Study of mixing, CP violation, and polarization of the $B_s \to D_s^{(*)+} D_s^{(*)-}$ and $B_s \to D_s^{(*)-} h^+$ Decays at Belle

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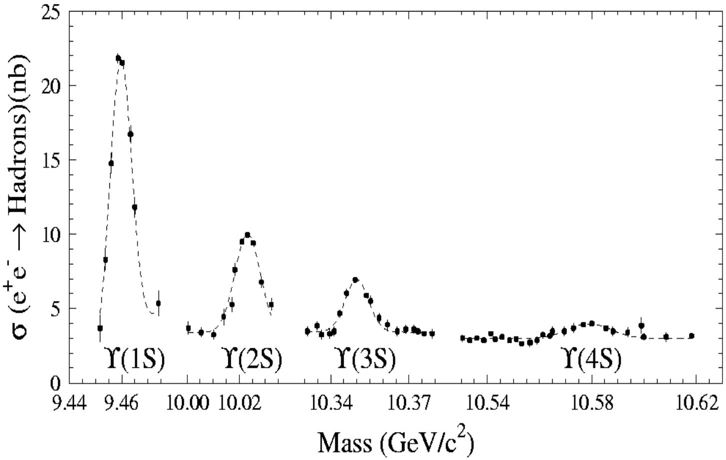
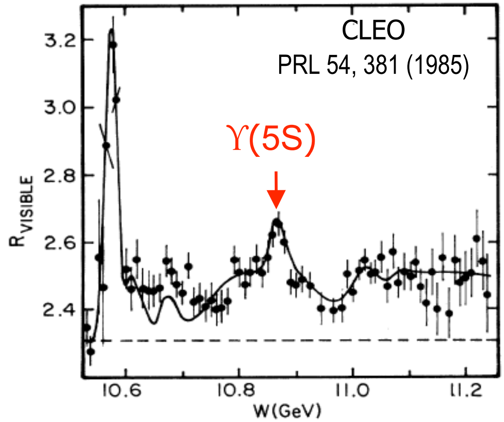
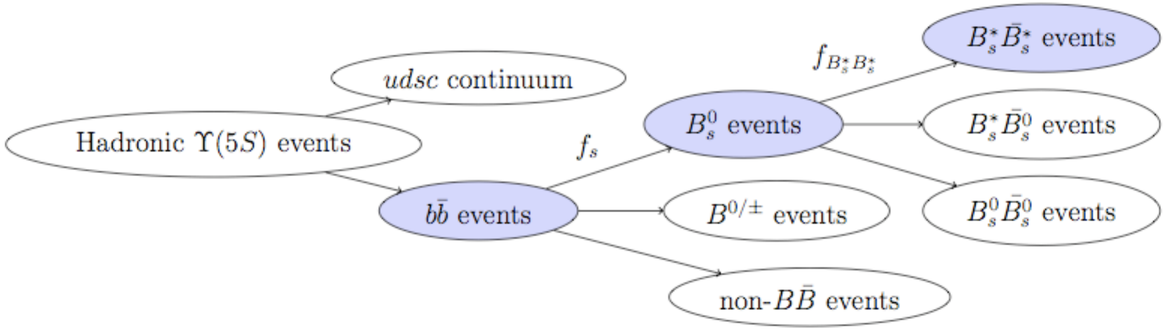
Υ Resonances ($b\bar{b}$ bound states)





- The Υ resonances are bound states of $b\bar{b}$ quarks.
- The lightest Υ resonance producing $B\bar{B}$ pair is $\Upsilon(4S)$
- The $\Upsilon(5S)$ resonance is heavy enough to produce $B_s^{(*)}\bar{B}_s^{(*)}$ pairs
- A large background due to light-quark pair production (u, d, s, or c quark pairs)

Event Classification at $\Upsilon(5S)$



The total number of $B_s\bar{B}_s$ pairs: $N_{B_s\bar{B}_s} = \mathcal{L} \times \sigma_{b\bar{b}}^{\Upsilon(5S)} \times f_s$

