PROCEEDINGS OF SCIENCE

Beauty to open charm final states at LHCb

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The LHCb detector at the Large Hadron Collider is designed for Physics beyond the Standard Model searches in charge-parity violation and rare decays. Decays of beauty mesons to open-charm final states also enable a wide spectrum of spectroscopy studies, especially investigation of $c\bar{c}$ and $c\bar{s}$ systems. New results, including Run 1 and Run 2 data set, with several new branching fraction measurements, are presented in this paper.

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1. Introduction

LHCb [1] is an experiment at the Large Hadron Collider (LHC) dedicated to flavour physics studies. The main physics goal of LHCb concentrate on searches for New Physics phenomena in the decays of heavy mesons. These studies can impose essential constraints on the parameters of the CKM matrix. Any significant discrepancies between these constraints and theoretical predictions can be a sign of the New Physics effects. LHCb is a single-arm spectrometer. It covers the pseudorapidity range $2<\eta<5$. At high energies, the $b\overline{b}$ pairs are produced mainly in the same forward or backward cone; hence the full 4π geometry of the detector is not required [1].

2. Studies of $B^0 \rightarrow D_s^+\pi^-$

One of the key elements of the extended tests of CKM matrix elements is a precise measurement of the CKM matrix element V_{ub} - the strength of the $b \rightarrow u$ transition. At LHCb, the 5.0 fb^{-1} data sample was used in the branching fraction measurement of $B^0 \rightarrow D_s^+\pi^-$ ($D_s^+ \rightarrow K^+K^-\pi^+$) [2] normalised to $B^0 \rightarrow D^-\pi^+$ ($D^- \rightarrow K^+\pi^-\pi^-$). This branching fraction is proportional to the CKM matrix element $|V_{ub}|$:

$$\mathcal{B}(B^0 \rightarrow D_s^+\pi^-) = \Phi|V_{ub}|^2|V_{cs}|^2|F(B^0 \rightarrow \pi^-)|^2 f^2_{D_s^+}|a_{NF}|^2 \quad (1)$$

where Φ is a phase-space factor, $F(B^0 \rightarrow \pi^-)$ is a form factor, $f^2_{D_s^+}$ is the D_s^+ decay constant, V_{cs} is

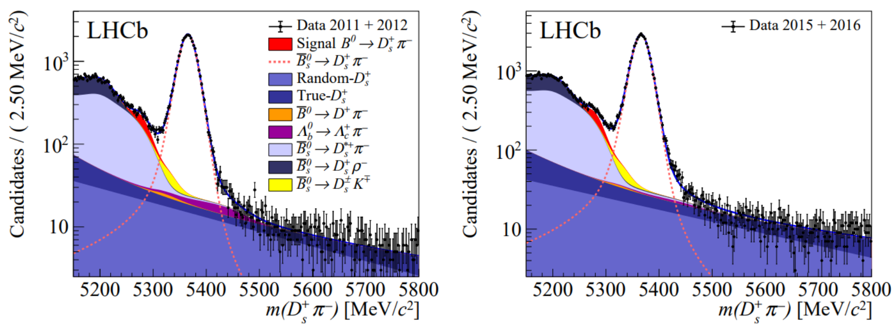

Figure 1: The $D_s^+\pi^-$ invariant mass distributions of signal $B^0 \rightarrow D_s^+\pi^-$ candidates, for 2011+2012 (left), and for 2015+2016 (right) data sample.

the CKM matrix element representing the $c \rightarrow s$ transition, and $|a_{NF}|$ encapsulates non-factorisable effects. Since the V_{cs} element is known to be close to unity, the $B^0 \rightarrow D_s^+\pi^-$ branching fraction can be used to probe the product of $|V_{ub}|$ and $|a_{NF}|$. Another measured parameter, important in charge-parity violation (CPV) studies with $B^0 \rightarrow D^-\pi^+$ decay, is the ratio of the amplitudes of the Cabibbo-suppressed $B^0 \rightarrow D_s^+\pi^-$ to the Cabibbo-favoured $B^0 \rightarrow D^-\pi^+$ decay. This ratio can be rewritten (assuming SU(3) symmetry) in terms of the branching fraction of signal and control modes, the Cabibbo angle θ_c and decay constants of the D^+ and D_s^+ mesons (Eq.2) [2].

