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

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

$B \to D\overline{D}'$ 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 $B \to D\overline{D}'$ 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 $\overline{B}_s^0 \to D^0\overline{D}^0$, $\overline{B}_s^0 \to D_s^+ D^-$ and $\overline{B}_s^0 \to D^+D^-$ 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

$$\frac{Br(\overline{B}_s^0 \to D^+D^-)}{Br(\overline{B}^0 \to D^+D^-)} = 1.08 \pm 0.20(stat.) \pm 0.10(syst.)\,,$$
$$\frac{Br(\overline{B}_s^0 \to D_s^+D^-)}{Br(B^0 \to D_s^+D^-)} = 0.050 \pm 0.008(stat.) \pm 0.004(syst.)\,,$$
$$\frac{Br(\overline{B}_s^0 \to D^0\overline{D}^0)}{Br(B^- \to D^0D_s^-)} = 0.019 \pm 0.003(stat.) \pm 0.003(syst.)\,,$$
$$\frac{Br(\overline{B}^0 \to D^0\overline{D}^0)}{Br(B^- \to D^0D_s^-)} = 0.0014 \pm 0.0006(stat.) \pm 0.0002(syst.)\,,$$
$$\frac{Br(\overline{B}_s^0 \to D_s^+D_s^-)}{Br(B^0 \to D_s^+D^-)} = 0.56 \pm 0.03(stat.) \pm 0.04(syst.)\,,$$
$$\frac{Br(B^- \to D^0D_s^-)}{Br(B^0 \to D_s^+D^-)} = 1.22 \pm 0.02(stat.) \pm 0.07(syst.)\,.$$

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

The decay $B_s^0 \to D^{*-}\pi^+$ 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 $B_s^0 \to D\overline{D}'$ 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 $B^0 \to D^{*-}\pi^+$, which is several orders of magnitude more abundant than $B_s^0 \to D^{*-}\pi^+$, is used as a normalisation channel. No significant signal is observed, so limits of $Br(B_s^0 \to D^{*-}\pi^+) < 6.1(7.8) \times 10^{-6}$ at 90% (95%) confidence level are set. The measured limit implies that rescattering may make substantial contributions to $B_s^0 \to D\overline{D}'$ and $B_s^0 \to \pi^-\pi^+$ decays, as recently suggested [2].

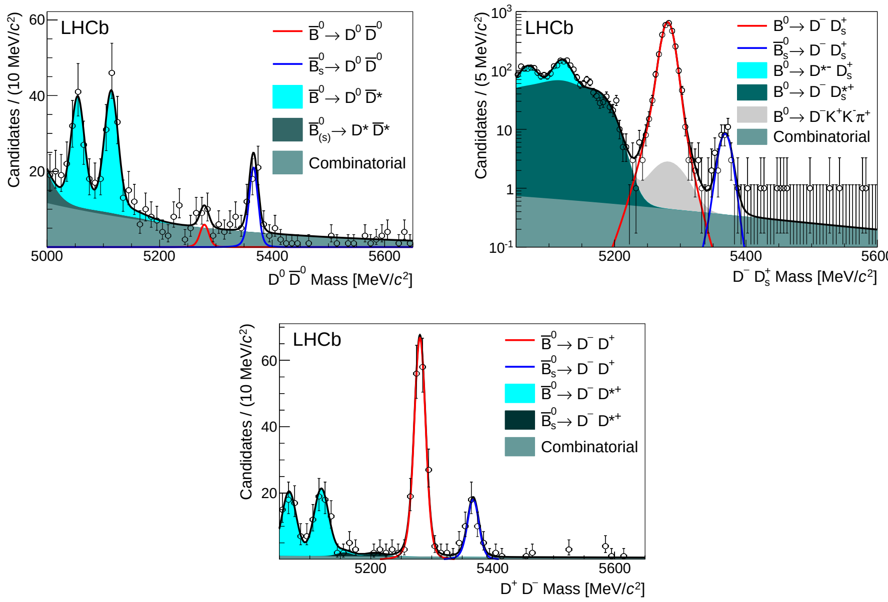

Figure 1: Invariant mass distributions for $\overline{B}{}^0_s \to D^0\overline{D}{}^0$, $\overline{B}{}^0_s \to D_s^+ D^-$ and $\overline{B}{}^0_s \to D^+ D^-$ candidate decays [4]. In the legends, "Combinatorial" denotes the combinatorial background component.