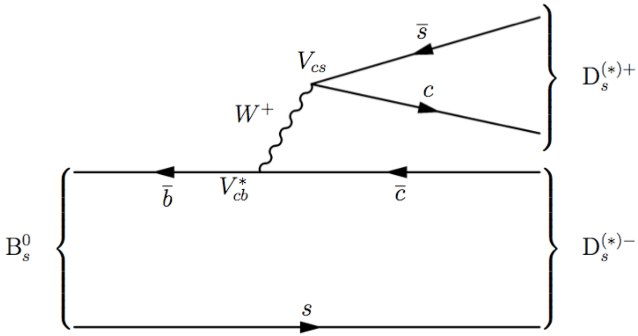
- ≻ Luminosity: $\mathcal{L}$= 121.4fb^{-1}
- ≻ $e^+e^- \to b\bar{b}$ cross section at $\Upsilon(5S)$ energy: $\sigma_{b\bar{b}}^{\Upsilon(5S)} = 0.340 \pm 0.016$ nb
- ≻ Fraction of the $\Upsilon(5S)$ decays producing B_s^0 mesons: $f_s = (17.2 \pm 3.0)\%$

  Phys.Rev.Lett. 98, 052001 (2007)

  $$\mathcal{B}(\Upsilon(5S) \to D_s X)/2 = f_s \times \mathcal{B}(B_s^0 \to D_s X) + (1 - f_s) \times \mathcal{B}(B \to D_s X)$$

- ≻ ≻ $N_{B_s^{(*)}B_s^{(*)}}$ =$(7.11 \pm 1.30) \times 10^6$

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



- ≻ CKM- favored and flavor-neutral
- ≻ Dominant CP-even final states

– $D_s^+ D_s^-$ pure CP-even

– $D_s^{*\pm} D_s^{\mp}$ should be CP-even
  for negligible CP violation in heavy quark limit Phys. Lett. B **316**, 567 (1993)

– $D_s^{*+} D_s^{*-}$ predominantly CP-even:
  expected CP-odd fraction is small Phys. Rev. D **42**, 3732 (1990)

– possible access to $\Delta\Gamma_s$

$\Delta\Gamma_s/\Gamma_s$ via $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ Decays

- $\succ$ In the heavy quark limit, while $(m_b - 2m_c) \to 0$ and $N_c \to \infty$
  - $\succ$ $b \to c\bar{c}s$ processes contribute constructively to $\Delta\Gamma_s$
  - $\succ$ $\Gamma[B_s^0(CP+) \to D_s^{(*)-} D_s^{(*)+}]$ saturates $\Delta\Gamma_s^{CP} = \Delta\Gamma_s/\phi_{12}$
  - $\succ$ assuming negligible CP violation, we can estimate $\Delta\Gamma_s/\Gamma_s$

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

Aleksan *et. al.*, PLB 316, 567 (1993) , Dunietz *et. al.* , PRD 63, 114015 (2001)

some theoretical uncertainty

- $\succ\succ$ 3-body $D_s^{(*)} D_{(s)}^{(*)} X$ and $D_{sJ} D_s$ final states are not included
- $\succ\succ$ $D_s^{*+} D_s^{*-}$ mode is expected to have a small CP-odd component

