Hadronic $B$ decays to open charm and time-independent $\gamma$ results at LHCb

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Studies of hadronic $B$ decays to open charm at LHCb have led to first observations of several $B \rightarrow D\bar{D}$ decays and of the decays $B^0 \rightarrow D^{*-}K^+\pi^-\pi^+$ and $B^0 \rightarrow D^0K^-\pi^+$. The branching fractions of other $B \rightarrow D\bar{D}$ decays, of $B^0 \rightarrow D^{*-}\pi^-\pi^-\pi^+$ and of $B^0 \rightarrow D^0K^+\pi^-$ have also been measured and a limit has been set in the search for the decay $B^0_s \rightarrow D^{*-}\pi^+$. In addition, constraints have been placed on the CKM angle $\gamma$ and related parameters using time-independent ADS and GGSZ analyses of $B^\pm \rightarrow DK^{\pm}$ decays.

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1. Hadronic $B$ decays to open charm

Several studies of hadronic $B$ decays to open charm have been performed at LHCb; details of the most recent measurements are given below. The inclusion of charge conjugated processes is implied throughout this section.

1.1 Studies of $B \to D\bar{D}'$ decays

$B \to D\bar{D}'$ decays can be used to probe CKM matrix elements [1] and to allow better theoretical understanding of the processes that contribute to $B$ meson decay, in particular the contributions from weak exchange, penguin annihilation and rescattering [2, 3].

Measurements of $B \to D\bar{D}'$ decay branching fractions relative to various normalisation decays have been performed using LHCb data corresponding to an integrated luminosity of 1 fb$^{-1}$ recorded at $\sqrt{s} = 7$ TeV [4]. The decays $B_s^0 \to D^0\bar{D}'^0$, $B_s^0 \to D_s^+\bar{D}'^-$ and $B_s^0 \to D^+\bar{D}'^-$ have been observed for the first time, with significances $\geq$ 10$\sigma$; Fig. 1 shows the invariant mass distributions for these decays. The measured ratios of branching fractions are

\[
\frac{Br(B_s^0 \to D^+\bar{D}'^-)}{Br(B^0 \to D^+\bar{D}'^-)} = 1.08 \pm 0.20(stat.) \pm 0.10(syst.) ,
\]

\[
\frac{Br(B_s^0 \to D_s^+\bar{D}'^-)}{Br(B^0 \to D_s^+\bar{D}'^-)} = 0.050 \pm 0.008(stat.) \pm 0.004(syst.) ,
\]

\[
\frac{Br(B_s^0 \to D^0\bar{D}'^0)}{Br(B^- \to D^0\bar{D}'^-)} = 0.019 \pm 0.003(stat.) \pm 0.003(syst.) ,
\]

\[
\frac{Br(B^0 \to D^0\bar{D}'^0)}{Br(B^- \to D^0\bar{D}'^-)} = 0.0014 \pm 0.0006(stat.) \pm 0.0002(syst.) ,
\]

\[
\frac{Br(B_s^0 \to D_s^+\bar{D}'^-)}{Br(B^0 \to D_s^+\bar{D}'^-)} = 0.56 \pm 0.03(stat.) \pm 0.04(syst.) ,
\]

\[
\frac{Br(B^- \to D^0\bar{D}'^-)}{Br(B^0 \to D_s^+\bar{D}'^-)} = 1.22 \pm 0.02(stat.) \pm 0.07(syst.) .
\]

1.2 Search for the decay $B_s^0 \to D^{\ast}\pi^+$

The decay $B_s^0 \to D^{\ast}\pi^+$ is expected to be mediated by weak exchange, with little contribution from rescattering [2]. A measurement of its branching fraction should therefore aid understanding of the mechanism behind the related decays $B_d^0 \to D\bar{D}'$ and $B_s^0 \to \pi^-\pi^+$ [5].

