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

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The semileptonic b-hadron decays, which proceed via charged-current interactions, provide powerful probes for testing the Standard Model and searching for New Physics effects. The advantages of studying such decays include the large branching fractions and reliable calculations of the hadronic matrix elements. Several SM features can be studied, such as the ratios of branching fractions, CKM parameters, properties of b-hadrons production, form factor parameters and Wilson coefficients. This contribution presents a selection of recent LHCb results on the measurements of the ratios between tauonic and muonic semileptonic decays, the evidence of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays and the branching fraction measurement of the $\Lambda \to p\mu^-\bar{\nu}_\mu$ decay. With the new data collected using the upgraded LHCb detector and higher instantaneous luminosity in Run 3, further improvements in the precision of semileptonic decay measurements are expected.

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1. Introduction

The semileptonic charged-current b hadron decays refer to the processes in which the b quark interacts with the charged W boson, such as $H_b \to H_c l \nu_l$ where $H_{b,c}$ denotes a hadron containing a b or c quark, l represents a charged lepton and ν_l is the corresponding neutrino. In the Standard Model (SM), the electroweak coupling strength is identical for all generations of leptons. This property, called Lepton Flavor Universality (LFU), can be violated in the presence of some new interactions between the b quark and the lepton, mediated by potential New Physics (NP) particles such as a leptoquark [1] or a charged Higgs [2].

Studying charged-current b hadron decays provides good opportunities to test the LFU by measuring the ratio of branching fractions

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c l \nu)}{\mathcal{B}(H_b \to H_c l' \nu)}, \tag{1}$$

where l and l' denote leptons of different generations. This ratio benefits from the cancellation of common systematic and hadronic form-factor uncertainties. At present, there is more than 3σ tension between the experimental results and theoretical predictions for the combination of $R(D^*)$ and $R(D)$ [3].

This proceeding presents recent LHCb results related to the measurements of $R(D^{(*)-})$ in in Section 2 and 3, the evidence for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays and $R(D^{**0})$ in Section 4 and the branching fraction measurement of $\Lambda \to p\mu^-\bar{\nu}_\mu$ decay in Section 5.

2. Measurement of $R(D^+)$ and $R(D^{*+})$ using $\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau$ decays

The first simultaneous measurement of $R(D^{(*)+})$ at LHCb is performed [4] using the data collected during 2015-2016, corresponding to an integrated luminosity of 2.0 fb^{-1} from pp collisions at a center-of-mass energy of 13 TeV. The decays $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, $D^{*+} \to D^+\pi^0$ and $D^+ \to K^-\pi^+\pi^+$ are considered in this analysis. Notably, this is the first LHCb measurement of $R(D^+)$.

In order to increase the statistics of the simulated sample, a technique referred to as tracker-only simulation [5] is used, where only the tracking components of the detector are simulated, while the PID response and related trigger quantities are emulated. This is the first analysis at LHCb using this strategy, which makes the simulation eight times faster compared to a fully simulated detector, and reduces the event size by 40%.

To extract branching fractions, this study uses a three-dimensional template fit, similarly to previous measurements employing $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decay [6]. The three fit variables are the four-momentum transferred to the $l^-\bar{\nu}_l$ system ($q^2 \equiv (p_B - p_{D^{(*)}})^2$), squared invariant mass of missing particles ($m^2_{miss} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$) and the energy of the muon in the B meson rest frame (E^*_μ). The $R(D^+)$ and $R(D^{*+})$ values [4] are determined to be

$$R(D^+) = 0.249 \pm 0.043\ (\text{stat}) \pm 0.047\ (\text{syst}),\ R(D^{*+}) = 0.402 \pm 0.081\ (\text{stat}) \pm 0.085\ (\text{syst}), \tag{2}$$

where the correlation coefficient between the two measurements is -0.39. The results are compatible with both the world average and agree with the SM prediction within about 1σ [7].