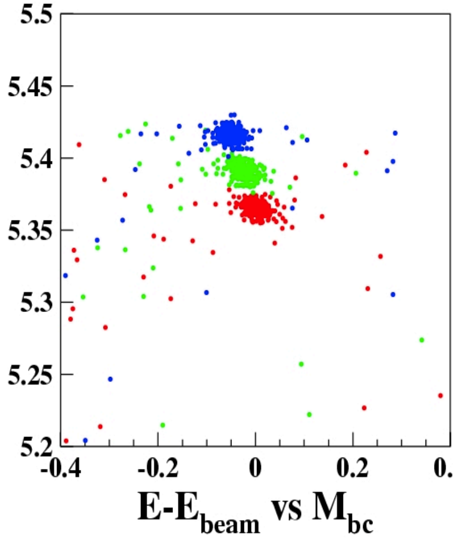
Event Selection

- Exclusively reconstruct B_s^0 decays to $D_s^+ D_s^-$, $D_s^{*\pm} D_s^{\mp}$ and $D_s^{*+} D_s^{*-}$
  - $D_s^+ \to \phi\pi^+, K_S K^+, K^{*0} K^+, \phi\rho^+, K^{*+} K_S, K^{*+} K^{*0}$
    - Charged tracks required to originate from near e^+e^- interaction point
    - Mass cut on intermediate resonances and $D_s^\pm$
  - $D_s^{*\pm} \to D_s^\pm \gamma$ with $|\Delta M_{D_s^* - D_s} - \Delta M^{PDG}| < 12 MeV$
- Observables: the energy difference and the beam energy constrained mass
  - $\Delta E = E_{B_s^0} - E^*$ within $[-0.15, 0.1] GeV$
  - $M_{bc} = \sqrt{E^{*2} - p_{B_s^0}^2}$ within $[5.25, 5.45] GeV/c^2$
- B_s^* always decays to $B_s\gamma$

- We don't reconstruct $\gamma \Rightarrow$ shifted ΔE and M_{bc}

- don't reconstruct γ

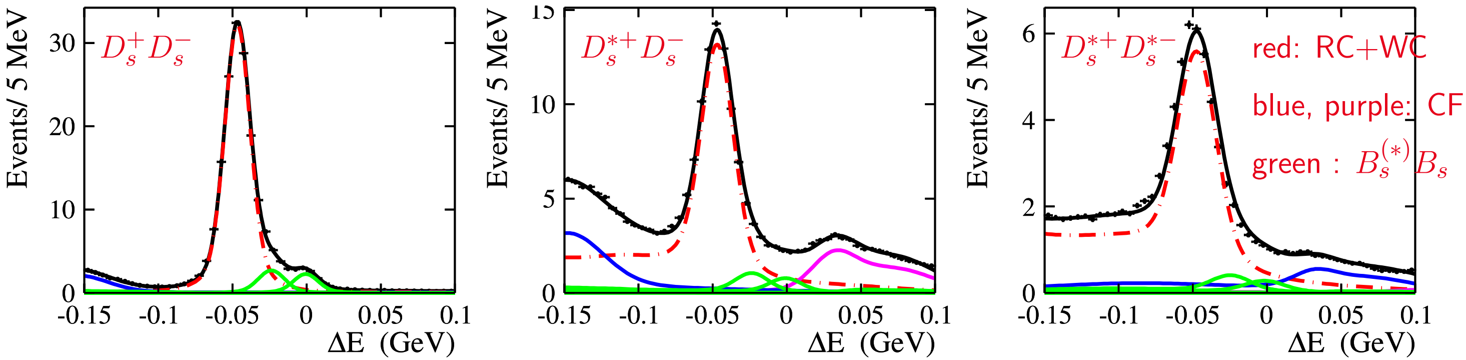
  $\Rightarrow$ shifted ΔE and M_{bc}



Best Candidate Selection

- simultaneous fit of three modes to account for large cross-feeds between signal modes
- one candidate per event selected with minimum χ^2 (MC: correct 75% of time)

$$\chi^2 = \frac{1}{2+N}\left\{ \begin{array}{l} \sum_{i=1}^{2}\left[(\widetilde{M}_{D_s^i} - M_{D_s})/\sigma_M\right]^2 + \\ \sum_{i=1}^{N}\left[(\widetilde{\Delta M}_{D_s^{*i}-D_s^i} - \Delta M_{D_s^*-D_s})/\sigma_{\Delta M}\right]^2 \end{array} \right\}$$