$$r_{D\pi} = \tan\theta_c \frac{f_{D^+}}{f_{D_s^+}}\sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^+\pi^-)}{\mathcal{B}(B^0 \rightarrow D^-\pi^+)}} \quad (2)$$

The relative production of B_s^0 and B^0 mesons, described by the ratio $\frac{f_s}{f_d}$ where f_s and f_d are the B_s^0 and B^0 hadronisation fractions, depends on the proton-proton (pp) collision energy. The $\frac{f_s}{f_d}$ is an important input for B_s^0 branching fraction measurements, normalised to B^0 decays.

The D_s^+ and D^- mesons are constructed using $K^+K^-\pi^+$ and $K^+\pi^-\pi^-$ final states, respectively. The combinatorial background suppression is enhanced by using a gradient boosted decision tree algorithm (BDTG). The invariant mass distributions of signal candidates are shown on Fig.1. The

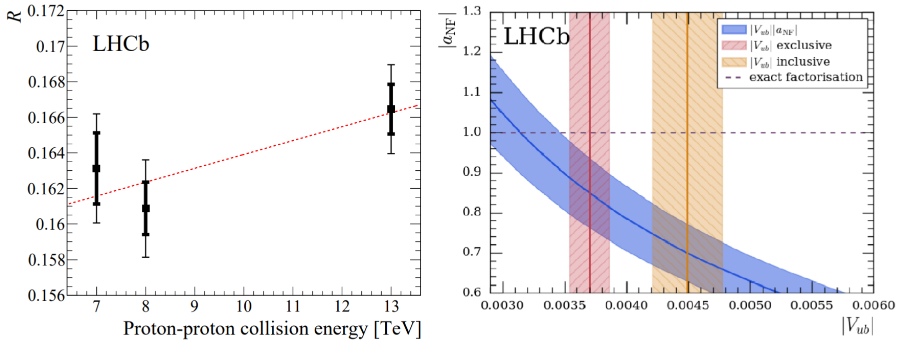

Figure 2: Visualisation of the pp collision energy dependence on the efficiency-corrected yield ratio of $B_s^0 \to D_s^+\pi^-$ and $B^0 \to D^-\pi^+$ decays, which scales with $\frac{f_s}{f_d}$ (left). Result of the determination of $|V_{ub}||a_{NF}|$ (right). The blue line represents the result of this measurement, the vertical bands are the known exclusive and inclusive measurements of $|V_{ub}|$, The horizontal dashed line at $|a_{NF}| = 1.0$ represents exact factorisation.

result of measurement of relative branching fraction is:

$$\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-\pi^+)} = (7.7 \pm 0.7 \pm 0.5 \pm 0.3) \times 10^{-3}$$

where the first uncertainty is statistical, the second systematic and the third comes from the control channel. The absolute branching fraction is:

$$\mathcal{B}(B^0 \to D_s^+\pi^-) = (19.4 \pm 1.8 \pm 1.3 \pm 1.2) \times 10^{-6}$$

