Measurement of the inclusive branching fractions for B_s decays into D mesons

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Motivation for studying B_s mesons

Decays of B_s mesons provide a powerful tool for:

- studying strong interactions at low energy;
- measuring parameters of the Standard Model;
- searching for New Physics phenomena.

Sources of B_s mesons:

- high energy hadron collisions (Tevatrone, LHC);
- $e^+e^- \to \Upsilon(5S) \to B_s^{(*)}\bar{B}_s^{(*)}$ (KEKB).

Production of B_s at $\Upsilon(5S)$ resonance

f_s – the B_s^0 production fraction at the $\Upsilon(5S)$ energy.

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

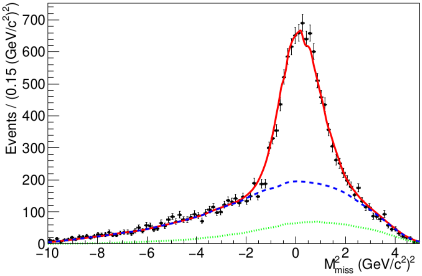
Experimental result $\mathcal{B}(B_s^0 \to D_s^{\pm}X) = (93 \pm 25)\%$

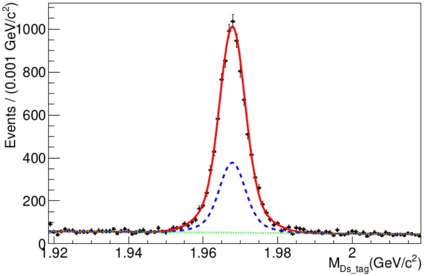
Theoretical estimate $\mathcal{B}(B_s^0 \to D_s^{\pm}X) = (92 \pm 11)\%$
$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) = (8 \pm 7)\%$

The new Belle results:
$\mathcal{B}(B_s^0 \to D_s^{\pm}X) = (60.2 \pm 5.8 \pm 2.3)\%$ (Belle PRD 105, 012004, 2022);
$\frac{\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)}{\mathcal{B}(B_s^0 \to D_s^{\pm}X)} = 0.416 \pm 0.018 \pm 0.092$ (Belle JHEP08(2023)131)

New result of the Belle experiment

Semileptonic tag: $B_s \to D_s^- X l^+ \nu_l$
$M^2_{miss} = (\sqrt{s}/2 - \delta E - E_{D_s l})^2 - (\vec{p}_{D_s l})^2$



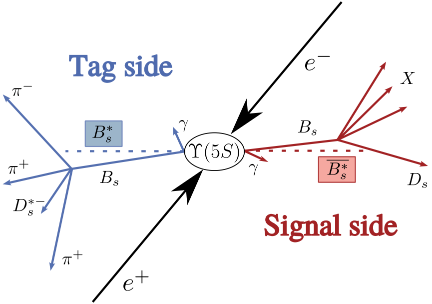


Purpose: new measurement of $\mathcal{B}(B_s^0 \to D_s^\pm X)$ via hadronic tagging. The first direct measurements of $\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)$ and $\mathcal{B}(B_s^0 \to D^\pm X)$.

Measurement of all three branching fractions will allow a consistency check of the results.

The idea of direct measurement

- Reconstruction and selection of B_s^0 candidates is performed in FEI;
- The number of tags is determined by fit to the $M(B_s)$ distribution;
- For each B_s the rest of the event is built and D meson is reconstructed there;



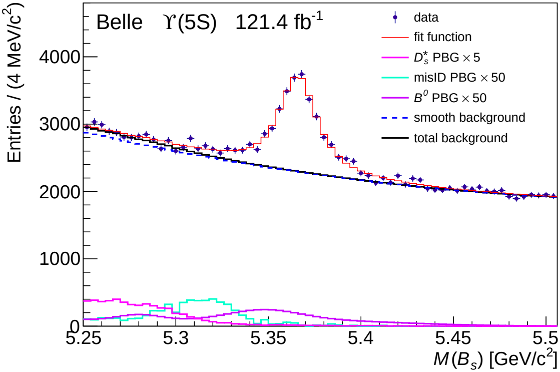
The idea of direct measurement

- Reconstruction and selection of B_s^0 candidates is performed in FEI;
- The number of tags is determined by fit to the $M(B_s)$ distribution;
- For each B_s the rest of the event is built and D meson is reconstructed there;
- The distribution in $M(B_s)$ and $M(D)$ is fitted to obtain the number of $B_s - D$ pairs:

$$N_{B_s-D} = N_{B_s} \cdot \mathcal{B}(B_s^0 \to D/\bar{D}X) \cdot \mathcal{B}_D \cdot \varepsilon_D^{\mathrm{ROE}},$$