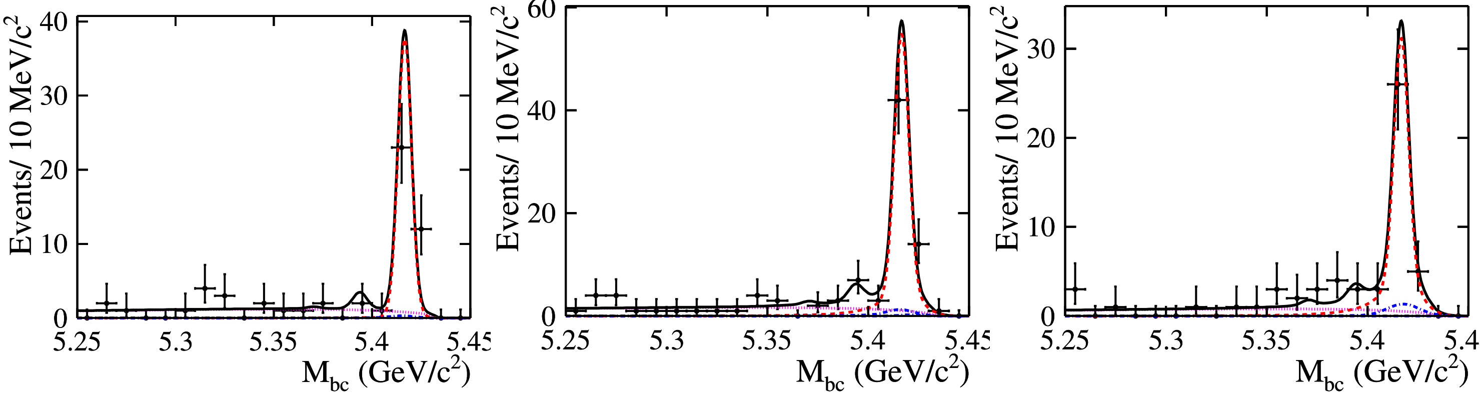


- Relative fractions of signal components (%)

B_s^0 Generated Modes	RC	WC	CF I	CF II
$D_s^+ D_s^-$	76.1	6.0fixed	17.1 ($D_s^{*\pm} D_s^{\mp}$)	0.8 ($D_s^{*+} D_s^{*-}$)
$D_s^{*\pm} D_s^{\mp}$	44.4	38.5fixed	8.2 ($D_s^+ D_s^-$)fixed	8.9 ($D_s^{*+} D_s^{*-}$)
$D_s^{*+} D_s^{*-}$	31.8	37.6fixed	2.0 ($D_s^+ D_s^-$)fixed	28.6 ($D_s^{*\pm} D_s^{\mp}$)fixed

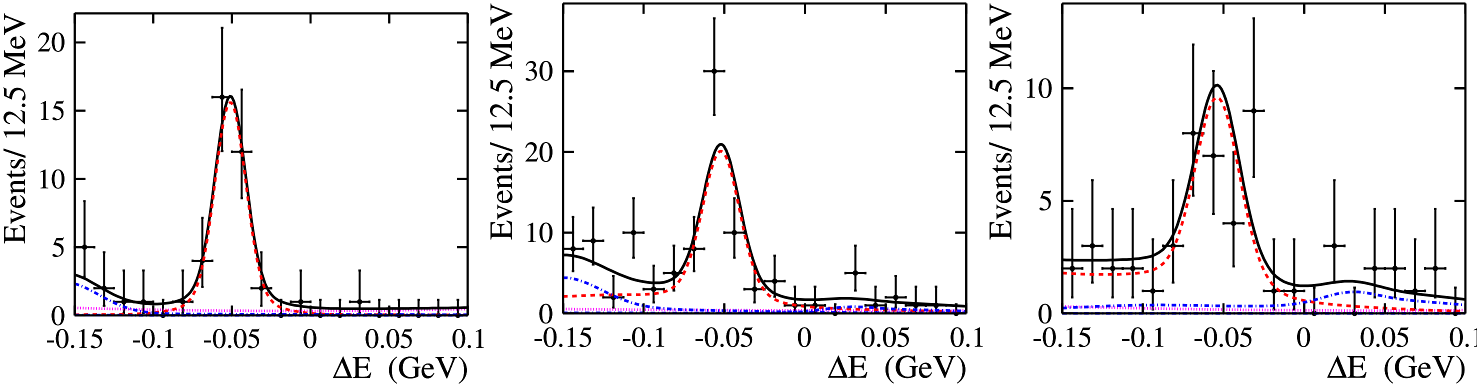
Fit Results with 121.4 fb^{-1}

Events in $\Delta E[-0.1, 0.0]$



$N^{RC} \Rightarrow \quad D_s^+ D_s^- = 33.1^{+6.0}_{-5.4} \qquad D_s^{*+} D_s^- = 44.5^{+5.8}_{-5.5} \qquad D_s^{*+} D_s^{*-} = 24.4^{+4.1}_{-3.8}$

Events in $M_{bc}[5.4, 5.43]$



Results

- Simultaneous 2D extended unbinned ML fit to ΔE and M_{bc}
- The yields of the RC components from $B_s^* B_s^*$ production are the common parameters.