Using this measurement, the product:

$$|V_{ub}||a_{NF}| = (3.14 \pm 0.20 \pm 0.25) \times 10^{-3}$$

is obtained, where the first uncertainty is from the $B^0 \to D_s^+\pi^-$ branching fraction measurement and the second from the CKM and QCD parameters. This is the most precise single measurement of $\mathcal{B}(B^0 \to D_s^+\pi^-)$ to date. The determination of $|V_{ub}||a_{NF}|$ can be compared to the known inclusive and exclusive measurements of $|V_{ub}|$ to provide the constraint on the $|a_{NF}|$ parameter as shown in Fig.2 - right. The $r_{D\pi}$ is found to be:

$$r_{D\pi} = 0.0163 \pm 0.0011 \pm 0.0033$$

where the first uncertainty arises from the uncertainties propagated from Eq.2 and the second from possible non-factorisable SU(3)-breaking effects, estimated to be 20% [3]. The centre-of mass energy dependence is obtained from a linear fit using the statistical and uncorrelated systematic uncertainties and is found to be $R = 0.156(6) + 0.0008(6)\sqrt{s}$, where $\sqrt{s}$ is in TeV (Fig.2 - left). The observed trend is in agreement with the LHCb measurement of the $\frac{f_s}{f_d}$ dependence upon the pp collision energy [4].

3. Studies of $B \rightarrow D^* D K$ and $B^0 \rightarrow D^* D^0 K$

Studies of the $B \rightarrow D^{(*)}\overline{D}^{(*)}K$ processes enable a wide spectrum of spectroscopy studies through intermediate resonant structures that occur within these decays: $c\overline{s}$ in $D^{(*)}K$ system and $c\overline{c}$ in $D^{(*)}D^{(*)}$ system. The family of $B \rightarrow D^{(*)}\overline{D}^{(*)}K$ decays benefits from a very low combinatorial background that allows for extended amplitude studies [5] The full dataset of 9.1 fb^{-1} collected at LHCb during Run 1 and Run 2 is used in branching fractions measurement of $B^+ \rightarrow D^{*+}D^-K^+$, $B^+ \rightarrow D^{*-}D^+K^+$ and $B^0 \rightarrow D^{*-}D^0K^+$ decays. The D^+ mesons are reconstructed from the $K^-\pi^+\pi^+$ final state and D^0 mesons from $K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$. The model used in the mass fits is composed of two components. The signal of B meson decay is modeled using double-sided Crystal Ball function. Although the combinatorial background contribution is very small, the exponential function was employed to model the background. The result of the analysis of Run 1 and Run 2 datasets are shown in Fig.3 The branching fractions are calculated using corrected signal yields. The correction is applied by candidate-by-candidate background subtraction and efficiency correction. The branching fractions of the decays of D mesons to the different final states are also taken into account. In the equation:

$$N^{corr} = \frac{\sum_i \frac{W_i}{\epsilon_i^{sel}(x_i)\epsilon^{acc}} - \eta^{corr}_{peaking}}{\mathcal{B}(D^*)\mathcal{B}(\overline{D})} \tag{3}$$

i runs over all candidates in the fitted data sample, W_i stands for each candidate's signal weight, the first efficiency is the efficiency of selection, and the second is related to the acceptance of the detector. The efficiency-corrected residual peaking background ($\eta^{corr}_{peaking}$) is subtracted from the signal region. Calculation of relative branching fraction allows to cancel many uncertainties such as those coming from $b\overline{b}$ production cross-section or uncertainties in the luminosity, while other like the uncertainty of tracking efficiency of the slow pion from D^* decay are negligible. However, uncertainties related to the model used in the fit or PID requirement are also taken into account. The measured branching fraction ratios are presented below, where the first of the uncertainties is statistical, the second systematic, and the third is due to the uncertainties on the D-meson branching fractions. Worthy of notice is that these are the most accurate measurements of these ratios to date.