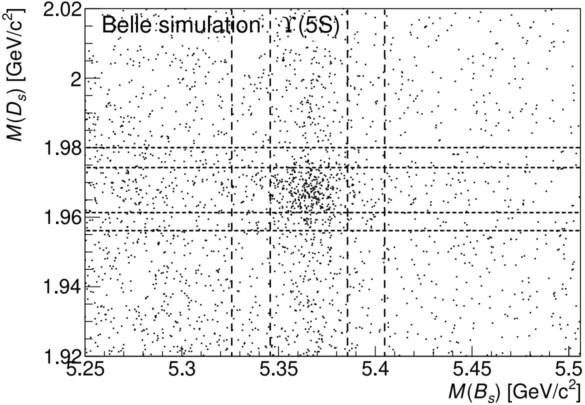
$$\mathcal{B}(B_s^0 \to D/\bar{D}X) = \frac{N_{B_s-D}}{N_{B_s} \cdot \mathcal{B}_D \cdot \varepsilon_D^{\mathrm{ROE}}}.$$

Yield of B_s^0 tags



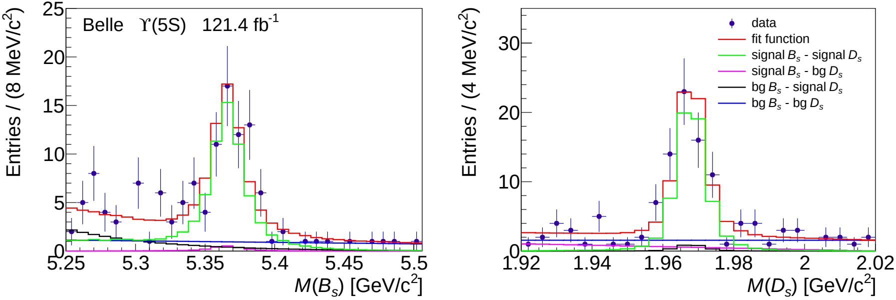
Decay	$\mathcal{P}_{B_s}$ requirement	Number of tags, N_{B_s}
$B_s^0 \to D_s^{\pm} X$	> 0.0012	12501 ± 310
$B_s^0 \to D^0/\bar{D}^0 X$	> 0.0050	9609 ± 190
$B_s^0 \to D^{\pm} X$	> 0.0200	6485 ± 122

Two-dimensional distribution



Fit to the distribution in $M(B_s)$ and $M(D_s)$ in data

$D_s^+ \to \phi\pi^+$:

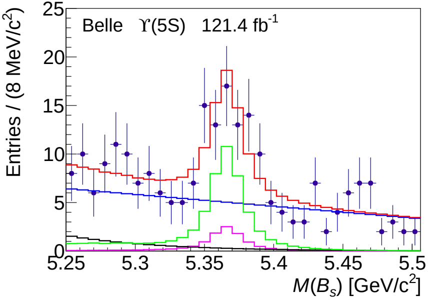


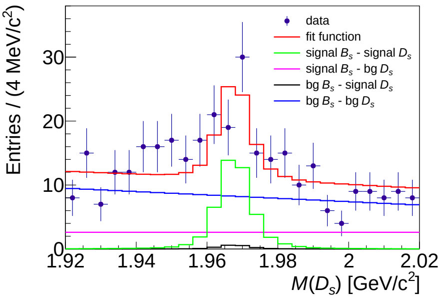
$$N_{B_s - D_s} = 85 \pm 12.$$

$$\mathcal{B}(B_s^0 \to D_s^{\pm} X) = (73.0 \pm 10.6 \pm 5.2)\%.$$

Fit to the distribution in $M(B_s)$ and $M(D_s)$ in data

$D_s^+ \to \bar{K}^{*0} K^+$:



