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Recent results from LHCb on charged-current decays of b-hadrons

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Semileptonic b-hadron decays proceed via charged-current interactions and provide powerful probes for testing the Standard Model of particle physics and for searching for New Physics effects. The advantages of performing studies of semileptonic decays include the reliable predictions of the strong interactions and the large branching fractions. In this contribution, the most recent LHCb results, obtained by exploiting the semileptonic decays, are presented.

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1. Precision measurement of the Λ_c, Ξ_c^+ and Ξ_c^0 baryon lifetimes

Measurements of the lifetimes of hadrons containing heavy (b or c) quarks play an important role in testing theoretical approaches that perform calculations of Standard Model processes. The validation of such tools is important, as they can then be used to search for deviations from Standard Model expectations in other processes. For instance, in Heavy Quark Effective Theory at low level, all charm lifetimes are equal. Sizable corrections increase as the mass of heavy quark decrease and therefore measurements of charm-hadron lifetimes are sensitive to these high-order contributions [1, 2]. Particle lifetimes are also required to compare measured b- or c-hadron decay branching fractions to corresponding predictions for partial decay widths which allows for more stringent tests of theoretical predictions.

Recently, the LHCb collaboration reported a measurement of the Ω_c lifetime ($\tau_{\Omega_c} = 268 \pm 24 \pm 10 \pm 2$ fs) [3] that was nearly four times larger than, and inconsistent with, the world average value [4] . The lifetimes of the other three ground state singly charmed baryons (Λ_c, Ξ_c^+ and Ξ_c^0) were last measured almost twenty years ago, and are only known with precisions of 3%, 6% and 10%, respectively [4].

LHCb has performed a new measurement of the lifetimes of the Λ_c, Ξ_c^+ [5]and Ξ_c^0 baryons using samples of semileptonic $\Lambda_b \to \Lambda_c \mu^- \bar{\nu}_\mu X$, $\Xi_b^0 \to \Xi_c^+ \mu^- \bar{\nu}_\mu X$, and $\Xi_b^- \to \Xi_c^- \mu^- \bar{\nu}_\mu X$ decays (where X represents any additional undetected particles). The Λ_c and Ξ_c^+ baryons are both reconstructed in the $pK^-\pi^+$ final state and the Ξ_c^0 baryon is observed through its decay to $pK^-K^-\pi^+$. The measurement uses proton-proton (pp) collision data samples, collected by the LHCb experiment, corresponding to an integrated luminosity of 3.0 fb^{-1}, of which 1.0 fb^{-1} was recorded at a center-of-mass energy of 7 fb^{-1} and 2.0 fb^{-1} at 8 TeV. To reduce the uncertainties associated with systematic effects, the lifetime ratio

$$r_{H_c} \equiv \frac{\tau_{H_c}}{\tau_{D^+}}$$

is measured, where the τ_{D^+} is the lifetime of the D^+ meson, reconstructed using $B \to D^+ \mu^- \bar{\nu}_\mu X$ decays, with $D^+ \to K^-\pi^+\pi^+$. The symbols H_b and H_c refer to the b or c hadron considered. The signal yields have been extracted by performing a binned maximum-likelihood fit to the invariant mass distributions of D^+, Λ_c, Ξ_c^+ and Ξ_c^0. The decay time of each H_c candidate is determined from the positions of the H_b and H_c decay vertices, and the measured H_c momentum. The background-subtracted decay-time spectra are obtained using the *sPlot* technique [6], where the measured H_c mass is used as the discriminating variable. To improve the accuracy of the *sPlot* background subtraction, a correction to the H_c mass is applied to remove a small dependence of the mean reconstructed H_c mass on its reconstructed decay time, t_{rec}. Only H_c candidates with decay time larger than zero are used in the fit. The decrease in signal yield as the decay time near zero is mainly due to the H_c decay-time resolution, typically in the 85–100 fs range, which results in migration of the signal into the negative decay-time region. The charm-hadron lifetime ratios are determined by a simultaneous binned χ^2 fit to the decay-time spectra of the signal charm hadron and the $.D^+$ The fit projection is shown in Fig 1.