A search for the decay has been performed with LHCb data corresponding to an integrated luminosity of 1 fb$^{-1}$ recorded at $\sqrt{s} = 7$ TeV [6]. The decay $B^0 \to D^{\ast}\pi^+$, which is several orders of magnitude more abundant than $B_s^0 \to D^{\ast}\pi^+$, is used as a normalisation channel. No significant signal is observed, so limits of $Br(B_d^0 \to D^{\ast}\pi^+) < 6.1(7.8) \times 10^{-6}$ at 90% (95%) confidence level are set. The measured limit implies that rescattering may make substantial contributions to $B_s^0 \to D\bar{D}'$ and $B_s^0 \to \pi^-\pi^+$ decays, as recently suggested [2].
resulting in a first observation of the decay $B^0 \rightarrow D^{*+} \pi^- \pi^0 \pi^+$ branching fractions

$B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ can be used as a normalisation decay for $B^0 \rightarrow D^{*-} \tau^+ (\rightarrow \pi^+ \pi^- \pi^+ \nu_\tau) \nu_\tau$; an excess of $B^0 \rightarrow D^{*-} \tau^+ (\rightarrow \pi^+ \pi^- \pi^+ \nu_\tau) \nu_\tau$ decays over the Standard Model (SM) expectation has recently been observed [7].

The branching fractions of $B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ and the related decay $B^0 \rightarrow D^{*-} K^+ \pi^- \pi^+$, relative to $Br(B^0 \rightarrow D^{*-} \tau^+)$ and $Br(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)$ respectively, have been measured with LHCb data corresponding to an integrated luminosity of 1 fb$^{-1}$ recorded at $\sqrt{s} = 7$ TeV [8]. The resulting values are

$$
\frac{Br(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)}{Br(B^0 \rightarrow D^{*-} \pi^+)} = 2.64 \pm 0.04(stat.) \pm 0.13(syst.) \, , \\
\frac{Br(B^0 \rightarrow D^{*-} K^+ \pi^- \pi^+)}{Br(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)} = (6.47 \pm 0.37(stat.) \pm 0.35(syst.)) \times 10^{-2} ;
$$

the decay $B^0 \rightarrow D^{*-} K^+ \pi^- \pi^+$ has been observed for the first time.

A search for resonant structure within the $B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ decay has also been performed, resulting in a first observation of the decay $B^0 \rightarrow D_1(2420)^0 (\rightarrow D^{*-} \pi^+) \pi^- \pi^+$ at 5.3$\sigma$ significance; the measured branching fraction relative to $Br(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)$ is

$$
\frac{Br(B^0 \rightarrow D_1(2420)^0 (\rightarrow D^{*-} \pi^+) \pi^- \pi^+)}{Br(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)} = (2.04 \pm 0.42(stat.) \pm 0.22(syst.)) \times 10^{-2} .
$$
1.4 Measurement of $B^0(s) \rightarrow DK\pi$ branching fractions

$B^0 \rightarrow D^0/\bar{D}^0 K^{+}\pi^{-}$ decays are sensitive to the CKM angle $\gamma$; a future $\gamma$ measurement using these decays will require careful treatment of the potential background from $B^0_s \rightarrow D^0 K^-\pi^+$ decays.

Inclusive branching fraction measurements of $B^0 \rightarrow D^0 K^+\pi^-$ and $B^0_s \rightarrow D^0 K^-\pi^+$ decays have been made using LHCb data corresponding to an integrated luminosity of 1 fb$^{-1}$ recorded at $\sqrt{s} = 7$ TeV [9]. Figure 2 shows the invariant mass distribution for the candidate decays.

The measured branching fraction values, quoted relative to the normalisation branching fraction of $B^0 \rightarrow D^0\pi^+\pi^-$, are

$$\frac{Br(B^0 \rightarrow \bar{D}^0 K^+\pi^-)}{Br(B^0 \rightarrow \bar{D}^0 \pi^+\pi^-)} = 0.106 \pm 0.007(\text{stat.}) \pm 0.008(\text{syst.}),$$

$$\frac{Br(B^0_s \rightarrow \bar{D}^0 K^-\pi^+)}{Br(B^0 \rightarrow \bar{D}^0 \pi^+\pi^-)} = 1.18 \pm 0.05(\text{stat.}) \pm 0.12(\text{syst.});$$

the inclusive $B^0_s \rightarrow \bar{D}^0 K^-\pi^+$ decay has been observed for the first time.