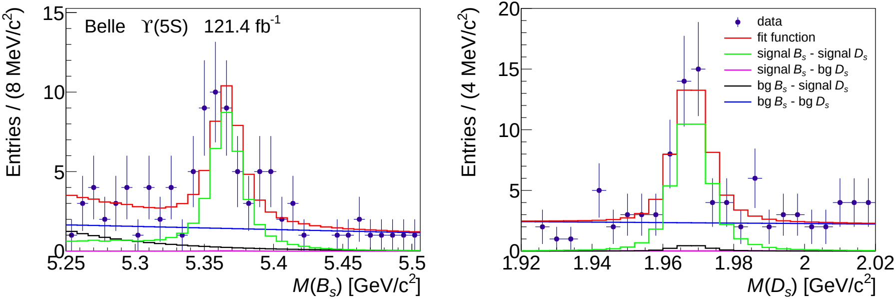


$$N_{B_s-D_s} = 53 \pm 13.$$

$$\mathcal{B}(B_s^0 \to D_s^{\pm} X) = (54.1 \pm 11.7 \pm 3.7)\%.$$

Fit to the distribution in $M(B_s)$ and $M(D_s)$ in data

$D_s^+ \to K_S^0 K^+$:



$$N_{B_s - D_s} = 55 \pm 10.$$

$$\mathcal{B}(B_s^0 \to D_s^{\pm} X) = (88.2 \pm 16.2 \pm 7.0)\%.$$

$\mathcal{B}(B_s^0 \to D_s^{\pm} X)$ results

$$\phi\pi^+: \quad \mathcal{B}(B_s^0 \to D_s^{\pm} X) = (73.0 \pm 10.6 \pm 5.2)\%;$$

$$\bar{K}^{*0}K^+: \quad \mathcal{B}(B_s^0 \to D_s^{\pm} X) = (54.1 \pm 11.7 \pm 3.7)\%;$$

$$K_S^0 K^+: \quad \mathcal{B}(B_s^0 \to D_s^{\pm} X) = (88.2 \pm 16.2 \pm 7.0)\%.$$

We average these branching fractions using HFLAV fitting method and obtain:

$$\mathcal{B}(B_s^0 \to D_s^{\pm} X) = (68.6 \pm 7.2 \pm 4.0)\%.$$

The p-value of this fit is 28%. Our result is in agreement with Belle result $(60.2 \pm 5.8 \pm 2.3)\%$.
Averaging the new value with the previous one, we find

$$\mathcal{B}(B_s^0 \to D_s^{\pm} X) = (63.4 \pm 4.5 \pm 2.2)\%.$$

Production rates at the $\Upsilon(5S)$ resonance

Using the new value of $\mathcal{B}(B_s^0 \to D_s^{\pm} X)$, we recalculate f_s, using the method described in Ref.(JHEP08(2023)131):

$$f_s = (21.8 \pm 0.2 \pm 2.0)\%. \quad (1)$$

To improve its accuracy, we use the relation

$$f_s + f_{BBX} + f_{\not{B}} = 1.$$

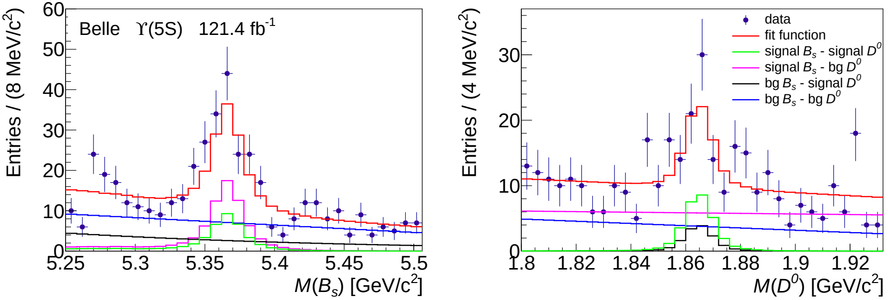
Thus, we obtain

$$\begin{aligned} f_s &= (21.4^{+1.5}_{-1.7})\%; \\ f_{BBX} &= (73.8^{+1.5}_{-2.9})\%; \\ f_{\not{B}} &= (4.8^{+3.6}_{-0.5})\%. \end{aligned}$$

These results supersede the previous values of production rates $f_s = (22.0^{+2.0}_{-2.1})\%$ (Belle JHEP08(2023)131), $f_{BBX} = (75.1 \pm 4.0)\%$, $f_{\not{B}} = (4.9 \pm 0.6)\%$ (Belle JHEP06(2021)137)