Mode	$Y^{RC}_{B_s^* B_s^*}$ (events)	$\varepsilon^{RC}_{B_s^* B_s^*}$ $(\times 10^{-4})$	$\mathcal{B}$ (%)	S
$D_s^+ D_s^-$	$33.1^{+6.0}_{-5.4}$	4.72	$0.58^{+0.11}_{-0.09} \pm 0.13$	11.6
$D_s^{*+} D_s^- + D_s^{*-} D_s^+$	$44.5^{+5.8}_{-5.5}$	2.08	$1.8 \pm 0.2 \pm 0.4$	13.3
$D_s^{*+} D_s^{*-}$	$24.4^{+4.1}_{-3.8}$	1.01	$2.0 \pm 0.3 \pm 0.5$	8.6
Sum	$102.0^{+9.3}_{-8.6}$		$4.3 \pm 0.4 \pm 1.0$	

Branching Fraction

$$\mathcal{B} = \frac{Y}{2 \times N_{B_s^* B_s^*} \times \varepsilon_{MC} \times \varepsilon_{PID}}$$

Significance w/ syst. errors

$$S = \sqrt{-2ln(\mathcal{L}_0 / \mathcal{L}_{max})}$$

$\Delta\Gamma_s$ Measurements

	Y (events)	$\mathcal{B}$ (%)
$B_s \to D_s^{(*)} D_s^{(*)}$	$102.0^{+9.3}_{-8.6}$	$4.3 \pm 0.4 \pm 1.0$
$\Delta\Gamma_s/\Gamma_s$	$(9.0 \pm 0.9 \pm 2.2)$ %	

$$\Delta\Gamma_s/\Gamma_s = 2\mathcal{B}/(1-\mathcal{B})$$

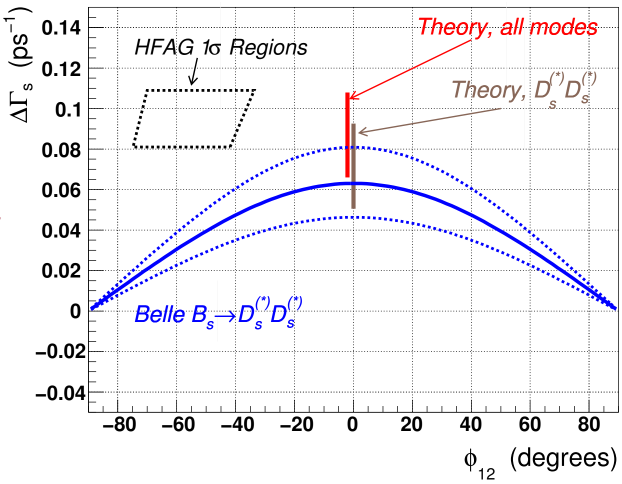
for $\Gamma_s = 1.463 \pm 0.030$ ps^{-1} $\Rightarrow$ $\Delta\Gamma_s = 0.062 \pm 0.016$ ps^{-1}

- Theoretical Estimations:
  $\Delta\Gamma_s/\Gamma_s = (13.3 \pm 3.2)\%$ arXiv:hep-ph/1102.4274

  only with $D_s^{(*)+} D_s^{(*)-}$:
  $\Delta\Gamma_s/\Gamma_s = (10.2 \pm 3.0)\%$ Phys. Rev. D 84, 074037

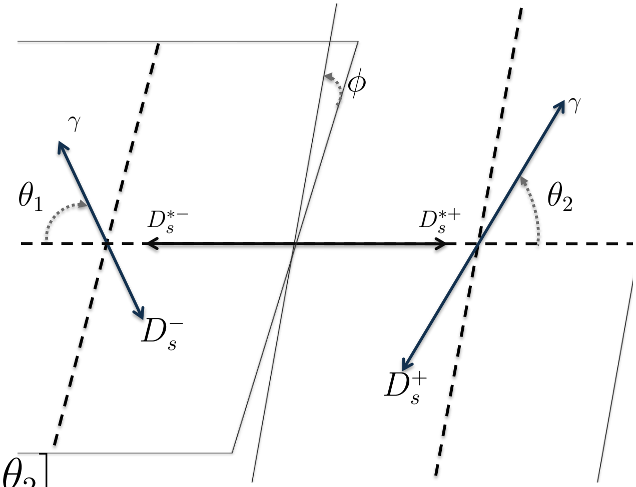
- putting back the CP violating phase

$$\Delta\Gamma_s/\Gamma_s = \frac{1/\cos\phi - \sqrt{1/\cos^2\phi - 4\mathcal{B}(1-\mathcal{B})}}{1-\mathcal{B}}$$