![Figure 2: Invariant mass distribution for $B^0 \rightarrow \bar{D}^0 K^+\pi^-$ and $B^0_s \rightarrow \bar{D}^0 K^-\pi^+$ candidate decays [9].](image)

2. Time-independent $\gamma$ results

The CKM angle $\gamma = \text{arg}(- (V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*))$ is the least well-constrained angle of the Unitarity Triangle. The current tightest experimental constraints on $\gamma$ come from indirect measurements, giving a precision of $\approx 4^{\circ}$ [10, 11], but these may be sensitive to new, non-SM, physics effects in loop processes. It is therefore important to compare them with the SM benchmark obtained by measuring $\gamma$ directly with tree-level decays. The world average values of $\gamma$ from direct measurements are $\gamma = (66 \pm 12)^{\circ}$ [10] and $\gamma = (70.8 \pm 7.8)^{\circ}$ [11].

At LHCb, both time-independent and time-dependent$^1$ measurements of $\gamma$ are performed. Time-independent measurements are made using tree-level $B \rightarrow DX$ decays, where $D$ represents a $D^0$ or $\bar{D}^0$ meson; sensitivity to $\gamma$ arises when $D^0$ or $\bar{D}^0$ decay to the same final state, due to interference effects. In conjunction with a measurement of $\gamma$, the related parameters $r_B$ (the magnitude of the ratio of amplitudes of the interfering decays) and $\delta_B$ (the strong phase difference between them) are also measured.

$^1$For LHCb time-dependent $\gamma$ results and $\gamma$ average, see [12].
2.1 ADS analysis of $B^{\pm} \to D(\to K\pi\pi\pi)K^{\pm}$ and $B^{\pm} \to D(\to K\pi\pi\pi)\pi^{\pm}$ decays

The ADS method [13] uses $B \to DX$ decays with the $D$ meson decaying to a final state which is not a CP eigenstate. The full decay can take one of two paths: in one case, the favoured $B$ decay is followed by a doubly Cabibbo-suppressed $D$ decay; in the other case the suppressed $B$ decay is followed by a Cabibbo-allowed $D$ decay. Overall, the sensitivity to $\gamma$ is maximised because the interfering amplitudes from the two decay paths are comparable in size.

A study of $B^{\pm} \to D(\to K\pi\pi\pi)K^{\pm}$ and $B^{\pm} \to D(\to K\pi\pi\pi)\pi^{\pm}$ decays has been performed at LHCb using data corresponding to an integrated luminosity of 1 fb$^{-1}$ recorded at $\sqrt{s} = 7$ TeV [14]. The $D$ decay is treated inclusively, with no attempt made to separate the resonant structures of the decay. The suppressed ADS decays $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{\mp}\pi^{\mp})K^{\pm}$ and $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{\mp}\pi^{\mp})\pi^{\pm}$ have been observed for the first time, with significances of 5.1$\sigma$ and $>10\sigma$, respectively; Fig. 3 shows the invariant mass distributions for these decays.

![Invariant mass distributions for $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{\mp}\pi^{\mp})K^{\pm}$ and $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{\mp}\pi^{\mp})\pi^{\pm}$ candidate decays](image)

Figure 3: Invariant mass distributions for $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{\mp}\pi^{\mp})K^{\pm}$ and $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{\mp}\pi^{\mp})\pi^{\pm}$ candidate decays [14].

The ratios of suppressed to favoured decays, which are most sensitive to $\gamma$, $r_B$ and $\delta_B$, have been measured and are combined to obtain values for the ADS asymmetries and ratios,

$$A_{ADS(DK)}^{K^{3}\pi} = -0.42 \pm 0.22 , \quad R_{ADS(DK)}^{K^{3}\pi} = 0.0124 \pm 0.0027 ,$$

$$A_{ADS(D\pi)}^{K^{3}\pi} = 0.13 \pm 0.10 , \quad R_{ADS(D\pi)}^{K^{3}\pi} = 0.0037 \pm 0.0004 ,$$

where the uncertainties are the combination of statistical and systematic contributions.

Using these results and measurements of parameters of the $D$ decay from CLEO-c [15], a constraint $r_{B(DK)} = 0.097 \pm 0.011$ is evaluated; the measurements do not allow significant constraints to be placed on the other underlying physics parameters.