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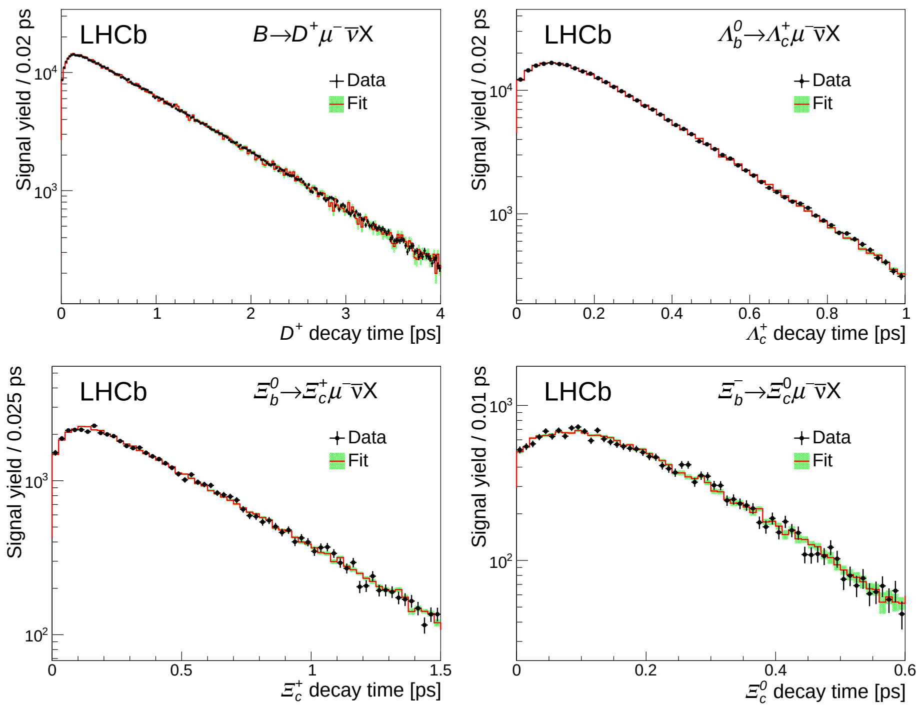

Figure 1: Decay-time spectra. Overlaid are the fit results along with the uncertainties due to finite sizes of the simulated samples.

The lifetimes are measured relative to that of the D^+ meson, and are determined to be

$$\tau_{\Lambda_c} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs}, \quad (1.1)$$

$$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs}, \quad (1.2)$$

$$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs}, \quad (1.3)$$

where the uncertainties are statistical, systematic, and due to the uncertainty in the D^+ lifetime. The measurements are approximately 3–4 times more precise than the current world average values. The Λ_c and Ξ_c^+ lifetimes are in agreement with previous measurements; however, the Ξ_0 baryon lifetime is approximately 3.3 standard deviations larger than the world average value.

2. Measurement of *b*-hadron fractions in 13 TeV pp collisions

The knowledge of b-hadron fragmentation fractions is important for many reasons. In particular, the knowledge of the production fraction of $\bar{B}_s$ and Λ_b^0 hadrons is a essential for determining absolute branching fractions ($\mathscr{B}$) of decays of these hadrons at the LHC. Then, it allows for relating the pp production cross-section from pQCD to the observed hadrons and it allows the characterization of the signal (background) composition in inclusive (exclusive) b-hadron analyses. These fractions must be determined experimentally because they are driven by strong dynamics in the non-perturbative regime.