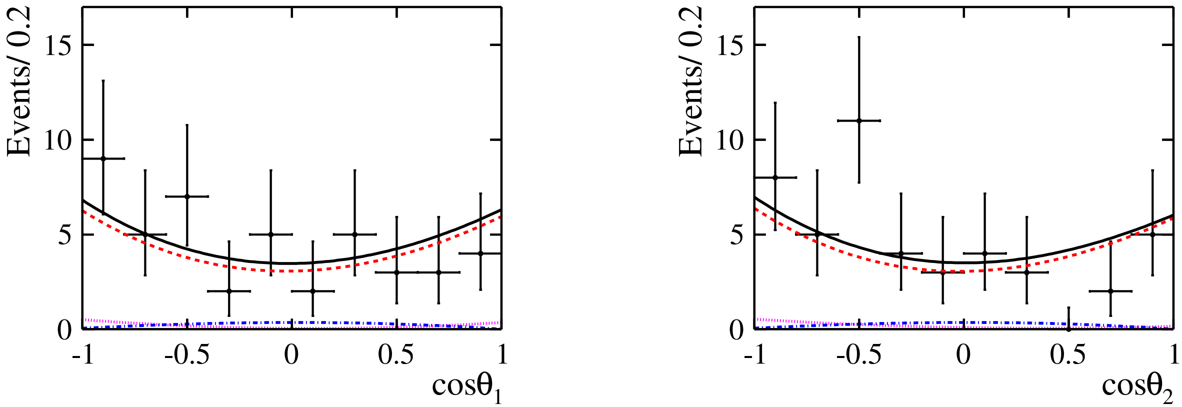
Polarization Measurement

- from analogous $B_s \to D_s^* D*$ decay
  - CP-odd fraction can be inferred to be $\sim 6\%$ (J. Rosner, PRD **42**, 3732 (1990))
  - Longitudinal polarization fraction to be $\sim 52\%$ (PDG)
- used same cuts as branching fraction measurement
- selected events in 2.5σ signal M_{bc}-ΔE region $(B_s^* B_s^*)$
- two polarization state:
  - $A_\pm$ transverse : CP-odd + CP-even
  - A_0 longitudinal : CP-even



$$\frac{d^2\Gamma(\theta_1,\theta_2)}{d\cos\theta_1 d\cos\theta_2} \propto \quad + |A_0|^2 \left[4\sin^2\theta_1 \sin^2\theta_2\right]$$
$$(|A_+|^2 + |A_-|^2)\left[(\cos^2\theta_1 + 1)(\cos^2\theta_2 + 1)\right]$$

$B_s^0 \to D_s^{*+} D_s^{*-}$: f_L measurement

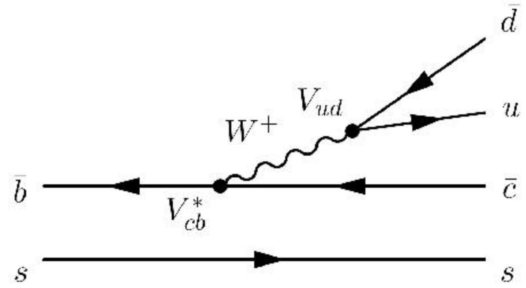


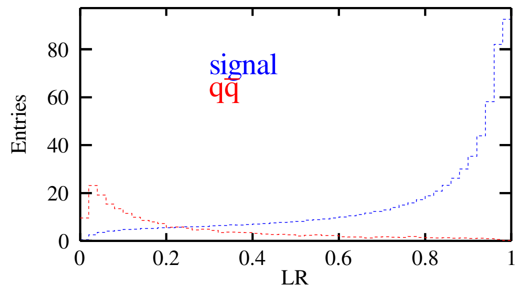
$$f_L = 0.06^{+0.18}_{-0.17} \pm 0.03$$

Source	$+\sigma$	$-\sigma$	Method
Signal PDF shape	0.008	0.010	
Background PDF shape	0.007	0.004	
Fixed WC fraction	0.013	0.015	
Fixed background fraction	0.022	0.022	
Continuum suppression	0.011	0	
MC efficiency	0.0004	0.0004	
Fit bias	0	0.0011	
Sum	0.030	0.031	