2.2 Dalitz (GGSZ) analysis of $B^{\pm} \to D(\to K_{S}^{0}\pi^{+}\pi^{-},K_{L}^{0}\pi^{+}\pi^{-},K^{+}K^{-})K^{\pm}$ decays

The GGSZ method [16, 17] allows $\gamma$ to be measured from the differences in amplitude of the $D \to K_{S}^{0}h^{+}h^{-}$ Dalitz plots coming from $B^{-} \to DK^{-}$ and $B^{+} \to DK^{+}$ decays. The structure of the multi-body $D$ decay must be taken into account as it leads to a variation in amplitude across the
Dalitz plane. One possible “model-independent” approach is to bin the Dalitz plane [16, 18] and input the measured value of the strong phase difference between the $D^0$ and $\bar{D}^0$ decays in each bin from CLEO-c studies [19].

Samples of $B^\pm \to D(\to K_S^0\pi^+\pi^-)K^\pm$ and $B^\pm \to D(\to K_S^0K^+K^-)K^\pm$ decays, selected from data corresponding to an integrated luminosity of 2 fb$^{-1}$ recorded at $\sqrt{s} = 8$ TeV, have been used to measure the observables $x_+ = r_{B(DK)} \cos(\delta_{B(DK)} \pm \gamma)$ and $y_+ = r_{B(DK)} \sin(\delta_{B(DK)} \pm \gamma)$ with the model-independent approach [20]. The resulting preliminary values,

\[
\begin{align*}
x_+ &= (-8.7 \pm 3.1(stat.) \pm 1.6(syst.) \pm 0.6(extl.)) \times 10^{-2}, \\
y_+ &= (0.1 \pm 3.6(stat.) \pm 1.4(syst.) \pm 1.9(extl.)) \times 10^{-2}, \\
x_- &= (5.3 \pm 3.2(stat.) \pm 0.9(syst.) \pm 0.9(extl.)) \times 10^{-2}, \\
y_- &= (9.9 \pm 3.6(stat.) \pm 2.2(syst.) \pm 1.6(extl.)) \times 10^{-2},
\end{align*}
\]

where the third uncertainties arise from the CLEO-c input measurements, are the most precise measurements of these observables to date. The results have been combined with previous GGSZ measurements, made using data corresponding to an integrated luminosity of 1 fb$^{-1}$ recorded at $\sqrt{s} = 7$ TeV [21], to place constraints on $\gamma$, $r_B$ and $\delta_B$.

\[
\gamma = (57 \pm 16)^\circ, \quad r_{B(DK)} = (8.8^{+2.3}_{-2.4}) \times 10^{-2}, \quad \delta_{B(DK)} = (124^{+15}_{-17})^\circ;
\]

two-dimensional projections of the confidence regions for the three parameters are shown in Fig. 4.

**Figure 4:** Two-dimensional projections of the confidence regions onto the $(\gamma, r_{B(DK)})$ and $(\gamma, \delta_{B(DK)})$ planes. The diamonds indicate the central values and the 1, 2 and 3$\sigma$ boundaries are also shown [20].

### 3. Conclusions and prospects

Recent studies of hadronic $B$ decays to open charm at LHCb have led to the observation of several new $B \to D\bar{D}$ decay modes and of the decays $B^0 \to D^{*+}K^+\pi^-\pi^+$ and $B^0_s \to D^{*0}K^-\pi^+$. The branching fractions of other $B \to D\bar{D}$ decays, of $B^0 \to D^{*+}\pi^-\pi^+\pi^+$ and of $B^0 \to D^{*0}K^+\pi^-$ have also been measured and a limit has been set in the search for $B^0 \to D^{*+}\pi^-$. In addition, the suppressed ADS decays $B^\pm \to D(\to \pi^+K^0\pi^+\pi^-)K^\pm$ and $B^\pm \to D(\to \pi^+K^0\pi^+\pi^-)\pi^\pm$ have been observed for the first time, and ADS and GGSZ analyses of $B^\pm \to DK^\pm$ decays have allowed
Hadronic $B$ decays to open charm and time-independent $\gamma$ results at LHCb

Susan Haines

constraints to be placed on the CKM angle $\gamma$ and related parameters. Studies of new decay modes and analysis updates to include the data set recorded in 2012 will provide additional measurements and constraints on $\gamma$ in the near future.

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Hadronic B decays to open charm and time-independent γ results at LHCb
Susan Haines

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