Fit to the distribution in $M(B_s)$ and $M(D^0)$ in data

$D^0 \to K^-\pi^+$:



$$N_{B_s-D^0} = 56 \pm 16.$$

$$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) = (21.5 \pm 6.1 \pm 1.8)\%$$

$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)$ result

Using the new value of $\mathcal{B}(B_s^0 \to D_s^{\pm} X)$ and the ratio $\frac{\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)}{\mathcal{B}(B_s^0 \to D_s^{\pm} X)} = 0.416 \pm 0.018 \pm 0.092$, we obtain:

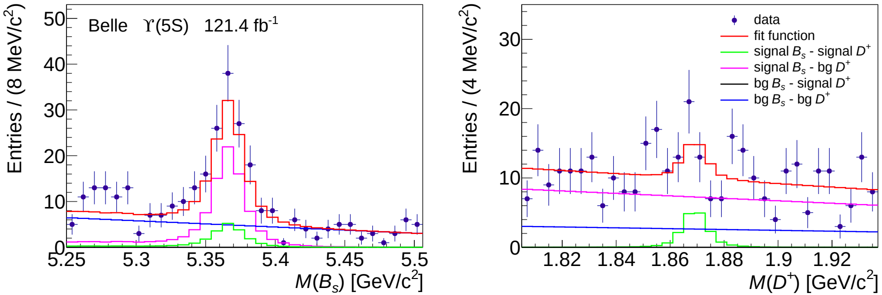
$$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) = (26.5 \pm 2.3 \pm 5.9)\%,$$

We average this value with our result $\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) = (21.5 \pm 6.1 \pm 1.8)\%$ and find

$$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) = (23.9 \pm 4.1 \pm 1.8)\%$$

Fit to the distribution in $M(B_s)$ and $M(D^+)$ in data

$D^+ \to K^-\pi^+\pi^+$:



$$N_{B_s - D^+} = 34 \pm 12.$$

$$\mathcal{B}(B_s^0 \to D^\pm X) = (12.6 \pm 4.6 \pm 1.3)\%.$$

The sum of three branching fractions

Using the updated values of $\mathcal{B}(B_s^0 \to D_s^\pm X)$ and $\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)$, and the new value of $\mathcal{B}(B_s^0 \to D^\pm X)$:

$$\mathcal{B}(B_s^0 \to D_s^\pm X) = (63.4 \pm 4.5 \pm 2.2)\%,$$
$$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) = (23.9 \pm 4.1 \pm 1.8)\%,$$
$$\mathcal{B}(B_s \to D^\pm X) = (12.6 \pm 4.6 \pm 1.3)\%.$$

We find the sum of three branching fractions which is $(99.9 \pm 7.6 \pm 3.8)\%$. The corresponding sum for B^+ and B^0 is $(107.9 \pm 3.4)\%$, which is in agreement with the sum for B_s^0.

Conclusion

The method of hadronic tagging of one B_s in $e^+e \to B_s^* \bar{B}_s^*$ is developed.
It allows to measure inclusive branching fractions:

$$\mathcal{B}(B_s^0 \to D_s^\pm X) = (68.6 \pm 7.2 \pm 4.0)\%,$$
$$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X) = (21.5 \pm 6.1 \pm 1.8)\%,$$
$$\mathcal{B}(B_s \to D^\pm X) = (12.6 \pm 4.6 \pm 1.3)\%.$$

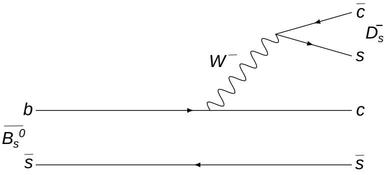
The new values of $\mathcal{B}(B_s^0 \to D_s^\pm X)$ and $\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)$ are in agreement with the previous measurements.
We also improve accuracy of production rates at the $\Upsilon(5S)$ resonance:

$$f_s = (21.3^{+1.6}_{-1.7})\%;$$
$$f_{BBX} = (73.9^{+1.6}_{-3.0})\%;$$
$$f_{\not{B}} = (4.8^{+3.7}_{-0.5})\%.$$

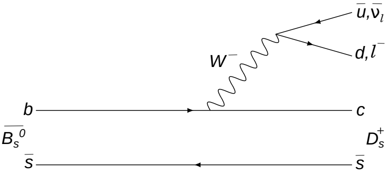
Back-up

Discussion of the result

The main contribution to $B_s^0 \to D_s^\pm X$ have the following diagrams:



