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# Determination of $f_s/f_d$ for 7 TeV $pp$ collisions and a measurement of the branching fraction of the decay $B^0 \to D^- K^+$

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**(The LHCb Collaboration)**

The relative abundance of the three decay modes $B^0 \to D^-K^+$, $B^0 \to D^-\pi^+$ and $B_s^0 \to D_s^-\pi^+$ produced in 7 TeV $pp$ collisions at the LHC is determined from data corresponding to an integrated luminosity of $35\,\mathrm{pb}^{-1}$. The branching fraction of $B^0 \to D^-K^+$ is found to be $\mathcal{B}\left(B^0 \to D^-K^+\right) = (2.01 \pm 0.18^{\mathrm{stat}} \pm 0.14^{\mathrm{syst}}) \times 10^{-4}$. The ratio of fragmentation fractions $f_s/f_d$ is determined through the relative abundance of $B_s^0 \to D_s^-\pi^+$ to $B^0 \to D^-K^+$ and $B^0 \to D^-\pi^+$, leading to $f_s/f_d = 0.253 \pm 0.017 \pm 0.017 \pm 0.020$, where the uncertainties are statistical, systematic, and theoretical respectively.

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Knowledge of the production rate of $B_s^0$ mesons is required to determine any $B_s^0$ branching fraction. This rate is determined by the $b\bar{b}$ production cross-section and the fragmentation probability $f_s$, which is the fraction of $B_s^0$ mesons amongst all weakly-decaying bottom hadrons. Similarly the production rate of $B^0$ mesons is driven by the fragmentation probability $f_d$. The measurement of the branching fraction of the rare decay $B_s^0 \to \mu^+\mu^-$ is a prime example where improved knowledge of $f_s/f_d$ is needed to reach the highest sensitivity in the search for physics beyond the Standard Model [1]. The ratio $f_s/f_d$ has not yet been measured at LHC.

The branching fraction ratio $B_s^0 \to D_s^-\pi^+/B^0 \to D^-K^+$ is dominated by contributions from colour-allowed tree-diagram amplitudes and is therefore theoretically well understood. In contrast, the ratio $B_s^0 \to D_s^-\pi^+/B^0 \to D^-\pi^+$ can be measured with a smaller statistical uncertainty due to the greater yield of the $B^0$ mode, but suffers from an additional theoretical uncertainty due to the contribution from a $W$-exchange diagram. Both ratios are exploited here to measure $f_s/f_d$ according to the equations [2, 3]

$$\frac{f_s}{f_d} = 0.0743 \times \frac{\tau_{B_d}}{\tau_{B_s}} \times \left[\frac{1}{\mathcal{N}_a\mathcal{N}_F}\frac{\epsilon_{D^-K^+}}{\epsilon_{D_s^-\pi^+}}\frac{N_{D_s^-\pi^+}}{N_{D^-K^+}}\right], \quad (1)$$

and

$$\frac{f_s}{f_d} = 0.982 \times \frac{\tau_{B_d}}{\tau_{B_s}} \times \left[\frac{1}{\mathcal{N}_a\mathcal{N}_F\mathcal{N}_E}\frac{\epsilon_{D^-\pi^+}}{\epsilon_{D_s^-\pi^+}}\frac{N_{D_s^-\pi^+}}{N_{D^-\pi^+}}\right]. \quad (2)$$

Here $\epsilon_X$ is the selection efficiency of decay $X$ (including the branching fraction of the $D$ decay mode used to reconstruct it) and $N_X$ is the observed number of decays of this type. Inclusion of charge conjugate modes is implied throughout. The term $\mathcal{N}_a$ parameterises non-factorizable SU(3)-breaking effects; $\mathcal{N}_F$ is the ratio of the form factors; $\mathcal{N}_E$ is an additional correction term to account for the $W$-exchange diagram in the $B^0 \to D^-\pi^+$ decay. Their values [2, 3] are $\mathcal{N}_a = 1.00 \pm 0.02$, $\mathcal{N}_F = 1.24 \pm 0.08$, and $\mathcal{N}_E = 0.966 \pm 0.075$. The latest world average [4] is used for the $B$ meson lifetime ratio $\tau_{B_s}/\tau_{B_d} = 0.973 \pm 0.015$. Other numerical factors have negligible associated uncertainties [5].

The observed yields of these three decay modes in $35\,\mathrm{pb}^{-1}$ of data collected with the LHCb detector in the 2010 running period are used to measure $f_s/f_d$ averaged over the LHCb acceptance and to improve the current measurement of the branching fraction of the $B^0 \to D^-K^+$ decay mode [6].