3. Measurement of $R(D^{*-})$ using $B^0 \to D^{*-}\tau^+\nu_\tau$ decays with hadronic τ

This measurement [8, 9] updates the previous $R(D^{*-})$ value, obtained using Run 1 data [10, 11], with the data collected by LHCb during 2015 and 2016. The τ^- candidates are reconstructed in the hadronic final state $3\pi(\pi^0)\nu_\tau$ where $3\pi \equiv \pi^+\pi^-\pi^-$ and the D^{*-} candidates are reconstructed in $D^{*-} \to \bar{D}^0(\to K^+\pi^-)\pi^-$. The decay $B^0 \to D^{*-}3\pi$ is chosen as normalization mode for deriving the branching fraction of the signal mode, and $R(D^{*-})$ can be obtained as

$$R(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \times \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}, \tag{3}$$

with the measured branching fraction of $B^0 \to D^{*-}\mu^+\nu_\mu$ [12]. The dominant background source is the decay in which 3π system comes from the B^0 vertex directly. To suppress this contribution, a minimal distance between the B^0 and 3π vertices along the beam direction is required. Boosted decision tree (BDT) classifiers are employed to suppress the combinatorial and partially reconstructed background. A classifier, named anti-D_s BDT, is trained using variables related to the energy of neutral particles within a cone geometry around the 3π system direction and other corrected kinematic variables. This BDT is used to suppress background where the D_s decays to $3\pi(X)$, mainly through $\eta(\to \pi^+\pi^-\pi^0)$ and $\eta'(\to \pi^+\pi^-\eta)$ intermediate states, which mimics the hadronic τ decay. The BDT output is also adopted as the fitting variable for the signal extraction.

A three-dimensional binned template fit to the variables $q^2 \equiv (p_B - p_{D^{(*)}})^2$, decay time of the τ^+ candidate (t_τ) and anti-D_s BDT are performed to extract $B^0 \to D^{*-}\tau^+\nu_\tau$ signal yields. With the measured $\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$ and $\mathcal{B}(B^0 \to D^{*-}3\pi)$, the measured $R(D^{*-})$ is

$$R(D^{*-}) = 0.260 \pm 0.015(\text{stat}) \pm 0.016(\text{syst}) \pm 0.012(\text{ext}), \tag{4}$$

where the third uncertainty is due to the uncertainties on the external branching fractions [8, 9]. Combined with the previous $R(D^{*-})$ results using hadronic τ decays [10, 11] and Run 1 data, the value of $R(D^{*-})$ [8, 9] is

$$R(D^{*-})_{\text{comb}} = 0.267 \pm 0.012(\text{stat}) \pm 0.015(\text{syst}) \pm 0.013(\text{ext}), \tag{5}$$

which is one of the most precise results to date and consistent with the world average and the SM prediction [3].

4. Evidence for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays

To understand the long standing discrepancy between the $R(D^{(*)})$ measurement and the SM prediction [3], potential sources of systematic effects are investigated and one of them is the limited knowledge on the $B \to D^{**}\tau^-\bar{\nu}_\tau$ decays which contaminates the $B \to D^*\tau^-\bar{\nu}_\tau$ sample.

With the 9.0 fb^{-1} data collected at centre-of-mass energies of 7, 8, and 13 TeV, a search for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays and the measurement of the branching fractions for $B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau$ decay are conducted [13], where the $D^{**0}_{1,2}$ is the combined contribution from the $D_1(2420)^0$ and $D_2^*(2460)^0$ mesons. Analogously to the $R(D^{*-})$ measurement using hadronic τ decays described in Sec. 3, this study adopts a similar strategy to suppress the background such as $B \to D^{**0}\pi^-\pi^-\pi^+X$

decays by requiring the displacement along the beam axis between the τ^- and B^- vertices. The anti-D_s BDT is adopted to suppress the background D_s^- decays to 3π, which mimic the hadronic τ decay.

A three-dimensional binned maximum likelihood fit to the anti-D_s BDT output, squared mass of $\tau^-\bar{\nu}_\tau$ system q^2 and the difference between the mass of D^{**0} and D^{*+} $\Delta m \equiv m(D^{*+}\pi^-) - m(D^{*+})$ is performed to extract the signal yields.

