $B_s^0 \to J/\psi\,\eta$

I. Adachi *et al.* (Belle), arXiv:0912.1434 (2009)



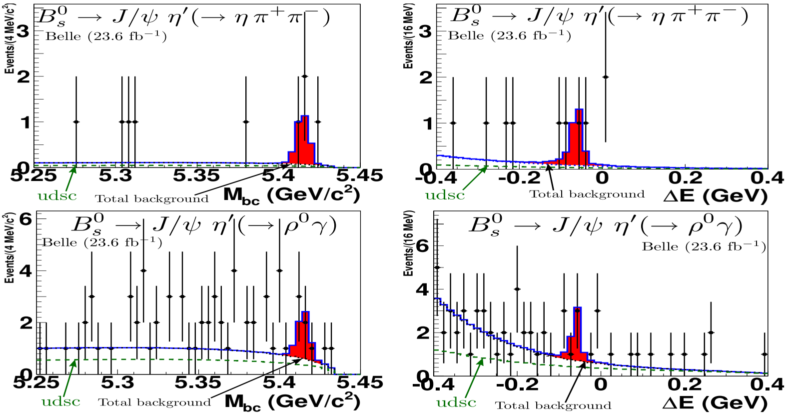


- $\eta \to \gamma\gamma + \eta \to \pi^0\pi^+\pi^-$ channels
- First Observation of 14.9 ± 4.1 events (7.3σ)

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

Observation of $B_s^0 \to J/\psi\,\eta'$

I. Adachi *et al.* (Belle), arXiv:0912.1434 (2009)



- 3 η' channels: $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$, $\eta' \to \eta(\to \pi^0\pi^+\pi^-)\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$
- First Evidence of 10.7 ± 4.6 events (3.8σ)

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

$B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ Analysis

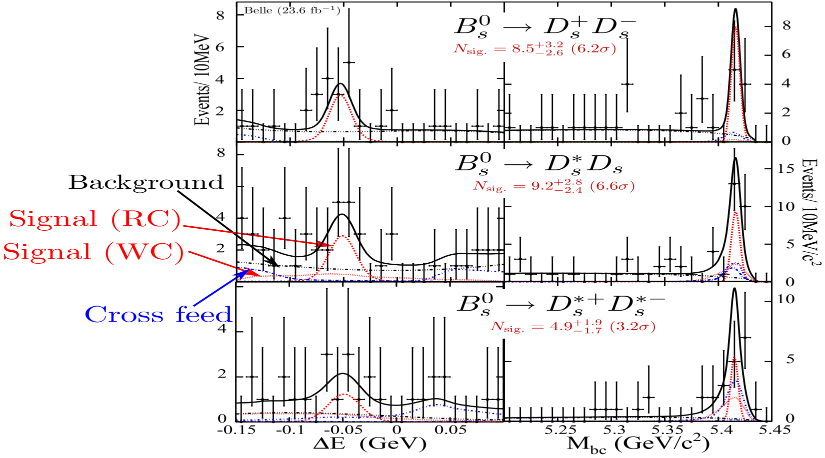
- CKM-favored **and** *CP*-even eigenstate (in heavy-quark limit).
- Dominates $\Delta\Gamma$ [Aleksan *et al.* Phys.Lett.B 316, 567]:

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

- Full reconstruction of $B_s^0 \to D_s^{(*)} D_s^{(*)}$
- D_s^+ reconstructed in 6 final states: $\phi\pi^+$, $K_S^0 K^+$, $\bar{K}^{*0} K^+$, $\phi\rho^+$, $K_S^0 K^{*+}$ and $\bar{K}^{*0} K^{*+}$
- $D_s^{*+} \to D_s^+ \gamma$ with $E_\gamma > 50$ MeV and $\left|M(D_s^+\gamma) - M(D_s^{*+})^{\mathrm{PDG}}\right| < 12\,\mathrm{MeV}/c^2$
- One candidate (all channels) per event:
  lowest χ^2 based on $M(D_s^+)$ and $M(D_s^{*+}) - M(D_s^+)$.
- Continuum rejection ($> 80\%$) (Fox-Wolfram moments), 95% of the signal remains.
- Overall signal efficiencies, including internal Branching fractions:
  3.3×10^{-4} $(D_s D_s)$, 1.4×10^{-4} $(D_s^* D_s)$, 0.6×10^{-4} $(D_s^* D_s^*)$

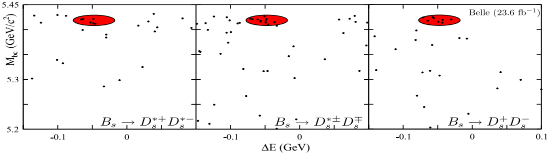
$B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ Fit