The LHCb experiment [7] is a single-arm spectrometer, designed to study $B$ decays at the LHC, with a pseudorapidity acceptance of $2 < \eta < 5$ for charged tracks. The first trigger level allows the selection of events with $B$ hadronic decays using the transverse energy of hadrons measured in the calorimeter system. The event information is subsequently sent to a software trigger, implemented in a dedicated processor farm, which performs a final online selection of events for later offline analysis. The tracking system determines the momenta of $B$ decay products with a precision of $\delta p/p = 0.35$–$0.5\%$. Two Ring Imaging Cherenkov (RICH) detectors allow charged kaons and pions to be distinguished in the momentum

range 2–100 GeV/$c$.

The three decay modes, $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$, $B^0 \to D^-(K^+\pi^-\pi^-)K^+$ and $B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$, are topologically identical and therefore can be selected using identical geometric and kinematic criteria, thus minimizing efficiency differences between them. Events are selected at the first trigger stage by requiring a hadron with transverse energy greater than 3.6 GeV in the calorimeter. The second, software, stage [8, 9] requires a two, three, or four track secondary vertex with a high sum $p_T$ of the tracks, significant displacement from the primary interaction, and at least one track with exceptionally high $p_T$, large displacement from the primary interaction, and small fit $\chi^2$.

The decays of $B$ mesons can be distinguished from background using variables such as the $p_T$ and impact parameter $\chi^2$ with respect to the primary interaction of the $B$, $D$, and the final state particles. In addition the vertex quality of the $B$ and $D$ candidates, the $B$ lifetime, and the angle between the $B$ momentum vector and the vector joining the $B$ production and decay vertices are used in the selection. The $D$ lifetime and flight distance are not used in the selection because the lifetimes of the $D_s^-$ and $D^-$ differ by about a factor of two.

The final event sample is selected using the gradient boosted decision tree technique [10]. The selection is trained on a mixture of simulated $B^0 \to D^-\pi^+$ decays and combinatorial background selected from the sidebands of the data mass distributions. The distributions of the input variables for data and simulated signal events show excellent agreement, justifying the use of simulated events in the training procedure.

Subsequently, $D^-$ ($D_s^-$) candidates are identified by requiring the invariant mass under the $K\pi\pi$ ($KK\pi$) hypothesis to fall within the selection window $1870^{+24}_{-40}$ ($1969^{+24}_{-40}$) MeV/$c^2$. The final $B^0 \to D^-\pi^+$ and $B_s^0 \to D_s^-\pi^+$ subsamples consist of events that pass a particle identification (PID) criterion on the bachelor particle, based on the difference in log-likelihood between the charged pion and kaon hypotheses (DLL) of DLL($K-\pi$) $< 0$. The $B^0 \to D^-K^+$ subsample consists of events with DLL($K-\pi$) $> 5$. Events not satisfying either condition are not used.

The relative efficiency of the selection procedure is evaluated for all decay modes using simulated events. As the analysis is only sensitive to relative efficiencies, the impact of differences between data and simulation is small. The relative efficiencies are $\epsilon_{D^-\pi^+}/\epsilon_{D^-K^+} = 1.221 \pm 0.021$, $\epsilon_{D^-K^+}/\epsilon_{D_s^-\pi^+} = 0.917 \pm 0.020$, and $\epsilon_{D^-\pi^+}/\epsilon_{D_s^-\pi^+} = 1.120 \pm 0.025$, where the errors are due to the limited size of the simulated event samples.

The relative yields of the three decay modes are extracted from unbinned extended maximum likelihood fits to the mass distributions. The signal mass shape is described by an empirical model derived from simulated events. The mass distribution in the simulation exhibits non-Gaussian tails on either side of the signal. The tail on the right-hand side is due to non-Gaussian detector effects and modelled with a Crystal Ball (CB) function [11]. A similar tail is present on the left-hand side of the peak. In addition, the low mass tail contains a second contribution due to events where hadrons have radiated photons that are not reconstructed. The sum of these contributions is modelled with a second CB function. The peak values of these two CB functions are constrained to be identical.

Various backgrounds have to be considered, in particular the crossfeed between the $D^-$ and $D_s^-$ channels, and the contamination in both samples from $\Lambda_b \to \Lambda_c^+\pi^-$ decays, where $\Lambda_c^+ \to pK^-\pi^+$. The $D_s^-$ contamination in the $D^-$ data sample is reduced by loose PID requirements, DLL($K-\pi$) $< 10$ and DLL($K-\pi$) $> 0$, for the pions and kaons from $D$ decays, respectively. The resulting efficiency to reconstruct $B_s^0 \to D_s^-\pi^+$ as background is evaluated, using simulated events, to be 30 times smaller than for $B^0 \to D^-\pi^+$ and 150 times smaller than for $B^0 \to D^-K^+$ within the $B^0$ and $D^-$ signal mass windows. Taking into account the lower production fraction of $B_s^0$ mesons, this background is negligible.