The normalization channels $B^- \to D^{**0}_{1,2} D_s^{(*)-}$ are used for the $\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau)$ measurement and the signal yields of the normalization modes are obtained after the sideband subtraction around the D_s^- mass peak. The branching fraction is obtained as

$$\mathcal{B}(B^- \to D^{**0}_{1,2}(\to D^{*+}\pi^-)\tau^-\bar{\nu}_\tau) = (0.051 \pm 0.013\ (\text{stat}) \pm 0.006\ (\text{syst}) \pm 0.009\ (\text{ext}))\%, \quad (6)$$

where the third uncertainty arises from the normalization mode branching fraction uncertainty [13]. The evidence for the decay $B^- \to D^{**0}(\to D^+\pi^-)\tau^-\bar{\nu}_\tau$ is obtained with a significance of 3.5σ [13]. Using the measured branching fractions of $B^- \to D^{**0}_{1,2}\mu^-\bar{\nu}_\mu$ [12], the value of $R(D^{**0}_{1,2})$ [13] is obtained as

$$R(D^{**0}_{1,2}) = (0.13 \pm 0.03\ (\text{stat}) \pm 0.01\ (\text{syst}) \pm 0.02\ (\text{ext}))\%, \quad (7)$$

These results represent the first measurements of both the branching fraction and the corresponding $R(D^{**0}_{1,2})$ value, which is consistent with the SM prediction.

5. branching fraction measurement of $\Lambda \to p\mu^-\bar{\nu}_\mu$ decay

Until now, there is no evidence for LFU violation in the decays of the $s \to u$ transition. With the measured $\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)$ [12], the measurement of decay ratio

$$R^{\mu e} \equiv \frac{\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)} \quad (8)$$

is performed [14] using the LHCb data collected at a center-of-mass energy of 13 TeV during 2016–2018, corresponding to an integrated luminosity of 5.4 fb^{-1}. The decay $\Lambda \to p\pi^-$ is used as normalization mode, adopting similar selections to the signal mode to reduce the systematic uncertainty. The main source of background is $\Lambda \to p\pi^-(\to \mu^-\bar{\nu}_\mu)$, which mimics the signal mode. To suppress this contribution, selection on the $p_T(\nu_\mu)$ vs $m(p\mu)$ plane is applied, where $m(p\mu)$ is the invariant mass of the $p\mu$ system and $p_T(\nu_\mu)$ denotes the corrected transverse momentum of the neutrino [14]. The Armenteros–Podolanski plane [15] (p_T of the oppositely charged decay products relative to the Λ flight direction vs their longitudinal momentum asymmetry) is also used to suppress backgrounds both in signal and normalization channels.

A binned maximum likelihood fit to the mass of $p\pi$ system, $m(p\pi)$ and the corrected mass $m_{\text{Corr}}(p\pi)$ using the corrected momentum of π is performed to distinguish the signal, normalization modes and background in data, and the branching fraction is extracted as $\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = (1.46 \pm 0.10)$, where the uncertainty includes statistical, systematic, and external uncertainties [14]. Compared with the previous result measured in the BESIII experiment [16], this result has a factor-of-two improvement in precision. And the $R^{\mu e}$ is obtained as $R^{\mu e}_{\text{exp}} = 0.175 \pm 0.012$ [14] which agrees with the SM prediction [17] within 1 σ.

6. Conclusion and Outlook

In this letter, the first simultaneous $R(D^{(*)+})$ measurement using $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ decay and an update of $R(D^{*-})$ with $\tau \to 3\pi$ decay are presented. Both results are compatible with the world average and SM prediction [3]. The branching fraction for decays $B^- \to D^{**0}_{1,2}(\to D^{*+}\pi^-)\tau^-\bar{\nu}_\tau$ and the corresponding $R(D^{**0}_{1,2})$ are measured for the first time and the evidence for the decay $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ is obtained. In addition, the first LHCb measurement of the branching fraction for the decay $\Lambda \to p\mu^-\bar{\nu}_\mu$ is introduced, providing the most precise result to date and showing consistency with the SM prediction [17].

Several LHCb measurements for LFU tests with Run 2 data are still ongoing. The upcoming Run 3 data, collected with the upgraded detector and software-only trigger systems and an instantaneous luminosity increased by a factor of five, will greatly enhance semileptonic analyses, enabling more precise measurements and helping to understand the present discrepancy in $R(D)$-$R(D^*)$.

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