- 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



Observation of $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$

Contribution to Moriond EW 2010



- $\mathcal{B}(B_s^0 \to D_s^+ D_s^-) = \left(1.0^{+0.4}_{-0.3}{}^{+0.3}_{-0.2}\right)\%$
  OK with CDF [PRL 100, 021803]
- $\mathcal{B}(B_s^0 \to D_s^{*\pm} D_s^{\mp}) = \left(2.8^{+0.8}_{-0.7} \pm 0.7\right)\%$
  first observation
- $\mathcal{B}(B_s^0 \to D_s^{*+} D_s^{*-}) = \left(3.1^{+1.2}_{-1.0} \pm 0.8\right)\%$
  first evidence

$$\mathcal{B}\left(B_s^0 \to D_s^{(*)+} D_s^{(*)-}\right) = \left(6.9^{+1.5}_{-1.3} \pm 1.9\right)\%$$

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

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

- The 3 modes are seen separately (22.6 signal events).
- $\pm 0.4\%$ uncertainty on $\Delta\Gamma/\Gamma$ due to theory
- Best (relative) precision on $\Delta\Gamma/\Gamma$ with 23.6 fb^{-1}.

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

- CP-eigenstate mode with a final state with only 4 charged particles
- Expectations $R_{f/\phi} = \frac{\mathcal{B}(B_s^0 \to J/\psi\, f_0)\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(B_s^0 \to J/\psi\, \phi)\mathcal{B}(\phi \to K^+K^-)}$:
  - $R_{f/\phi} \approx 0.2$ (Stone+Zhang [PRD 79, 074024])
  - $R_{f/\phi} = 0.42 \pm 0.11$ (CLEO ($D_s \to f_0 e^+ \nu_e$) [PRD 80, 052009])

$$\to \mathcal{B}(\mathbf{B_s^0} \to \mathbf{J/\psi\, f_0})\mathcal{B}(\mathbf{f_0} \to \pi^+\pi^-) \approx (\mathbf{1.3} - \mathbf{2.7})\, \mathbf{10^{-4}}$$

  - $\mathcal{B}(B_s^0 \to J/\psi\, f_0) = (3.1 \pm 2.4)\, 10^{-4}$ QCD (LO) [PRD 81, 074001]
    with $\mathcal{B}(f_0 \to \pi^+\pi^-) = \left(50^{+7}_{-9}\right)$ % BES data [CLEO, PRD 80, 052009]

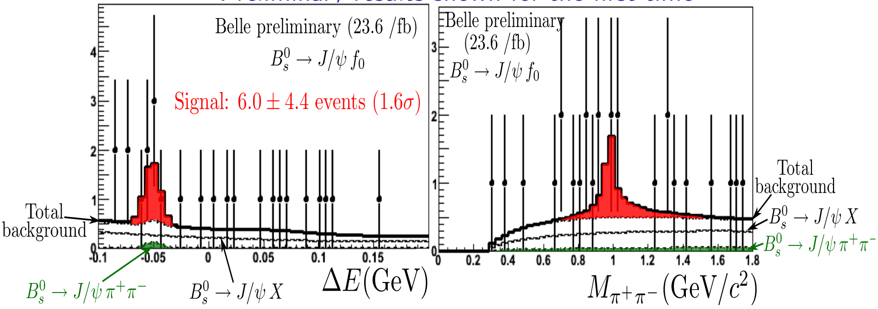
$$\to \mathcal{B}(\mathbf{B_s^0} \to \mathbf{J/\psi\, f_0})\mathcal{B}(\mathbf{f_0} \to \pi^+\pi^-) = (\mathbf{1.6} \pm \mathbf{1.3})\, \mathbf{10^{-4}}$$

Cf. S.Stone's talk for more details

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

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

Preliminary results shown for the first time



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

$$R_{f/\phi} < 0.275 \text{ (at 90\% C.L.)}$$

- We are sensitive to the region of interest !
- More to come with 120 fb^{-1}...

Conclusion:

- Large sample of B_s^0 mesons $\sim 2.8 \cdot 10^6$ analyzed:
- Study of (experimentally) dominant CKM-favored decay modes.
  - Study of $B_s^0 \to D_s^- \pi^+$ and evidence for $B_s^0 \to D_s^\mp K^\pm$
  - 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 $f_s = N_{B_s^{(*)} \bar{B}_s^{(*)}} / N_{b\bar{b}}$
- CP-eigenstate modes:
  - Analysis of $B_s^0 \to hh$
  - Evidences for $B_s^0 \to J/\psi\, \eta^{(\prime)}$
  - Competitive measurement of $\Delta\Gamma^{CP}/\Gamma$ with $B_s^0 \to D_s^{(*)} D_s^{(*)}$

$$\boxed{\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = \left(14.7^{+3.6+4.4}_{-3.0-4.2}\right)\,\%}$$

  - Search for $B_s^0 \to J/\psi f_0$ (New Belle result)

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

- Full Belle $\Upsilon(5S)$ sample $\geq$ **5 times larger** (14 millions B_s^0)
  $\longrightarrow$ Better precision can be achieved !

Thank you.

Di-lepton Asymmetry at Belle

- 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 $B^0\bar{B}^0$.

$$a_{sl}^{B_s^0} \approx 1.2\%$$

$$a_{sl}^{B_d} \approx 0.2\%$$