The contamination from $\Lambda_c$ decays is estimated in a similar way. However, different approaches are used for the $B^0$ and $B_s^0$ decays. A contamination of approximately 2% under the $B^0 \to D^-\pi^+$ mass peak and below 1% under the $B^0 \to D^-K^+$ peak is found, and therefore no explicit DLL($p-\pi$) criterion is needed. The $\Lambda_c$ background in the $B_s^0$ sample is, on the other hand, large enough that it can be fitted for directly.

A prominent peaking background to $B^0 \to D^-K^+$ is $B^0 \to D^-\pi^+$, with the pion misidentified as a kaon. The small $\pi \to K$ misidentification rate is compensated by the larger branching fraction, resulting in similar event yields. This background is modelled by obtaining a clean $B^0 \to D^-\pi^+$ sample from the data and reconstructing it under the $B^0 \to D^-K^+$ mass hypothesis. The resulting mass shape depends on the momentum distribution of the bachelor particle. The momentum distribution after the DLL($K-\pi$) $> 5$ requirement can be found by considering the PID performance as a function of momentum. This is obtained using a sample of $D^{*+}$ decays, and is illustrated in Fig. 1. The mass distribution is reweighted using this momentum distribution to reproduce the $B^0 \to D^-\pi^+$ mass shape following the DLL cut.

The combinatorial background consists of events with random pions and kaons, forming a fake $D^-$ or $D_s^-$ candidate, as well as real, $D^-$ or $D_s^-$ mesons that combine with a random pion or kaon. The combinatorial background is modelled with an exponential shape.

Other background components originate from partially reconstructed $B^0$ and $B_s^0$ decays. In $B^0 \to D^-\pi^+$ these originate from $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^-\rho^+$ decays, which can also be backgrounds for $B^0 \to D^-K^+$ in the case of a misidentified bachelor pion. In

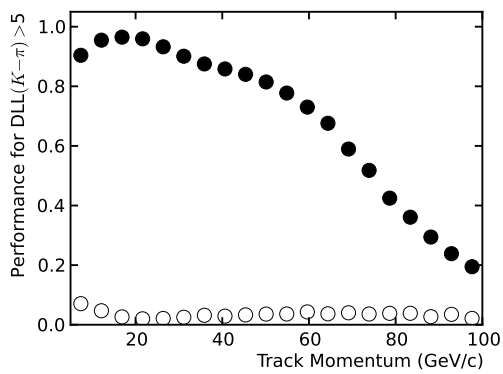


FIG. 1. Probability, as a function of momentum, to correctly identify a kaon (full circles) and to wrongly identify a pion as a kaon (open circles) when requiring DLL$(K-\pi) > 5$. The data are taken from a calibration sample of $D^* \to D(K\pi)\pi$ decays; the statistical uncertainties are too small to display.

$B^0 \to D^- K^+$ there is additionally background from $B^0 \to D^{*-} K^+$ decays. The invariant mass distributions for the partially reconstructed and misidentified backgrounds are taken from large samples of simulated events, reweighted according to the mass hypothesis of the signal being fitted and the DLL cuts.

For $B_s^0 \to D_s^- \pi^+$, the $B^0 \to D^- \pi^+$ background peaks under the signal with a similar shape. In order to suppress this peaking background, PID requirements are placed on both kaon tracks. The kaon which has the same sign in the $B_s^0 \to D_s^- \pi^+$ and $B^0 \to D^- \pi^+$ decays is required to satisfy DLL$(K-\pi) > 0$, while the other kaon in the $D_s^+$ decay is required to satisfy DLL$(K-\pi) > 5$. Because of the similar shape, a Gaussian constraint is applied to the yield of this background. The central value of this constraint is computed from the $\pi \to K$ misidentification rate. The $\Lambda_b \to \Lambda_c^+ \pi^-$ background shape is obtained from simulated events, reweighted according to the PID efficiency, and the yield allowed to float in the fit. Finally, the relative size of the $B_s^0 \to D_s^- \rho^+$ and $B_s^0 \to D_s^{*-} \pi^+$ backgrounds is constrained to the ratio of the $B^0 \to D^- \rho^+$ and $B^0 \to D^{*-} \pi^+$ backgrounds in the $B^0 \to D^- \pi^+$ fit, with an uncertainty of 20% to account for potential SU(3) symmetry breaking effects.