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

- Cabibbo-favored decays
  - relatively large branching fractions
- similarities between B_s and B_d predicted
- neutral particles in the final state can be reconstructed (photon, π^0)
- full reconstruction of the final states
  - $D_s^{*\pm} \to D_s^{\pm}\gamma$
  - $D_s^+ \to \phi\pi^+, K_S K^+, K^{*0}K^+$
- large background from $e^+e^- \to q\bar{q}(q = u, d, s, c)$
- good rejection with event shape parameters
  - jet-like $q\bar{q}$ vs. more spherical $B_s^{(*)} - \bar{B}_s^{(*)}$



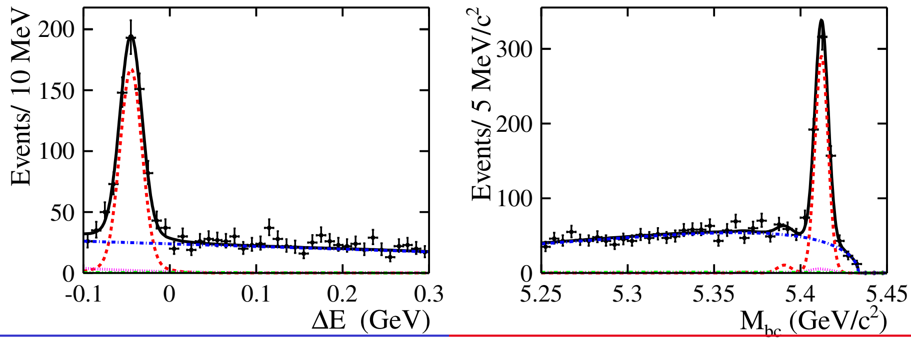


- $B_s^0 \to D_s^{(*)-}\pi^+$, $D_s^- K^+$ and $D_s^{(*)-}\rho^+$ measured with 23.6 fb^{-1} (PRL 102, 021801 (2009) and PRL 104, 231801 (2010))

Mode	Data Set (fb^{-1})	Branching Fraction
$D_s^-\pi^+$	23.6	$(3.67^{+0.35+0.43}_{-0.33-0.42} \pm 0.49)10^{-3}$
$D_s^{*-}\pi^+$	23.6	$(2.4^{+0.5}_{-0.4} \pm 0.3 \pm 0.4)10^{-3}$
$D_s^{*-}\rho^+$	23.6	$(11.8^{+2.2}_{-2.0} \pm 1.7 \pm 1.8)10^{-3}$

- five times more data with better tracking is available
- expect significant improvement especially for final states with neutral particles
- fit sample: $B_s \to D_s\pi$ with generic MC (signal + background $\approx$ 121 fb^{-1})