LHCb has recently measured [7] the ratios $f_s/(f_u + f_d)$ and $f_{\Lambda_b}/(f_u + f_d)$, where the denominator is the sum of B^- and $\bar{B}^0$ contributions. The measurement has been performed in the LHCb acceptance of pseudorapidity $2 < \eta < 5$ and transverse momentum $4 < p_t < 25$ GeV, in 13 TeV pp collisions using data collected by the LHCb experiment, corresponding to an integrated luminosity of 1.67 fb^{-1}. This measurement is an evolution of the previous b-hadron fractions measurements for 7 TeV pp collisions [8]. The analysis uses the inclusive semileptonic decays $H_b \to H_c X \mu^- \overline{\nu}_\mu$, where H_b indicates a b hadron, H_c a charm hadron, and X possible additional particles. Each of the different H_c plus muon final states can originate from the decay of different b hadrons. Semileptonic decays of $\bar{B}^0$ mesons usually result in a mixture of D^0 and D^+ mesons, while B^- mesons decay predominantly into D^0 mesons with a smaller admixture of D^+ mesons. Both include a tiny component of $D_s^+\bar{K}$ meson pairs. Similarly, $\bar{B}_s^0$ mesons decay predominantly into D_s^+ mesons, but can also decay into D^0K^+ and D^+K^0 meson pairs; this is expected if the $\bar{B}_s^0$ meson decays into an excited D_s^+ state that is heavy enough to decay into a DK pair. This contribution has been measured using $D^0K^+X\mu^-\overline{\nu}_\mu$ events. Finally, Λ_b baryons decay semileptonically mostly into Λ_c final states, but can also decay into D^0p and D^+n pairs. The theoretical basis for this measurement is the near equality of semileptonic widths, $\Gamma_{\rm SL}$, for all b-hadron species [9] whose differences are predicted to precisions of about 1%. Background contributions to the b-hadron candidates include hadrons faking muons, false combinations of charm hadrons and muons from the two b hadrons in the event, as well as real muons and charm hadrons from $B \to D\bar{D}X$ decays, where one of the D mesons decays into a final state containing a muon. All the backgrounds are evaluated in two-dimensional η and p_t intervals since the production fraction can depend on them. The separation between combinatorial background and nonresonant semileptonic decays was achieved exploiting the logarithm of the difference between the vertex χ^2 formed by the added hadron track (X) and the $D\mu$ system and the vertex χ^2 of the $D\mu$ system, $\ln(\Delta\chi^2_{\rm V})$, provides separation between combinatorial background and nonresonant semileptonic decays. To distinguish signal from background the $m(D^0h)_C \equiv m(D^0h) - m(D^0) + m(D^0)_{\rm PDG}$has been defined, and has been perform two-dimensional fits to the $m(D^0h)_C$ and $\ln(\Delta\chi^2_{\rm V})$ distributions, where $h = K^+(p)$ for right-sign $\bar{B}_s^0$ (Λ_b) decays. Fig. 2 shows the distribution of $f_s/(f_u + f_d)$ as a function of $p_t(H_b)$. A linear χ^2 fit has been performed. It incorporates a full covariance matrix has which takes into account the bin-by-bin correlations introduced from the kaon kinematics, and PID and tracking systematic uncertainties. These ratios, averaged over the b-hadron transverse momenta from 4 to 25 GeV and pseudorapidity from 2 to 5, are 0.122 ± 0.006 for $\bar{B}_s^0$, and 0.259 ± 0.018 for Λ_b, where the uncertainties arise from both statistical and systematic sources. The Λ_b ratio depends strongly on transverse momentum, while the $\bar{B}_s^0$ ratio shows a mild dependence.

3. Measurement of the relative $B^- \to D^0/D^{*0}/D^{**0}\mu\bar{\nu}_\mu$ branching fractions using B^- mesons from $\bar{B}_{s2}^{*0}$ decays

The composition of the inclusive bottom-to-charm semileptonic rate is not fully understood. Measurements of the exclusive branching fractions do not saturate the total $b \to c$ semileptonic rate as determined from analysis of the charged lepton's kinematic moments. One way to resolve this inclusive–exclusive gap is to make measurements of relative rates between different final states. The contribution of excited states to the total semileptonic rate can be studied using B decays in which the B momentum is known. The decay of the narrow resonance $\bar{B}_{s2}^{*0} \to B^-K^+$ can be used

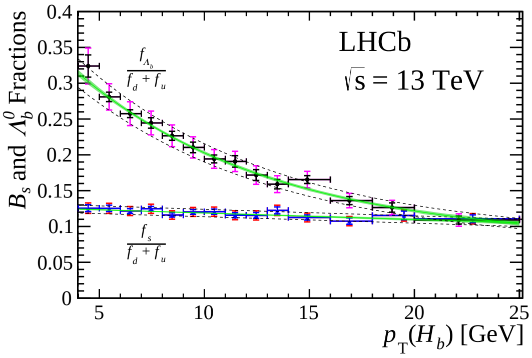

Figure 2: Measured B_s and Λ_b production fractions. The smaller (black) error bars show the combined bin-by-bin statistical and systematic uncertainties, and the larger (blue) ones show the global systematics added in quadrature.