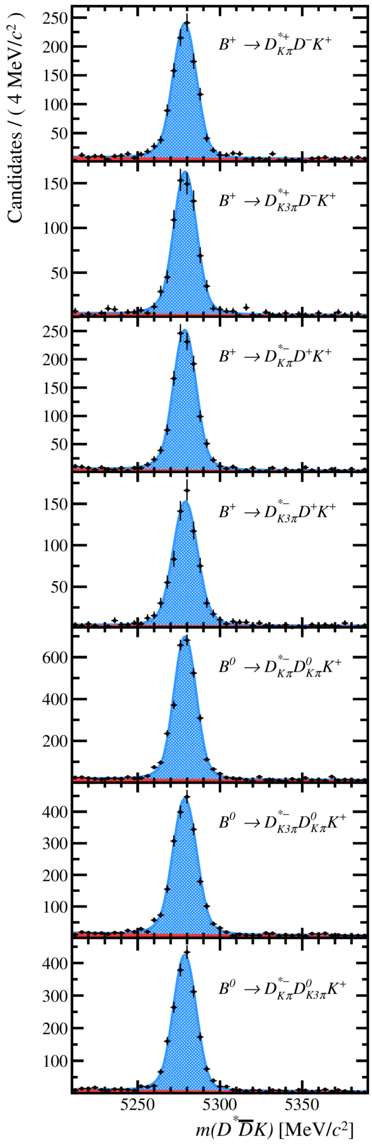

Figure 3: Fits to the invariant-mass distributions $m(D^{(*)}\overline{D}K)$ of $B \rightarrow D^*\overline{D}K$ for the combined Run 1 and Run 2 samples. Blue colour indicates the signal contribution, red shows the background contribution.

$$\frac{\mathcal{B}(B^+ \to D^{*+}D^-K^+)}{\mathcal{B}(B^+ \to \overline{D}^0 D^0 K^+)} = 0.517 \pm 0.015 \pm 0.013 \pm 0.011$$

$$\frac{\mathcal{B}(B^+ \to D^{*-}D^+K^+)}{\mathcal{B}(B^+ \to \overline{D}^0 D^0 K^+)} = 0.577 \pm 0.016 \pm 0.013 \pm 0.013$$

$$\frac{\mathcal{B}(B^0 \to D^{*+}D^0K^+)}{\mathcal{B}(B^0 \to D^- D^0 K^+)} = 1.754 \pm 0.028 \pm 0.016 \pm 0.035$$

$$\frac{\mathcal{B}(B^+ \to D^{*+}D^-K^+)}{\mathcal{B}(B^+ \to D^{*-}D^+K^+)} = 0.907 \pm 0.033 \pm 0.014$$

4. Studies of $B^0 \to D^0\overline{D}^0K^+\pi^-$

$B^0 \to D^{(*)}\overline{D}^{(*)}K^+\pi^-$ is a family of processes that allow studies of $c\overline{s}$ and $c\overline{c}$ systems via $b \to c\overline{c}s$ transition which occurs with either an external or internal W boson emission. [6]. These processes are especially interesting because they allow for measurements of the amplitude structure of the $D^{(*)}\overline{D}^{(*)}$ system and calculation of $c\overline{c}$ contribution above the open-charm threshold in $b \to s\ell^+\ell^-$ [7]. The LHCb performed the measurement of $B^0 \to D^0\overline{D}^0K^+\pi^-$, which has not been observed before. The branching fraction is measured relatively to $B^0 \to D^{*-}D^0K^+$ since both the signal and control modes decay to the same final state. The 2011, 2012, and 2016, 4.7 fb^{-1} data sample is used and split into two data taking categories: the Run 1 and 2016 samples.