1.3 Measurement of $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ and $B^0 \to D^{*-}K^+\pi^-\pi^+$ branching fractions

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

The branching fractions of $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ and the related decay $B^0 \to D^{*-}K^+\pi^-\pi^+$, relative to $Br(B^0 \to D^{*-}\pi^+)$ and $Br(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$ 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

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

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

A search for resonant structure within the $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ decay has also been performed, resulting in a first observation of the decay $B^0 \to \overline{D}_1(2420)^0(\to D^{*-}\pi^+)\pi^-\pi^+$ at 5.3σ significance; the measured branching fraction relative to $Br(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$ is

$$\frac{Br(B^0 \to \overline{D}_1(2420)^0(\to D^{*-}\pi^+)\pi^-\pi^+)}{Br(B^0 \to D^{*-}\pi^+\pi^-\pi^+)} = (2.04 \pm 0.42(stat.) \pm 0.22(syst.)) \times 10^{-2}\,.$$

1.4 Measurement of $B^0_{(s)} \to DK\pi$ branching fractions

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

Inclusive branching fraction measurements of $B^0 \to \overline{D}^0 K^+\pi^-$ and $B^0_s \to \overline{D}^0 K^-\pi^+$ 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 $B^0 \to \overline{D}^0 \pi^+\pi^-$, are

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

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

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

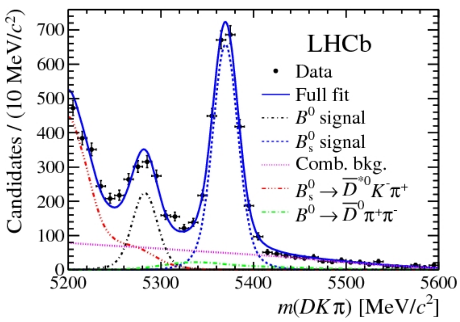

Figure 2: Invariant mass distribution for $B^0 \to \overline{D}^0 K^+\pi^-$ and $B^0_s \to \overline{D}^0 K^-\pi^+$ candidate decays [9].

2. Time-independent γ results

The CKM angle $\gamma = arg(-(V_{ud}V^*_{ub})/(V_{cd}V^*_{cb}))$ is the least well-constrained angle of the Unitarity Triangle. The current tightest experimental constraints on γ 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 γ directly with tree-level decays. The world average values of γ 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 γ are performed. Time-independent measurements are made using tree-level $B \to DX$ decays, where D represents a D^0 or $\overline{D}^0$ meson; sensitivity to γ arises when D^0 or $\overline{D}^0$ decay to the same final state, due to interference effects. In conjunction with a measurement of γ, the related parameters r_B (the magnitude of the ratio of amplitudes of the interfering decays) and δ_B (the strong phase difference between them) are also measured.

[1]For LHCb time-dependent γ results and γ average, see [12].

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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 γ 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 $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{+}\pi^{-})K^{\pm}$ and $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{+}\pi^{-})\pi^{\pm}$ have been observed for the first time, with significances of 5.1σ and $> 10\sigma$, respectively; Fig. 3 shows the invariant mass distributions for these decays.