projections into signal $B_s^* B_s^*$ region



Summary

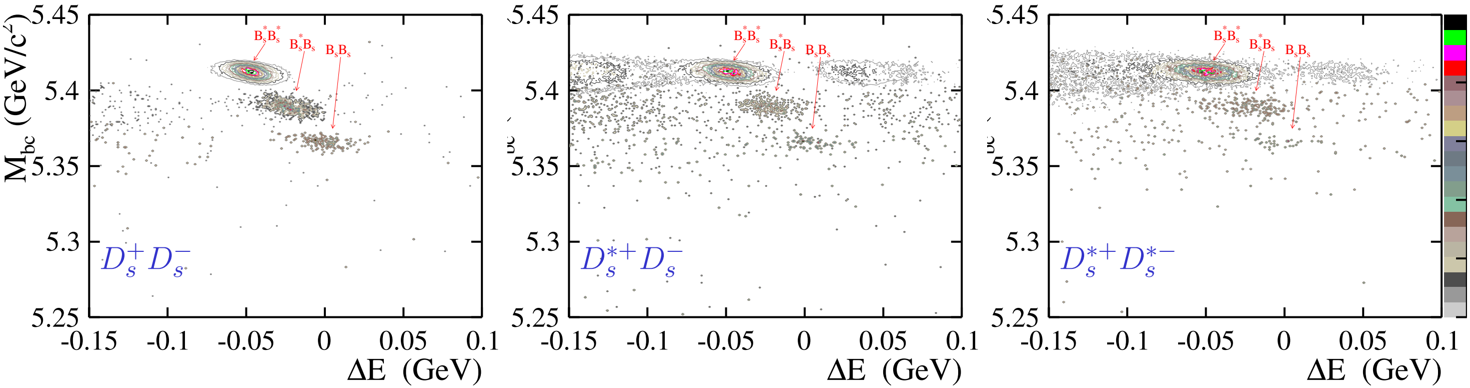
- Exclusive $\mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-})$ measurements with 121.4 fb^{-1} data
  - Good agreement with SM expectation and other measurements.
- Estimation of $\Delta\Gamma_s/\Gamma_s$, assuming negligible CPV
  - $\Delta\Gamma_s/\Gamma_s = (9.0 \pm 0.9 \pm 2.2)\%$
  - Theoretical uncertainties:
    size of 3-body partial widths is unknown, $\Rightarrow$ could be large
    CP-odd component of Ds*Ds* is unknown. $\Rightarrow$ expected to be small
- First polarization measurement of $B_s \to D_s^{*+} D_s^{*-}$ $f_L = 0.06^{+0.18}_{-0.17} \pm 0.03$
- Update of B_s^0 to $D_s^{(*)} h$ decays with full Belle data set is in progress.
  - absolute branching fraction measurements
  - polarization of VV final states

THANK YOU.

Backup

Event Distributions

- B_s **produced through:** $B_s^* \bar{B}_s^*$, $B_s^* \bar{B}_s$, $B_s \bar{B}_s$ **with** $f_{B_s^* \bar{B}_s^*} = (87.0 \pm 1.7)\%$
  - B_s^* always decays to $B_s \gamma$
  - We don't reconstruct $\gamma \Rightarrow$ shifted ΔE and M_{bc}



- **cross contamination between modes**
  - true D_s^{*+} decay, D_s^+ combined with a random photon $\rightarrow$ WC
  - true D_s^+ decay, combined with a random photon $\rightarrow$ CFup
  - true D_s^{*+} decay, lost its photon $\rightarrow$ CFdown
  - true D_s^{*+} or D_s^+ decay $\rightarrow$ RC

Systematic Errors (%)

Source	$D_s^+ D_s^-$		$D_s^* D_s$		$D_s^{*+} D_s^{*-}$	
	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$
Signal PDF Shape	2.7	2.2	2.2	2.4	5.1	3.8
Background PDF Shape	1.5	1.3	1.3	1.4	2.9	2.8
WC/CF fraction	0.5	0.5	4.7	4.5	11.0	9.7
$\mathcal{R}$ requirement $(q\bar{q})$ suppr.	3.1	0.0	0.0	2.7	0.0	2.1
Best candidate selection	5.5	0.0	1.5	0.0	1.5	0.0
$K^\pm$ Identification	7.0	7.0	7.0	7.0	7.0	7.0
K_s Reconstruction	1.1	1.1	1.1	1.1	1.1	1.1
π^0 Reconstruction	1.1	1.1	1.1	1.1	1.1	1.1
γ	-	-	3.8	3.8	7.6	7.6
Tracking	2.2	2.2	2.2	2.2	2.2	2.2
Polarization	0.0	0.0	0.8	2.4	0.4	0.2
MC statistics for ε	0.2	0.2	0.4	0.4	0.5	0.5
$D_s^{(*)}$ BF's	8.6	8.6	8.6	8.6	8.7	8.7
$N_{B_s^{(*)} B_s^{(*)}}$	18.3					
$f_{B_s^* \overline{B}_s^*}$	2.0					
Total	22.7	21.8	22.7	22.9	26.2	25.5

"External" errors (MC statistics for ε, $D_s^{(*)}$ BF's, $N_{B_s^{(*)} B_s^{(*)}}$, $f_{B_s^* \overline{B}_s^*}$)