The free parameters in the likelihood fits to the mass distributions are the event yields for the different event types, *i.e.* the combinatorial background, partially reconstructed background, misidentified contributions, the signal, as well as the peak value of the signal shape. In addition the combinatoric background shape is left free in the $B^0 \to D^- \pi^+$ and $B_s^0 \to D_s^- \pi^+$ fits, and the signal width is left free in the $B^0 \to D^- \pi^+$ fit. In the $B_s^0 \to D_s^- \pi^+$ and $B^0 \to D^- K^+$ fits the signal width is fixed to the value from the $B^0 \to D^- \pi^+$ fit, corrected by the ratio of the signal widths for these modes in simulated events.

The fits to the full $B^0 \to D^- \pi^+$, $B^0 \to D^- K^+$, and $B_s^0 \to D_s^- \pi^+$ data samples are shown in Fig. 2. The resulting $B^0 \to D^- \pi^+$ and $B^0 \to D^- K^+$ event yields are $4103 \pm 75$ and $252 \pm 21$, respectively. The number of misidentified $B^0 \to D^- \pi^+$ events under the $B^0 \to D^- K^+$ signal as obtained from the fit is $131 \pm 19$. This agrees with the number expected from the total number of $B^0 \to D^- \pi^+$ events, corrected for the misidentification rate determined from the PID calibration sample, of $145 \pm 5$. The $B_s^0 \to D_s^- \pi^+$ event yield is $670 \pm 34$.

The stability of the fit results has been investigated using different cut values for both the PID requirement

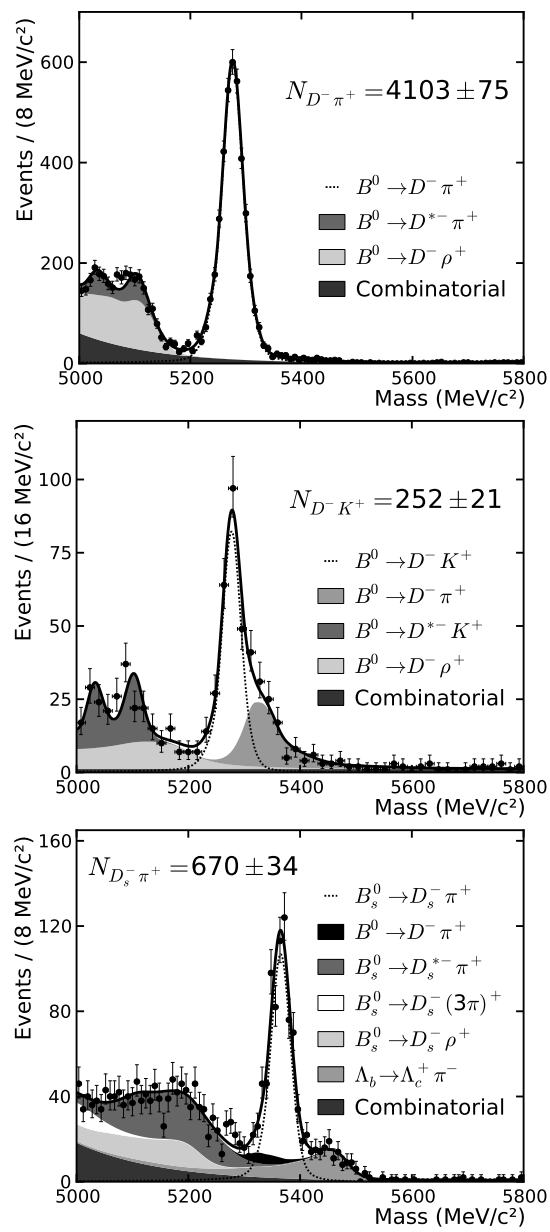


FIG. 2. Mass distributions of the $B^0 \to D^- \pi^+$, $B^0 \to D^- K^+$, and $B_s^0 \to D_s^- \pi^+$ candidates (top to bottom). The indicated components are described in the text.

TABLE I. Experimental systematic uncertainties for the $\mathcal{B}\left(B^0 \to D^- K^+\right)$ and the two $f_s/f_d$ measurements.

| | $\mathcal{B}\left(B^0 \to D^- K^+\right)$ | $f_s/f_d$ |
|---|---|---|
| PID calibration | 2.5% | 1.0%/2.5% |
| Fit model | 2.8% | 2.8% |
| Trigger simulation | 2.0% | 2.0% |
| $\mathcal{B}(B^0 \to D^- \pi^+)$ | 4.9% | |
| $\mathcal{B}(D_s^+ \to K^+ K^- \pi^+)$ | | 4.9% |
| $\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)$ | | 2.2% |
| $\tau_{B_s}/\tau_{B_d}$ | | 1.5% |

on the bachelor particle and for the multivariate selection variable. In all cases variations are found to be small in comparison to the statistical uncertainty.