to determine the B^- momentum in partially reconstructed decays without any assumptions on the decay products of the meson. In particular, by tagging B^- mesons produced from the decay of these excited $\bar{B}_{s2}^{*0}$ mesons, the B^- energy can be determined up to a quadratic ambiguity using the $\bar{B}_{s2}^{*0} \to B^-K^+$ and B^- decay vertices and by imposing mass constraints for the $\bar{B}_{s2}^{*0} \to B^-K^+$ and B^- mesons. Since only approximately 1% of B^- mesons originate from a $\bar{B}_{s2}^{*0} \to B^-K^+$ decay, this method requires a large data set. LHCb has published the measurement of the relative $B^- \to D^0/D^{*0}/D^{**0}\mu\bar{\nu}_\mu$ branching fractions (referred to as f_{D^0}, $f_{D^{*0}}$, and $f_{D^{**0}}$ respectively) in the $B^- \to D^0X\mu^-\bar{\nu_\mu}$ channel by exploiting this technique [10]. The most important sources are semileptonic decays of B^- and $\bar{B}^0$ mesons not originating from a $\bar{B}_{s2}^{*0}$ and $\bar{B}_{s1}^0$ decay, which represent 83% of the total number of selected candidates. The relative branching fractions are determined from a binned template maximum likelihood fit to the missing mass distributions $m^2_{miss} = (p_B - p^2_{vis})$ (wherep_B is the four momentum calculated from E_B and the B^- and p_{vis} that one of the $D^0\mu^-$ combination). The result of the template fit is shown in Fig. 3. We find the parameters of interest

$$f_{D^0} = \mathscr{B}(B^- \to D^0\mu^-\bar{\nu_\mu})/\mathscr{B}(B^- \to D^0X\mu^-\bar{\nu_\mu}) = 0.25 \pm 0.06,$$
$$f_{D^{**0}} = \mathscr{B}(B^- \to D^{**0}\mu^-\bar{\nu_\mu})/\mathscr{B}(B^- \to D^0X\mu^-\bar{\nu_\mu}) = 0.21 \pm 0.07,$$

with $f_{D^{*0}} = 1 - f_{D^0} - f_{D^{**0}}$, where the uncertainty is the total due to statistical and systematic uncertainties. The results are compatible with expectations based on previous exclusive measurements [11]. Moreover, it has been demonstrated that the reconstruction of the momentum of B decays with missing particles using B_{s2}^{*0} is a viable method at the LHCb experiment.

4. Search for the rare decays $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$

Leptonic decays of the B^+ meson are rare, as branching fractions are proportional to the squared magnitude of the small Cabibbo-Kobayashi-Maskawa (CKM) matrix element V_{ub}. Among these processes, the decays $B^+ \to \tau^+\nu_\tau$ and $B^+ \to \mu^+\nu_\mu$ have precise Standard Model (SM) predictions [12] given the absence of hadrons in the final state. The radiative version of the muonic decay, $B^+ \to \mu^+\nu_\mu\gamma$, is important for two reasons; it is a background for the $B^+ \to \mu^+\nu_\mu$ decay,