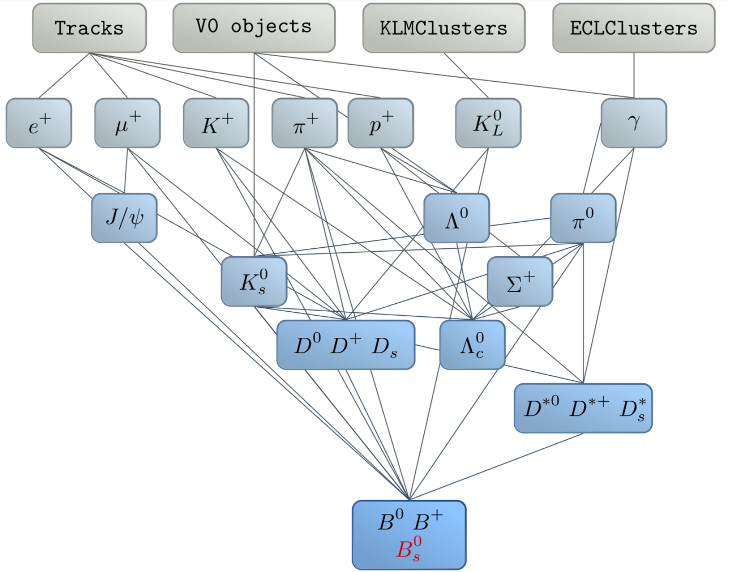
(a)



(b)

The fragmentation fraction of the $c\bar{s}$ pair into D_s^+ mesons of $(85 \pm 10)\%$, assumed in theoretical estimate, is probably an overestimate. Thus, measurements of the inclusive branching fractions of the B_s^0 meson provide information about dynamics of its decays.

FEI


Tracks
V0 objects
KLMClusters
ECLClusters
e^+
μ^+
K^+
π^+
p^+
K_L^0
γ
J/ψ
Λ^0
π^0
K_s^0
Σ^+
D^0 D^+ D_s
Λ_c^0
D^{*0} D^{*+} D_s^*
B^0 B^+
B_s^0

FEI variables

- B_s
  - SigProb of each daughter;
  - R_2 and $\cos\theta_{thrust}$, where θ_{thrust} is the angle between the thrust of the B candidate and the rest of the event (ROE);
  - Masses of the $\rho(\to\pi\pi)$ and $a_1(\to 3\pi)$ candidates (if they are available).
- D_s^*
  - SigProb of each daughter;
  - M.
- D_s
  - SigProb of each daughter;
  - M;
  - χ^2 of mass-vertex fit;
  - for 3-body decays: masses of all pairs of daughters (ϕ, K^*, ρ).
- J/ψ
  - SigProb of each daughter;
  - M.

FEI variables

- K_S
  - nisKsFinder output;
  - M.
- π^0
  - M;
  - p;
  - decay angle.
- γ
  - number of hits in cluster;
  - E_9/E_{25} ratio;
  - E;
  - p_t.
- $\pi^\pm$, $K^\pm$, $\mu^\pm$, $e^\pm$
  - identification variables;
  - p;
  - p_t.