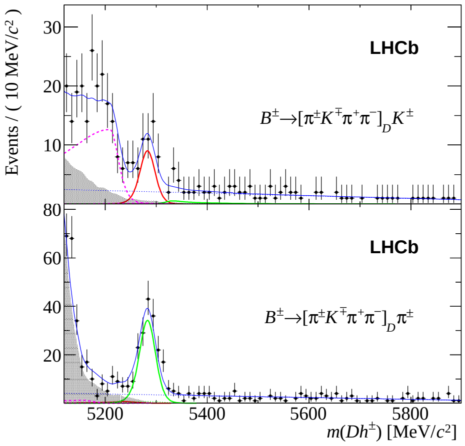

Figure 3: Invariant mass distributions for $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{+}\pi^{-})K^{\pm}$ and $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^{+}\pi^{-})\pi^{\pm}$ candidate decays [14].

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

$$A^{K3\pi}_{ADS(DK)} = -0.42 \pm 0.22\,, \qquad R^{K3\pi}_{ADS(DK)} = 0.0124 \pm 0.0027\,,$$
$$A^{K3\pi}_{ADS(D\pi)} = 0.13 \pm 0.10\,, \qquad R^{K3\pi}_{ADS(D\pi)} = 0.0037 \pm 0.0004\,,$$

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 $B^{\pm} \to D(\to K^0_S\pi^{+}\pi^{-}, K^0_S K^{+}K^{-})K^{\pm}$ decays

The GGSZ method [16, 17] allows γ to be measured from the differences in amplitude of the $D \to K^0_S h^{+}h^{-}$ 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 $\overline{D}^0$ 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 $x_{\pm} = r_{B(DK)}\cos(\delta_{B(DK)} \pm \gamma)$ and $y_{\pm} = r_{B(DK)}\sin(\delta_{B(DK)} \pm \gamma)$ with the model-independent approach [20]. The resulting preliminary values,

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

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 γ, r_B and δ_B,

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

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

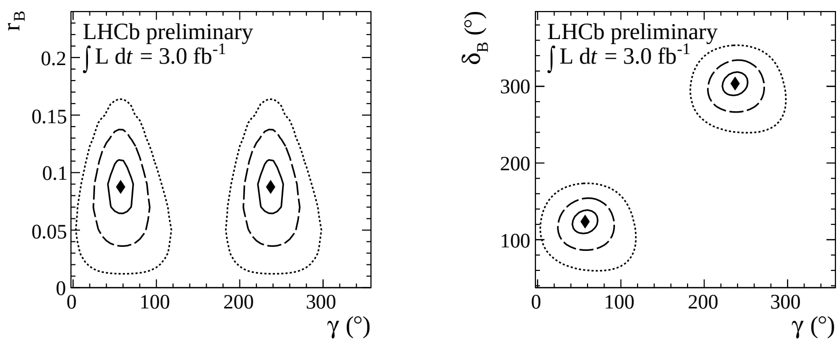

Figure 4: Two-dimensional projections of the confidence regions onto the $(\gamma, r_{B(DK)})$ and $(\gamma, \delta_{B(DK)})$ planes. The diamonds indicate the central values and the 1, 2 and 3σ boundaries are also shown [20].

3. Conclusions and prospects

Recent studies of hadronic B decays to open charm at LHCb have led to the observation of several new $B \to D\overline{D}'$ decay modes and of the decays $B^0 \to D^{*-}K^+\pi^-\pi^+$ and $B_s^0 \to \overline{D}^0K^-\pi^+$. The branching fractions of other $B \to D\overline{D}'$ decays, of $B^0 \to D^{*-}\pi^+\pi^-\pi^+$ and of $B^0 \to \overline{D}^0K^+\pi^-$ have also been measured and a limit has been set in the search for $B_s^0 \to D^{*-}\pi^+$. In addition, the suppressed ADS decays $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^+\pi^-)K^{\pm}$ and $B^{\pm} \to D(\to \pi^{\pm}K^{\mp}\pi^+\pi^-)\pi^{\pm}$ have been observed for the first time, and ADS and GGSZ analyses of $B^{\pm} \to DK^{\pm}$ decays have allowed constraints to be placed on the CKM angle γ 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 γ in the near future.

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