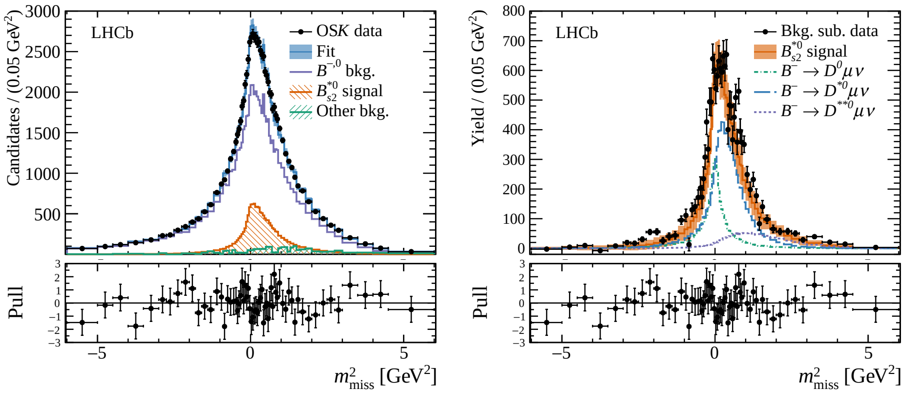

Figure 3: Template fit to the missing-mass distribution. The full distribution (left) is shown, comparing the background to the sum of the signal templates. The background-subtracted distribution (right) is compared to the breakdown of the signal componentsThe statistical uncertainty in the background templates is represented as the shaded band around the fit.

and its branching fraction is a direct measurement of the inverse moment of the B meson light cone distribution amplitude, which is very difficult to calculate theoretically [13]. A B decay vertex with just a single charged particle makes these searches highly challenging in the LHC environment. This problem is not present for the decay $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ that receives a contribution from the $B^+ \to \mu^+\nu_\mu\gamma^*$ with $\gamma^* \to \mu\mu$ amplitude, where the annihilation to the $\mu^+\nu_m u$ pair occurs through an intermediate B^* meson. It also receives contributions from the $B^+ \to \mu^+\nu_\mu V$ amplitude, where V denotes a vector meson such as the ω or the ρ, that can decay to a pair of muons. With these contributions, nearly all decays have a muon pair with a mass below 1 GeV$/c^2$. A recent theoretical calculation based on vector-meson dominance predicts that the corresponding branching fraction, $\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)$, is around 1.3×10^{-7} [14]. LHCb has recently published the search for the decay $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ [16] using a partial reconstruction method that infers the momentum of the missing neutrino to obtain a mass estimate of $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ decays. This search uses proton-proton collision data corresponding to an integrated luminosity of 4.7 fb^{-1} collected during the three periods 2011 (7 TeV collision energy), 2012 (8 TeV) and 2016 (13 TeV) at the LHCb experiment. The main categories of background are: combinatorial; misidentified combinations, where two muons are correctly identified but the third particle is a misidentified hadron; and partially reconstructed decays that have an almost identical final state to the signal. Probabilities of misidentifying hadrons as muons are obtained from data as a function of momentum and pseudorapidity by using control samples where the hadron species are determined purely from the kinematic properties of the decay chain [15]. The level of partially reconstructed backgrounds, instead, where three muons are correctly identified but one or more particles in addition to a neutrino are not reconstructed, is determined using simulation. The branching fraction of $B^+ \to \mu^+\mu^-\mu^+\nu_\mu$ signal is obtained by normalising to the $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ decay as

$$\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu_\mu) = \mathscr{B}(B^+ \to J/\psi K^+) \times \mathscr{B}(J/\psi \to \mu^+\mu^-) \\ \times \frac{\varepsilon(B^+ \to J/\psi K^+)}{\varepsilon(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)} \times \frac{N(B^+ \to \mu^+\mu^-\mu^+\nu_\mu)}{N(B^+ \to J/\psi K^+)},$$

where N is the yield of the decay, ε is the overall efficiency to reconstruct and select the decay. The braching fractions are taken from Ref. [4]. In order to determine the signal yield, an extended unbinned maximum-likelihood fit is performed to the corrected mass distribution. To improve the sensitivity of the mass fit, an event-by-event uncertainty on the corrected mass is calculated by propagating the uncertainties of the primary vertex and secondary vertex. No signal is observed for the decay and an upper limit of 1.6×10^{-8} at 95% confidence level is set on the branching fraction, where the lowest of the two $\mu\mu$ mass combinations is below 980 MeV/c^2. Under the assumption that the decay is dominated by intermediate vector mesons, the limit for the full kinematic region stays the same. The limit on the branching fraction is in tension with a recent theoretical calculation based on the vector-dominance model [14].

5. Conclusion

Semileptonic decays are a laboratory for testing the b-hadron properties. The last LHCb results are presented in this contribution and several other measurements are ongoing.

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