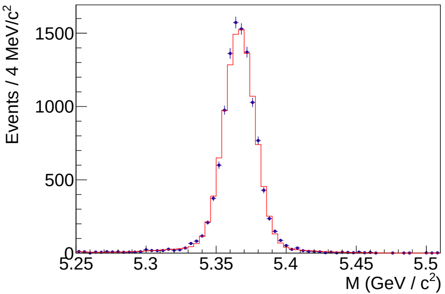
FEI reconstruction channels

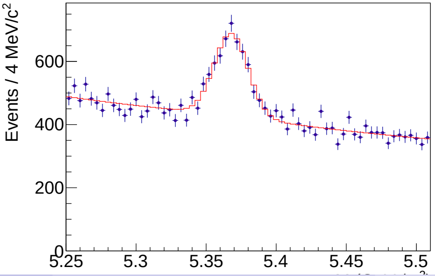
$B_s^0 \to$	$B^+ \to$	$B^0 \to$
${D_s}^-\pi^+$	$\bar{D}^0\pi^+$	$D^-\pi^+$
$D_s^-\pi^+\pi^0$	$\bar{D}^0\pi^+\pi^0$	$D^-\pi^+\pi^0$
$D_s^-\pi^+\pi^+\pi^-$	$\bar{D}^0\pi^+\pi^+\pi^-$	$D^-\pi^+\pi^+\pi^-$
$D_s^{*-}\pi^+$	$\bar{D}^{*0}\pi^+$	$D^{*-}\pi^+$
$D_s^{*-}\pi^0\pi^+$	$\bar{D}^{*0}\pi^+\pi^0$	$D^{*-}\pi^+\pi^0$
$D_s^{*-}\pi^+\pi^+\pi^-$	$\bar{D}^{*0}\pi^+\pi^+\pi^-$	$D^{*-}\pi^+\pi^+\pi^-$
$D_s^- D_s^+$	$D_s^+ \bar{D}^0$	$D_s^+ D^-$
$D_s^{*-} D_s^+$	$D_s^{*+} \bar{D}^0$	$D_s^{*+} D^-$
$D_s^- D_s^{*+}$	$D_s^+ \bar{D}^{*0}$	$D_s^+ D^{*-}$
$D_s^{*-} D_s^{*+}$	$D_s^{*+} \bar{D}^{*0}$	$D_s^{*+} D^{*-}$
$J/\psi\, K^+K^-$	$J/\psi\, K^+$	$J/\psi\, K_S^0$
$J/\psi\, K^+K^-\pi^0$	$J/\psi\, K_S^0\,\pi^+$	$J/\psi\, K^+\pi^-$
	$J/\psi\, K^+\pi^+\pi^-$	
$\bar{D}^0K^-\pi^+$	$D^-\pi^+\pi^+$	$D^{*-}K^+K^-\pi^+$
$\bar{D}^{*0}K^-\pi^+$	$D^{*-}\pi^+\pi^+$	
$D_s^-K^+$		

FEI

$D^0 \to$	$D^+ \to$	$D_s^+ \to$
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$K^+K_S^0$
$K^-\pi^+\pi^+\pi^-$	$K_S^0\pi^+$	$K^+K^-\pi^+\pi^0$
$K_S^0\pi^+\pi^-$	$K_S^0\pi^+\pi^0$	$K^+K_S^0\pi^+\pi^-$
$K_S^0\pi^+\pi^-\pi^0$	$K_S^0\pi^+\pi^+\pi^-$	$K^-K_S^0\pi^+\pi^+$
K^+K^-	$K^+K^-\pi^+$	$K^+K^-\pi^+\pi^+\pi^-$
$K^+K^-K_S^0$		$K^+\pi^+\pi^-$
		$\pi^+\pi^+\pi^-$
		$K^+K_S^0\pi^0$
		$K_S^0K_S^0\pi^+$
		$\eta'\pi^+$
		$\eta'\pi^+\pi^0$

Simultaneous fit





Event selection

$\mathcal{B}(B_s^0 \to D_s^{\pm} X)$:

- B_s:
  - $|p_{cm} - 0.42| < 0.09\ \mathrm{GeV}/c$;
  - $\mathcal{P}_{B_s} > 0.0012$.
- D_s:
  - $|dr|$ <0.5 cm, $|dz|$ <2.0 cm;
  - $\mathcal{L}_{K/\pi} > 0.1$, $\mathcal{L}_{\pi/K} > 0.1$;
  - $\phi\pi^+$: $|M_{KK} - 1.019| < 0.040\ \mathrm{GeV}/c^2$, $|\cos\theta_{hel}| > 0.3$;
  - K^*K^+: $|M_{K\pi} - 0.892| < 0.100\ \mathrm{GeV}/c^2$, $|\cos\theta_{hel}| > 0.3$;
  - $K_S^0 K^+$: $|M_{K_S^0} - 0.498| < 0.015\ \mathrm{GeV}/c^2$ + standard criteria.

$\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)$:

- B_s:
  - $|p_{cm} - 0.42| < 0.09\ \mathrm{GeV}/c$;
  - $\mathcal{P}_{B_s} > 0.005$.
- $D^0 \to K^-\pi^+$:
  - $|dr|$ <0.5 cm, $|dz|$ <2.0 cm;
  - $\mathcal{L}_{K/\pi} > 0.6$, $\mathcal{L}_{\pi/K} > 0.1$.