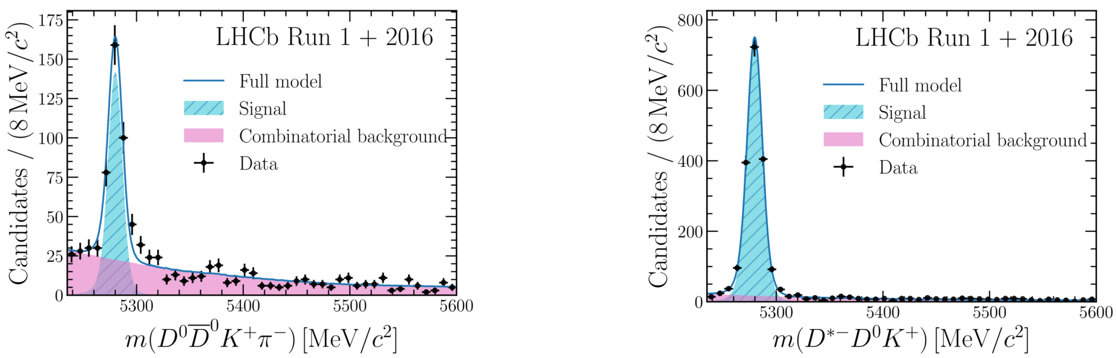

Figure 4: Invariant-mass distributions and fit projections for B^0 candidates in the signal $B^0 \to D^0\overline{D}^0K^+\pi^-$ mode (left), and in the control mode $B^0 \to D^{*-}D^0K^+$ (right).

The fit to the signal and control mode is performed separately to the four data samples, corresponding to the two trigger categories (TIS and TOS[1]) and two data taking periods (Run 1 and 2016). The invariant-mass distributions for signal and control modes are modeled with a double-sided Crystal Ball function. For the signal and control mode fits, each data sample's combinatorial background is modeled with an exponential function. Fig.4 presents the fits to the signal and control modes for all subsamples combined.

[1]Events that were not rejected by hardware trigger are split into two independent categories: TIS - Trigger on Signal with a positive decision based on information from the hadronic calorimeter and TOS - Trigger Independent of Signal based on signatures from other particles in the event.

The invariant-mass distributions of m($D^0\overline{D}^0$), m(D^0K^+) and m($K^+\pi^-$) after background subtraction show the hints for resonance structures visible at the masses of the $\psi(3770)$, $D^*_{s2}(2573)^+$ and $D^*_{s(1,3)}(2860)^+$, and $K^*(892)^0$ states (Fig.5). Further studies of these projections will be performed in the future. Uncertainty of the branching fraction is calculated by taking into account uncertainty of the signal and background model, sample size, PID weighting, the selection including classifier, and others. The ratio of the signal and control mode branching fraction is measured to be $R = (14.2 \pm 1.1 \pm 1.0)\%$, where the first uncertainty is statistical, and the second is systematic. The absolute branching fraction of $B^0 \to D^0\overline{D}^0K^+\pi^-$ is:

$$\mathcal{B}(B^0 \to D^0\overline{D}^0K^+\pi^-) = (3.50 \pm 0.27 \pm 0.26 \pm 0.30) \times 10^{-4}$$

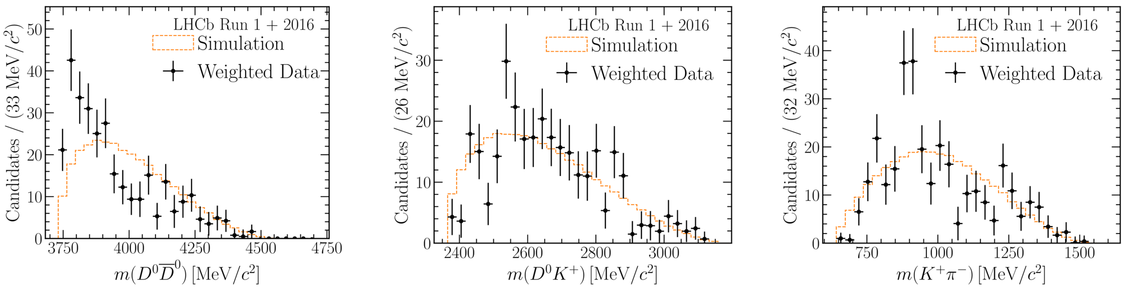

Figure 5: Projections of background-subtracted data in m($D^0\overline{D}^0$) (left), m(D^0K^+) (center), m($K^+\pi^-$) (right).

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