The relative branching fractions are obtained by correcting the event yields by the corresponding efficiency factors; the dominant correction comes from the PID efficiency. The dominant source of systematic uncertainty is the knowledge on the $B^0 \to D^- \pi^+$ branching fraction (for the $B^0 \to D^- K^+$ branching fraction measurement) and the knowledge of the $D^-$ and $D_s^-$ branching fractions (for the $f_s/f_d$ measurement). An important source of systematic uncertainty is the knowledge of the PID efficiency as a function of momentum, which is needed to reweight the mass distribution of the $B^0 \to D^- \pi^+$ decay under the kaon hypothesis for the bachelor track. This enters in two ways: firstly as an uncertainty on the correction factors, and secondly as part of the systematic uncertainty, since the shape for the misidentified backgrounds relies on correct knowledge of the PID efficiency as a function of momentum. The $f_s/f_d$ measurement using $B^0 \to D^- K^+$ and $B_s^0 \to D_s^- \pi^+$ is more robust against PID uncertainties, since the final states have the same number of kaons and pions.

Other systematics are due to limited simulated event samples (affecting the relative selection efficiencies), neglecting the $\Lambda_b \to \Lambda_c^+ \pi^-$ and $B_s^0 \to D_s^- \pi^+$ backgrounds in the $B^0 \to D^- \pi^+$ fits, and the limited accuracy of the trigger simulation. The sources of systematic uncertainty are summarized in Tab. I.

The efficiency corrected ratio of $B^0 \to D^- \pi^+$ and $B^0 \to D^- K^+$ yields is combined with the world average of the $B^0 \to D^- \pi^+$ [12] branching ratio to give

$$\mathcal{B}\left(B^0 \to D^- K^+\right) = (2.01 \pm 0.18 \pm 0.14) \times 10^{-4}. \quad (3)$$

The first uncertainty is statistical and the second systematic.

The theoretically cleaner measurement of $f_s/f_d$ uses $B^0 \to D^- K^+$ and $B_s^0 \to D_s^- \pi^+$ and is made according to Eq. 1. Accounting for the exclusive $D$ branching fractions $\mathcal{B}(D^+ \to K^- \pi^+ \pi^+) = (9.14 \pm 0.20)\%$ [13] and $\mathcal{B}(D_s^+ \to K^- K^+ \pi^+) = (5.50 \pm 0.27)\%$ [14], the value of $f_s/f_d$ is found to be

$$f_s/f_d \ = 0.250 \pm 0.024^{\text{stat}} \pm 0.017^{\text{syst}} \pm 0.017^{\text{theor}}, \quad (4)$$

where the first uncertainty is statistical, the second systematic, and the third theoretical. The theoretical uncertainty is dominated by the form factor ratio. The statistical uncertainty is dominated by the yield of the $B^0 \to D^- K^+$ mode.

The statistically more precise but theoretically less clean measurement of $f_s/f_d$ uses $B^0 \to D^- \pi^+$ and $B_s^0 \to D_s^- \pi^+$ and is, from Eq. 2,

$$f_s/f_d \ = 0.256 \pm 0.014^{\text{stat}} \pm 0.019^{\text{syst}} \pm 0.026^{\text{theor}}. \quad (5)$$

The two values for $f_s/f_d$ can be combined into a single value, taking all correlated uncertainties into account. The value of $f_s/f_d$ is :

$$f_s/f_d \ = 0.253 \pm 0.017^{\text{stat}} \pm 0.017^{\text{syst}} \pm 0.020^{\text{theor}}. \quad (6)$$

In summary, with 35 pb$^{-1}$ of data collected using the LHCb detector during the 2010 LHC operation at a centre-of-mass energy of 7 TeV, the branching fraction of the Cabibbo-suppressed $B^0$ decay mode $B^0 \to D^- K^+$ has been measured with better precision than the current world average. Additionally, two measurements of the $f_s/f_d$ production fraction are performed from the relative yields of $B_s^0 \to D_s^- \pi^+$ with respect to $B^0 \to D^- K^+$ and $B^0 \to D^- \pi^+$. These values of $f_s/f_d$ are in good agreement with the values determined at LEP and at the Tevatron [4].

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