$\mathcal{B}(B_s^0 \to D^{\pm} X)$

- B_s:
  - $|p_{cm} - 0.42| < 0.09\ \mathrm{GeV}/c$;
  - $\mathcal{P}_{B_s} > 0.02$.
- $D^+ \to K^-\pi^+\pi^+$:
  - $|dr|$ <0.5 cm, $|dz|$ <2.0 cm;
  - $\mathcal{L}_{K/\pi} > 0.1$, $\mathcal{L}_{\pi/K} > 0.6$.

Systematic uncertainty

Source	Channel $\phi\pi^+$	$\bar{K}^{*0}K^+$	$K_S^0K^+$	Combined
Signal shape	2.3	1.8	1.6	2.0
Broken signal	0.9	0.9	0.9	0.9
Smooth background	1.6	1.0	1.1	1.4
Tracking	1.1	1.1	1.1	1.1
K/π identification	2.1	1.9	0.7	1.7
K_S^0 reconstruction	–	–	2.3	0.6
D_s momentum	0.8	0.6	0.2	0.6
Dalitz plot	0.8	0.8	–	0.6
FEI efficiency	3.6	3.6	3.6	3.6
MC statistics	4.4	4.5	5.7	2.7
$\mathcal{B}(D_s \to KK\pi)$	1.9	1.9	–	1.4
$\mathcal{B}(D_s \to K_S K)$	–	–	2.4	0.6
$\mathcal{B}(K_S^0 \to \pi^+\pi^-)$	–	–	< 0.1	–
Total	7.2	6.9	7.9	5.9

Systematic uncertainty

Source	$B_s^0 \to D^0/\bar{D}^0 X$	$B_s^0 \to D^\pm X$
Signal shape	2.0	0.6
Broken signal	1.1	2.9
Smooth background	0.3	0.9
Tracking	0.7	1.1
K/π identification	1.2	3.0
D momentum	0.2	<0.1
FEI efficiency	2.1	2.1
MC statistics	7.5	9.0
$\mathcal{B}(D \to K\pi(\pi))$	0.8	1.7
Total	8.3	10.4

Correlated uncertainties

Source	Semileptonic tag	This work	Combined
Uncorrelated	3.0	5.3	2.6
Tracking	1.1	1.1	1.1
K/π identification	1.3	1.7	1.5
$\mathcal{B}(D_s \to KK\pi)$	1.5	1.4	1.4
$\mathcal{B}(D_s \to K_S K)$	0.4	0.6	0.5
Total			3.5

Results at the $\Upsilon(4S)$ resonance

	$\mathcal{B}(B^0 \to D^0 X)$, %	$\mathcal{B}(B^0 \to D^+ X)$, %	$\mathcal{B}(B^0 \to D_s X)$, %
Result	$53.2 \pm 1.0 \pm 1.0$	$38.9 \pm 0.7 \pm 0.7$	$11.6 \pm 0.4 \pm 0.5$
PDG	55.5 ± 3.2	39.2 ± 3.5	$11.8^{+2.2}_{-2.0}$

	$\mathcal{B}(B^+ \to D^0 X)$, %	$\mathcal{B}(B^+ \to D^+ X)$, %	$\mathcal{B}(B^+ \to D_s X)$, %
Result	$79.3 \pm 1.0 \pm 0.8$	$11.1 \pm 0.5 \pm 0.4$	$13.0 \pm 0.4 \pm 0.4$
PDG	87.6 ± 4.1	12.4 ± 1.3	9.0 ± 1.4

Results at the $\Upsilon(4S)$ resonance

Using the ratio of production rates f^{+-}/f^{00} at the $\Upsilon(4S)$, we find

$$\mathcal{B}(B \to D^0/\bar{D}^0 X) = (66.7 \pm 0.7 \pm 0.6)\%,$$

$$\mathcal{B}(B \to D_s^+/D_s^- X) = (12.3 \pm 0.3 \pm 0.3)\%.$$

These branching fractions are in agreement with the last Belle results:

$$\mathcal{B}(B \to D^0/\bar{D}^0 X) = (66.65 \pm 0.04 \pm 1.77)\%,$$

$$\mathcal{B}(B \to D_s^+/D_s^- X) = (11.28 \pm 0.03 \pm 0.55)\%.$$

We take the accuracy with which this test is carried out as a systematic error of our method.